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Development and application of a multi-axis dynamometer for measuring grip force

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Objective: This paper describes the development and application of a novel multi-axis hand dynamometer for quantifying 2D grip force magnitude and direction in the flexion-extension plane of the fingers. *Methods*: A three-beam reconfigurable form dynamometer, containing two active beams for measuring orthogonal forces and moments regardless of point of force application, was designed, fabricated and tested. Maximum grip exertions were evaluated for 16 subjects gripping cylindrical handles varying in diameter. *Results*: Mean grip force magnitudes were 231 N (SD = 67.7 N), 236 N (72.9 N), 208 N (72.5 N) and 158 N (45.7 N) for 3.81 cm, 5.08 cm, 6.35 cm and 7.62 cm diameter handles, respectively. Grip force direction rotated clockwise and the centre of pressure moved upward along the handle as handle diameter increased. *Conclusions*: Given that the multi-axis dynamometer simultaneously measures planar grip force magnitude and direction, and centre of pressure along the handle, this novel sensor design provides more grip force characteristics than current sensor designs that would improve evaluation of grip characteristics and model-driven calculations of musculoskeletal forces from dynamometer data.

Practitioner Summary: The dynamometer was designed to isolate and describe force vectors produced by the finger segments. It may be particularly more suitable than current grip force dynamometers for improving model-based estimations of musculoskeletal forces and stresses that could ultimately improve ergonomic design of devices that interface with the hand.

Keywords: 2D grip force; multi-axis grip dynamometer; handle design

1. Introduction

Frequent and intensive use of hand-operated instruments, such as knives, drills or electronic devices, has been associated with increased risk for chronic musculoskeletal injuries (National Institute for Occupational Safety and Health 1997; National Research Council 2001). An essential aspect of controlling external hand loading is to understand the normal and shear (tangential) forces created between the fingers and the handle. If these relationships were better understood, one could better estimate internal biomechanical loading and design handles that minimise musculoskeletal forces.

The Jamar dynamometer (J.A. Preston Corporation, Clifton, NJ, USA) has been the standard instrument for quantifying grip strength for many years. Similar dynamometers have been used to characterise normative grip capacities for large and diverse groups of people (Blackwell, Kornatz, and Heath 1999; Harkonen, Piirtomaa, and Alaranta 1993; Mathiowetz et al. 1985). Although simple and easy to use, this type of dynamometer measures force in only one direction and has a handle form factor that is not representative of most handles encountered in everyday activities.

Improved grip dynamometers have been designed, but limitations related to the ease, detail and accuracy of grip force measurements and handle shape still exist (Amis 1987; Edgren, Radwin, and Irwin 2004; Irwin and Radwin 2007; Fowler and Nicol 1999; McGorry 2001; Radwin, Masters, and Lupton 1991). Amis (1987) developed a dynamometer that can only measure force exerted by one finger at a time, replicate only a cylindrical handle shape and is specific for a given hand size. The dynamometer described by Fowler and Nicol (1999) is also limited by an inability to measure force from multiple fingers simultaneously. In addition, the sensor cannot divide the total finger force into the contribution from each finger segment. While Radwin, Masters, and Lupton (1991) used a dynamometer to measure force vectors, their instrument cannot resolve the contribution from individual finger segments and it must be gripped twice (Edgren, Radwin, and Irwin 2004). Finally, McGorry (2001) developed a dynamometer that can compute grip force direction only in cases where very careful anthropometric measurements are made of the hand gripping the handle.

Instrumented gloves and force sensor mats applied to handles provide another method for measuring grip force (Hall 1997; Kong and Freivalds 2003; Kong, Freivalds, and Kim 2004; Kong and Lowe 2005; Radwin et al. 1992; Seo and Armstrong 2008; Seo et al. 2007) but important limitations exist. While a glove eliminates the need for the handle to be instrumented, the presence of the glove and embedded sensors may affect grasp interaction between the hand and the handle. Also, while force sensor mats enable measurement of force for each finger segment, each sensor requires calibration

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and can only measure normal force. Furthermore, force sensor mats may shift during use or may be difficult to appropriately contour to account for the geometry of an arbitrarily shaped object. In addition, glove- or handle-mounted sensors may not provide coverage for the entire finger or hand and therefore do not necessarily measure all of the grip force.

If external hand forces can be measured more accurately and easily such that one can more accurately estimate internal musculoskeletal loading with the aid of a biomechanical model, the ergonomic design of hand-held tools and devices could be improved. To this end, a multi-axis grip dynamometer was developed. Our multi-axis dynamometer has the benefits of computing the location of finger force application and preventing thumb forces from confounding finger force, both of which can improve the accuracy of grip force measurements. Like the sensor presented in the study by Radwin, Masters, and Lupton (1991), different caps can be affixed to the dynamometer in order to mimic a wide variety of handle sizes and geometries. Additional benefits of our dynamometer include continuous measurement of grip force such that the rate of force development, fatigue and force variability can be easily determined. This dynamometer has been tested for repeatability and validity in both younger and older adults (Irwin and Sesto 2010). The objectives of this paper are to describe the development and application of the multi-axis grip dynamometer.

2. Methods

2.1. Dynamometer design

The strain gauge dynamometer described by Radwin, Masters, and Lupton (1991), and as used by Edgren, Radwin, and Irwin (2004) and Irwin and Radwin (2007), was the basis for the design of the multi-axis dynamometer. The design objectives for the dynamometer required it to: (1) measure force up to a defined force limit, (2) have sufficient sensitivity to measure very small forces, (3) isolate the forces produced by fingers, (4) measure two independent force vectors per beam (including magnitude, angle and vertical centre of pressure), (5) make all the relevant measurements in one grip exertion, and (6) adapt to a wide range of handle sizes and handle geometries.

As described by Radwin, Masters, and Lupton (1991), an array of strain gauges can be arranged at the base of a cantilever beam so that shear stresses are maximised and therefore the effects of bending stresses are theoretically completely removed. This is described mechanically as:

$$\sigma = \frac{Mc}{I}, \tag{1}$$

where σ is the bending stress in the beam, M the moment from applied load, c the distance from neutral axis and I the moment of inertia.

By mounting the strain gauges in pockets milled at the base, the distance from the neutral axis ‘c’ approaches zero, bending stresses are minimised and all the strain measured by the gauges is shear. Since the load application point does not alter the shear strain (see Equation (2)), the shear strain measurement is the same regardless of point of load application along the cantilever such that:

$$\tau = \frac{VQ}{IT}, \tag{2}$$

where τ represents shear stress, V shear force, Q shear flow and T thickness.

Depending on the curvature and shape of a handle, the point of force application along the finger should affect the force readings. The dynamometer was therefore designed to account for and quantify force vector angles. Compared to the Radwin, Masters, and Lupton (1991) design, the new dynamometer beam includes an additional array of strain gauges in pockets orthogonal to the original set (Figure 1). The gauges were mounted on the neutral axis of the pocket web with the grid lines oriented at 45°. These gauges allow force measurement in the perpendicular direction. Therefore, forces can be measured in both transverse directions so a more complete profile of the forces involved in gripping is obtained.

In addition to the strain gauges mounted in the pockets, another two sets of bending strain gauges are mounted, without pockets, close to the base of the cantilever beam (Figure 1). These strain gauges detect bending moments. Along with the force measurements from the pocket gauges, which are unaffected by point of application, these gauges are used to determine the location that the resultant grip force is applied along the long axis of the beam (Equation (3)). Recording the vertical position of the hand on the dynamometer allows estimation of the contribution of each finger to the overall grip force such that:

$$M = F \times H, \tag{3}$$

where M is the bending moment due to applied force, F the applied force and H the vertical distance from the bending moment strain gauges to the point of force application.

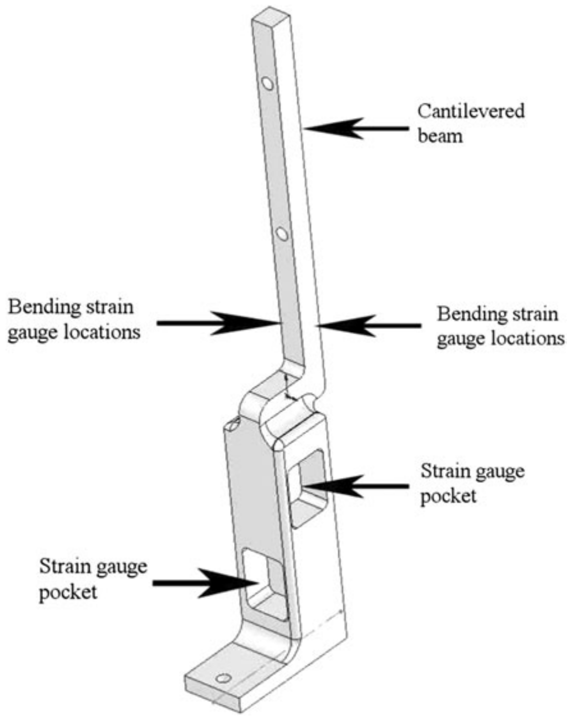

Figure 1. Strain gauge locations.

The strain gauges were configured as a full Wheatstone bridge. Micro-Measurement (Raleigh, NC, USA) strain gauges (350 Ω) packaged as rosette were used and and compensated for 2024-T81 aluminium. Since the lower (instrumented) section of each beam is larger than the cantilevered section, the cantilevered segment is offset from the bottom segment to allow multiple beams to be mounted close together without interference. This is important for simulating small diameter handles. Figure 2 defines all of the variables that are measured using a single instrumented beam. The value for each variable is described in Table 1.

The three aluminium beams, with associated caps, are depicted in Figure 3. Two of the beams are instrumented as in Figure 1, and a third is a non-instrumented static reference beam. The instrumented beams are designed to be sensitive enough to detect forces in the range of 5–250 N, yet be sufficiently stiff to resist deflections of more than a few millimetres when large forces are applied.

The static reference beam serves two functions. First, it is a stationary reference point from which the instrumented beam deflections, and therefore the forces applied, can be measured. Second, it eliminates artefact forces produced by the thumb. An adjustable flange is connected to the thumb beam and its cap when gripping smaller diameter handles to ensure

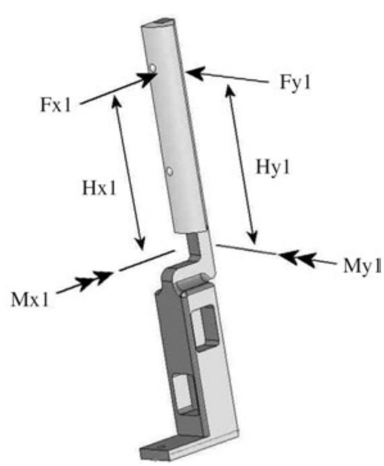

Figure 2. Measurement capabilities of one instrumented beam.

Table 1. Measurement of dynamometer variables.

Variable	Measurement method
F_{1x}	Strain gauges mounted in pockets
F_{1y}	
M_{1x}	Strain gauges mounted on side of beam
M_{1y}	
H_{1y}	Calculated from $M_{1x} = H_{1y} \times F_{1y}$
H_{1x}	Calculated from $M_{1y} = H_{1x} \times F_{1x}$

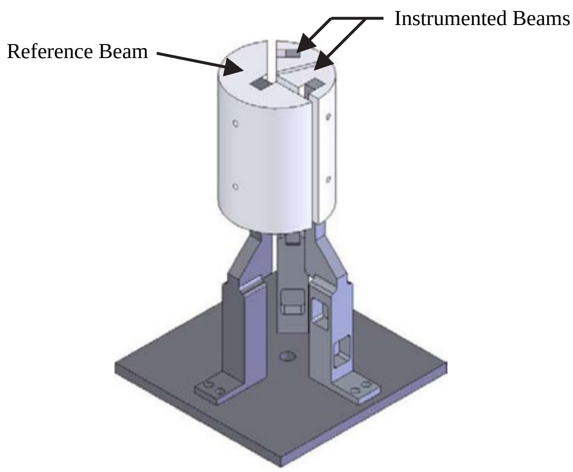

Figure 3. Dynamometer with 7.62 cm diameter caps.

the thumb does not come into contact with the instrumented beams. When the flange is present, the thumb exerts force against the flange so it does not interfere with the measured finger forces.

2.2. Dynamometer calibration

2.2.1. Procedure

A calibration study of the multi-axis dynamometer was conducted to ensure force linearity, sensitivity and accuracy in measuring multiple force vector information. Each beam was calibrated independently. The beams were oriented and rigidly clamped horizontally. Three known weights (9.8 N, 58.4 N, 80.6 N) were suspended at seven points along the long axis of the beam (1.27 cm from the bending gauges to 8.89 cm in 1.27 cm increments) similar to that discussed by Radwin, Masters, and Lupton (1991), and the resulting output voltage was measured. The bending moment strain gauges, designed to help determine the location on the long axis where the resultant force acts, were calibrated in a similar fashion.

2.2.2. Data Analysis

Linear regression analyses were performed to investigate variation in output voltage due to suspended weight location for various applied loads. Linear regression analysis was also performed to examine output voltage due to applied bending moment.

2.3. Pilot maximal grip force study

2.3.1. Subjects

A total of 16 subjects (8 male and 8 female) participated in the maximum grip force study. Participants ranged in age from 22 to 41 years old. Average hand length was 18.77 cm (SD = 1.47 cm) and average hand breadth was 8.13 cm (0.65 cm). All subjects were right-hand dominant and were required to be injury-free in the right arm. Participants were interviewed and demographic data were collected. They were paid on an hourly basis and the experimental protocol was reviewed and approved by the University of Wisconsin Human Subjects Committee.

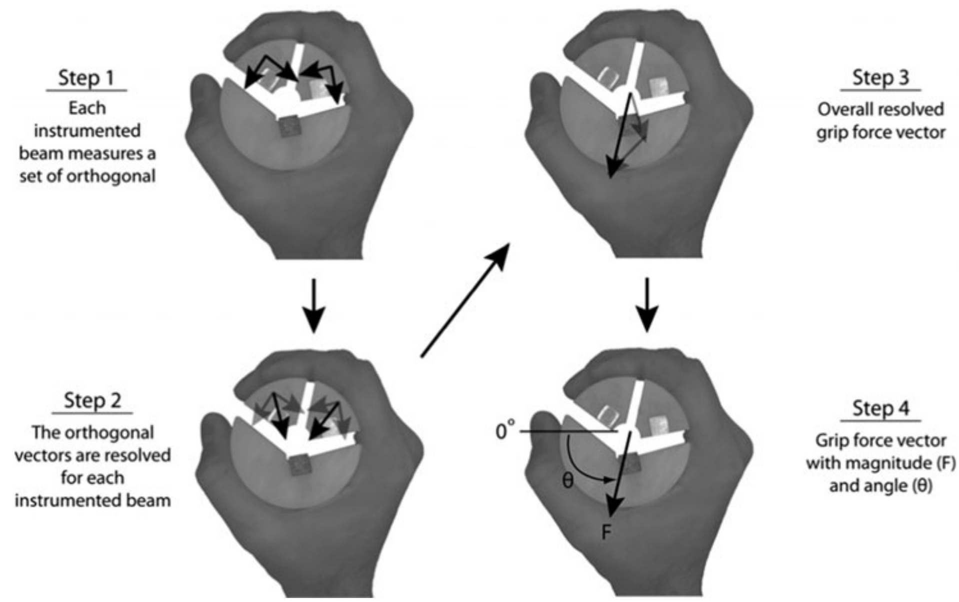

Figure 4. Hand placement and grip force measurement.
Note: For each subject, the metacarpophalangeal joints were aligned with the vertical gap between the proximal instrumented beam and the reference beam on the handle to ensure consistent hand placement for calculation of vertical centres of pressure. Components of grip force are measured by proximal and distal instrumented beams (Step 1). Grip force is calculated after a series of vector additions (Steps 2–4). The origin of the force is located at the centre of the instrumented (fingers) and reference (thumb) beams.

2.3.2. Procedure

Grip force testing was conducted according to the procedures recommended by the American Society of Hand Therapists (Mathiowetz et al. 1985). Subjects were seated with elbow joint flexed at approximately 90° with the forearm and wrist in a neutral position. The metacarpophalangeal (MCP) joints were aligned with the vertical gap between the proximal instrumented beam and the reference beam on the handle to ensure consistent hand placement for calculation of vertical centres of pressure (Figure 4).

Subjects were instructed to squeeze the multi-axis dynamometer using maximum force for 5 s. The start and stop times were announced by the experimenter. The experimenter visually inspected the force data after each trial and selected the portion of the force output after the grip forces had stabilised. Two replications were performed at each of four handle sizes (handle 1 = 3.81 cm, handle 2 = 5.08 cm, handle 3 = 6.35 cm and handle 4 = 7.62 cm) for a total of eight exertions. A three-minute rest was given between trials. The order in which the handles were presented was randomised.

2.3.3. Data analysis

The resultant of the orthogonal force components measured by each instrumented beam was calculated. The grip force vector (F) magnitude and angle were then calculated by finding the vector sum of the resultant vectors of each instrumented beam (Figure 4). The magnitude of F was used to determine which replication produced the maximum grip force. Only the data from the trial producing the maximum grip force were used in the analysis. For each beam, the centres of pressure were averaged.

Hand sizes were divided into the largest and smallest 50% based on median hand length ($n = 8$ for both groups). The effects of handle diameter on grip force characteristics (magnitude, direction, centre of pressure) were evaluated using the analysis of variance and *post hoc* Bonferroni pairwise analysis. In cases where a characteristic varied linearly with handle diameter, a regression analysis was performed.

3. Results

3.1. Dynamometer design

As expected, the output voltages from the pocket strain gauges were insensitive to the location of applied force along the length of the dynamometer (Figure 5). Also, output voltage from bending moment strain gauges varied linearly with bending moment ($R^2 = 0.99$).

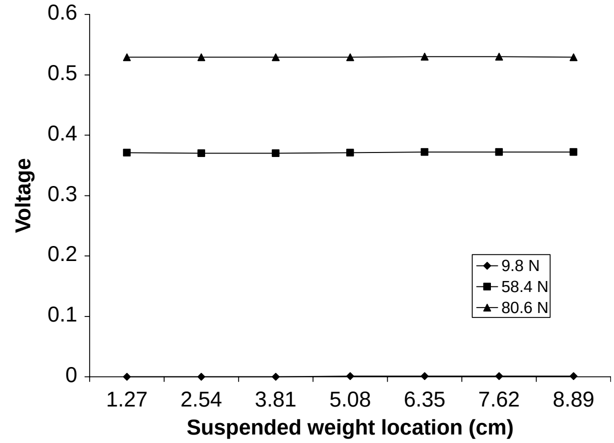

Figure 5. Strain gauges characteristics.
Note: The strain gauges mounted in the pockets produce the same force measurement regardless of point of force application.

3.2. Pilot maximum grip force study

With few exceptions, grip force magnitude decreased and the grip force vector rotated clockwise, i.e. away from the thumb tip (see angle reference in Step 4, Figure 4), with an increase in grip handle diameter. Specifically, mean grip force magnitudes were 231 N (SD = 67.7 N), 236 N (72.9 N), 208 N (72.5 N) and 158 N (45.7 N) for the 3.81 cm, 5.08 cm,

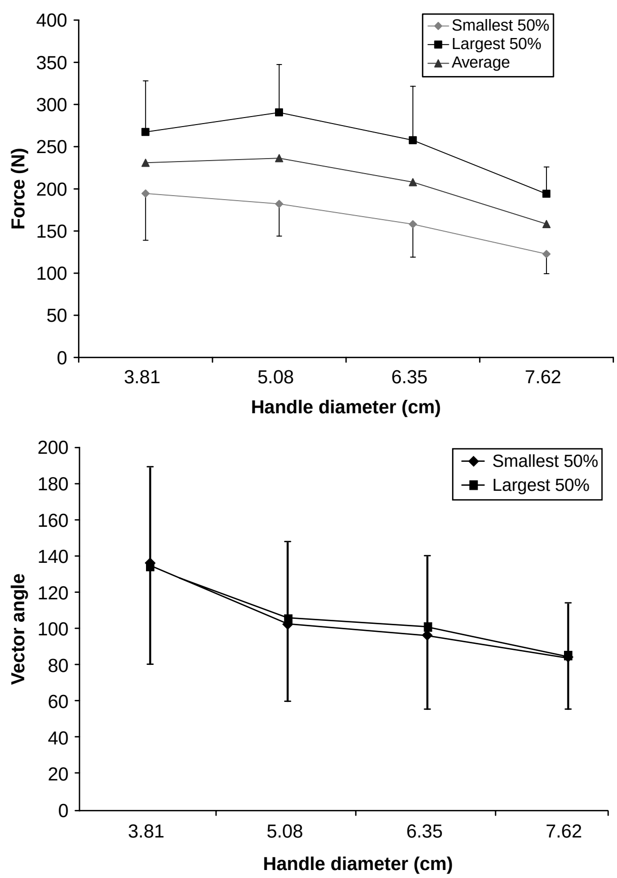

Figure 6. Grip force magnitude and directional variations with handle diameter.
Note: Grip force magnitude decreased with increase in handle diameter ($p < 0.05$) except when comparing force magnitudes for handle 1 and handle 2, and for handle 1 and handle 3. Grip force vector direction decreased with increase in handle diameter ($p < 0.05$) except when comparing force directions for handle 2 and handle 3. A decrease in force vector direction corresponds to clockwise rotation in force vector towards the thumb tip (Figure 4).

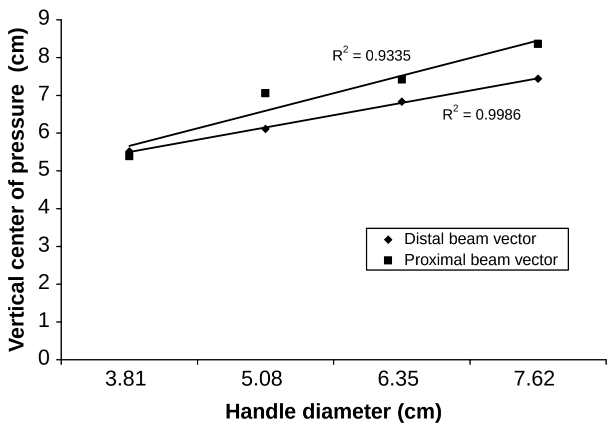

Figure 7. Vertical centres of pressure variations with handle diameter.
Note: Vertical centre of pressure for each instrumented beam increased linearly with grip handle diameter.

6.35 cm and 7.62 cm diameter handles, respectively. Significant differences existed for all comparisons except for handle 1 versus both handles 2 and 3 (Figure 6; $F(3,13) = 27.286$, $p < 0.01$). Corresponding mean resultant grip force directions were 134° (13.6°), 107° (4.7°), 99.2° (8.2°) and 85.9° (7.9°). Significant differences existed for all comparisons except for handle 2 versus handle 3 ($F(3,13) = 27.286$, $p < 0.01$).

Vertical centres of pressure for both the proximal ($F(3,8) = 5.0$, $p < 0.05$) and distal ($F(3,13) = 19.8$, $p < 0.05$) instrumented beams moved upward, in the direction of the radial side of the palm, with grip handle diameter (Figure 7) and varied proportionally with handle diameter. The coefficient of determination for the variation in the proximal beam was 0.9335 and for the distal beam was 0.9986.

4. Discussion

The goals of the study were to describe the development and application of a novel multi-axis dynamometer that measures 2D grip force in the flexion-extension plane of the fingers. The novel sensor design permitted continuous measurement of force that could account for contributions from different segments of the finger, provided that separate segments were in contact with the proximal and distal instrumented beams. Force measurement was made independent of the point of force application while simultaneously measuring applied handle torque that permitted calculation of the centre of pressure of force. The handle was modifiable for different grip sizes and object geometries, and only needed to be gripped once to measure force and centre of pressure. We believe this multi-axis grip dynamometer, an extension of previous work from our laboratory (Edgren, Radwin, and Irwin 2004; Radwin, Masters, and Lupton 1991), is the first of its kind and represents an enhancement to current grip force dynamometers in the field.

The calibration results demonstrate favourable characteristics of the dynamometer design. The calibration for the pocket strain gauges illustrate that the dynamometer could be gripped arbitrarily without impacting grip force measurement. This characteristic enables straightforward use of the dynamometer particularly in circumstances where subjects may tend to grip differently, e.g. for a range of different hand sizes, or following injury or disease. The calibration results for the bending moment strain gauges show well-defined, simple relationship between output voltage, applied force and location of applied force. It is no surprise that there was a linear relationship between output voltage in the bending moment strain gauges and the applied bending moment.

The novel design of the dynamometer facilitates estimation of the relative contributions of proximal and distal finger segments during gripping when such finger segments were aligned with each instrumented beam. Specifically, this was accomplished by integrating output of the strain gauges mounted on the surface of the beams that measured bending moments with output of the pocket-mounted strain gauges used to find the vertical centres of pressure (Equation (3)). As previously shown, grip force vector direction decreased with increasing handle diameter, i.e. the force rotated clockwise towards the thumb for all subjects (Figures 4 and 6). This result agrees with that of a previous study (Edgren, Radwin, and Irwin 2004) in which 2D grip force was measured in men and women with various sized hands using two grip exertions in orthogonal directions. We also showed that maximum grip force variation with handle diameter was shaped like an inverted-U, in which grip force initially increased and then decreased with increasing handle diameter (Figure 6). This variation is consistent with previous studies in which other handle shapes were employed but only the normal force component of grip force was measured (Edgren, Radwin, and Irwin 2004; Irwin and Radwin 2007; Fitzhugh 1973; Oh and

Radwin 1993). This agreement suggests that grip force variation is robust to handle shape and that the normal force component predominates the other grip force components.

Grip force variation with handle diameter could be reflective of underlying changes in muscle architecture, e.g. muscle fibre lengths. Increases in handle diameter required finger joints to extend, which in turn produced elongations in the long finger flexor muscles, flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP). If the lengths of these muscles were such that they operated on the ascending limb of their force-length curves during grip of the smaller handles (diameters of 3.81–5.08 cm) and on the descending limb during grip of the larger handles (diameters of 5.08–7.62 cm), then well-known changes in muscle force generation capacity due to muscle length variations (Aubert, Roquet, and Van der Elst 1951) could contribute to the measured grip force profile. Alterations in muscle moment arms while handling differ size handles could also contribute to grip force variation. Drawing conclusions from possible muscle moment arm changes, however, is less straightforward. Results from a recent cadaveric study (Franko 2011) showed that changes in FDS and FDP moment arms due to finger extension are not monotonic, though, for most joints, the changes appear to be small over a large joint range (0°–80° of flexion). Perhaps, then, FDS and FDP muscle moment arm changes did not contribute much to variations in grip force with handle diameter. Finally, muscle activation could have influenced grip force as well. In the absence of direct muscle activity measurements or model predictions, it is difficult to speculate how it could have affected grip force measurement. Nevertheless, presumed changes in muscle fibre lengths remain a highly plausible contributing factor given that it was possible for changes in FDS and FDP muscle force generation capacity to mirror that of grip force variation with handle diameter. This is a topic for future research.

In this study, we also illustrated that the centre of pressure moved up the handle towards the index and middle fingers as handle diameter increased (Figure 7). Such displacement of the vertical centre of pressure could be explained by reduced force contribution from the smaller fingers. Perhaps, as the handle diameter increased, the smaller fingers gradually extended to postures where it was increasingly difficult to exert force on the handle. As a result, the centre of pressure moved up and away from the smaller fingers towards the larger fingers. The results from previous research intimate that the position of the vertical centre of pressure remained constant. Amis (1987) reported that the contribution percentage of normal force for each finger was relatively consistent across handle diameters, which would result in no change of the centre of pressure. It is possible that including shear force, as well as normal force, in the measurement of force vectors helps to explain differences in finger force contributions between studies. Radwin et al. (1992) demonstrated similar results to the current study with the index and middle fingers contributing more to the overall pinch force as load level increased. These findings may be useful in the design of hand-held products and equipment. For example, the centre of pressure data could be used to position triggers and buttons in the most beneficial places. It could also be used to design tapered handles that take advantage of the measured trend that certain fingers produce proportionately more force at certain handle diameters.

This multi-axis dynamometer also has numerous additional potential applications including its use as a clinical evaluation instrument (Irwin and Sesto 2010) as well as for ergonomic design. Clinically, researchers have been attempting to link grip strength to overall body strength and general health (Onder et al. 2005; Rantanen et al. 1999; Voorbij and Steenbekkers 2001). In addition to simply measuring grip force, this dynamometer could be used to non-invasively evaluate injury, disease or age-related deficits in maintenance and control of musculoskeletal structures.

Grip force measurements may also serve as direct input to the appropriate musculoskeletal model. Force magnitude and direction and grasp contact point locations – which are unavailable with most grip dynamometers – are integral inputs for biomechanical models for calculation of musculoskeletal kinetics. Calculation of joint or musculotendon forces and stresses in the hand that are influenced by grip force direction and location of vertical centre of pressure might lead to improved hand biomechanical models.

5. Conclusion

In this study, we described the development and application of a novel multi-axis hand dynamometer for quantifying grip force magnitude and direction in the flexion-extension plane of the fingers. This dynamometer was capable of measuring forces produced by different finger segments and prevents confounding influence from the thumb in a single exertion by the hand. Enhanced capabilities of this dynamometer could provide more accurate measurements of grip force that improve model-driven calculations of musculoskeletal kinetics which could, in turn, improve ergonomic design of devices that interface with the hand, e.g. multi-degree-of-freedom handles like joystick controllers or other mechanical devices. The dynamometer could also be potentially used as a tool to assist in evaluation of musculoskeletal injury. As stated earlier, we believe this multi-axis grip dynamometer is the first of its kind and represents an enhancement to current grip force dynamometers in the field.

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