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Technical Note

A linear force-summing hand dynamometer independent of point of application

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Theory, design and construction details are presented for a versatile strain gauge hand dynamometer. What distinguishes this instrument is that sensitivity is completely independent of the location. Force is applied so it is capable of linearly summing forces exerted at multiple locations along the length of the active area of the dynamometer. In addition to including the basic principles of this transducer, a template for the instrument and an accompanying spread sheet is provided for computing transducer response characteristics for instruments of arbitrary size, including sensitivity and force range, depending on particular measurement requirements. Variations of this dynamometer were constructed and used for measuring grip and pinch strength, as well as for measuring submaximal exertions produced during manual activities and tasks. Because this dynamometer is compact and rigid, one of suitable dimensions may be substituted as a handle for tools or objects handled during work for directly measuring applied exertions and grip force. Examples of practical applications of this instrument are given for hand biomechanics, hand tool ergonomics, and clinical evaluations.

Keywords: Biomechanics, dynamometer, force, hand grip, instrumentation, strain gauge

Nomenclature

c	Distance from neutral axis (mm)
E	Young's Modulus (N/mm^2)
E_i	Input voltage (V)
E_o	Output voltage (V)
ϵ	Principle strain
G	Shear Modulus (N/mm^2)
I	Moment of inertia (mm^4)
M	Moment due to bending (N·mm)
υ	Poisson's Ratio
Q	Shear flow (mm^3)
R	Resistance (Ω)
S	Transducer sensitivity (V/N)
S_g	Strain gauge factor
σ	Bending stress (N/mm^2)
T	Thickness through beam (mm)
τ	Shear stress (N/mm^2)
V	Shear load (N)

Introduction

Biomechanics study of hand exertions requires instruments capable of measuring forces ranging from very light touch ($< 0{\cdot}05$ N) to the large compression forces that can be developed during power grip (> 500 N). Hand force measurements are further complicated by the fact that forces are unevenly applied and distributed throughout the palmar and finger surfaces and often involve use of multiple digits. A dynamometer capable of linearly summing the forces applied at multiple points is therefore needed for assessing accurately the total force applied to objects and handles during grasp and pinch. In addition, the transducer must be rigid for measuring isometric forces, and it should be compact enough to attach to handles for measuring forces exerted during activities of daily living, hand tool operation and manual work.

A conventional strain gauge instrument that measures forces using the strain produced from the bending moment of a cantilever beam can achieve the needed linearity, sensitivity, accuracy and force range, but is extremely limited because the point of application must be controlled in order to know the particular bending moment arm. Furthermore, these instruments cannot linearly sum forces

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applied at arbitrary locations along the beam. Because of these constraints, the simple cantilever beam strain gauge system will not suffice for practical hand biomechanical measurements when using an instrumented handle for measuring grip and hand exertions.

Pronk and Niesing (1981) described a strain gauge dynamometer used for grip strength measurements that was independent of point of application of force. This instrument was based on the principle of measuring the shearing stress acting in the cross-section of a beam when a transverse force was applied. This permits the instrument to be independent of the point of application and linearly sum forces. The dynamometer they developed was suitable for measuring grip at maximal contraction levels ranging between 5 N to 500 N for an accuracy of better than 5%. Since the concept resulted in a compact transducer, the authors of this paper considered that it might be useful for measuring actual forces exerted during manual tasks by constructing a dynamometer having dimensions corresponding to objects grasped, such as handles on hand tools. The major obstacle was designing a dynamometer having the desired response properties, such as sensitivity and force range, while conforming to specific handle size constraints.

This paper presents a procedure for designing a linear force summing strain gauge dynamometer for measuring hand force given specific size constraints, and contains examples of applications in biomechanics research, clinical evaluations and ergonomics investigations. A template for the basic hand dynamometer design has been developed and a spreadsheet is included in this paper for illustrating how specific dynamometer parameters are computed, depending on the desired measurement requirements including force range, sensitivity, accuracy and geometric constraints. This spreadsheet may be used for designing hand dynamometers used for a variety of ergonomics applications.

Transducer principles

Instead of basing the dynamometer on sensing bending stresses produced when an applied force creates a bending moment in a cantilever beam, which is commonly used in many strain gauge instruments and is highly dependent on point of application, this dynamometer employs the principle of sensing shear beam stresses. The following discussion describes the theory behind this transducer.

When force (F) is applied against a beam, stresses are produced from both bending and shear. The bending stress (σ) in a beam is described by the moment (M), the distance from the neutral axis (c), and the moment of inertia (I) of the beam as:

$$\sigma = \frac{Mc}{I} \qquad \ldots(1)$$

The shearing stress (τ) in a beam subjected to bending is related to the shear load (V), shear flow (Q), thickness (T) and I such that:

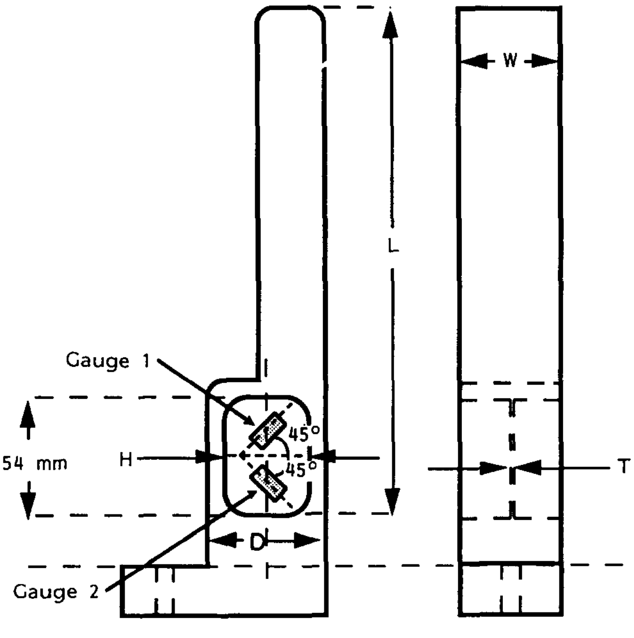
$$\tau = \frac{VQ}{IT} \qquad \ldots(2)$$

By selecting a measurement point directly on the neutral axis of the beam (such that $c = 0$), bending stresses from Eqn (1) are minimised ($\lim_{c \to 0} \sigma = 0$), and because of its location on the neutral axis of the beam, shear stresses are maximised because shear flow is maximum. Consequently, the effects of bending stresses are completely removed from the strain gauges (since $\sigma \to 0$), and all strain at the measurement point is strictly due to shear stress. Furthermore, since M, which is dependent on the load application point, does not affect shear strain (See Eqn 2), and because V is not influenced by M, the strain at the measurement point is totally independent of the point of application.

A drawing of the basic transducer geometry and strain gauge placement is shown in Fig. 1. In order to maximise sensitivity of the cantilever beam, a section of the beam was milled out over the neutral axis (centre line), producing an I-beam web where the strain gauges were located. Two strain gauges are mounted inside the milled out pocket on each side of the web at an angle of 45° with respect to the neutral axis. The 45° orientation aligns the gauges with the principal stress and strain directions on the neutral axis, which are strictly due to shear. The diagram in Fig. 1 exposes Gauge 1 and Gauge 2. Gauge 3 and Gauge 4 are located on the opposite side of the web, and are aligned exactly with Gauge 1 and Gauge 2, respectively. Gauge 1 and Gauge 3 sense a positive strain, while Gauge 2 and Gauge 4 sense a negative strain. As long as the strain gauges are symmetrically mounted across the neutral axis, the bending stresses detected by the far ends of the strain gauges will cancel each other.

The change in resistance $\frac{\Delta R}{R}$ for a strain gauge having a gauge factor S_g is related to the strain (ϵ) in the direction of the grid lines such that:

$$\frac{\Delta R}{R} = S_g \epsilon \qquad \ldots(3)$$



Side view

Front view

Fig. 1 Schematic diagram containing dimensional variables for general dynamometer design. Dimensions that are varied include length (L), width (W), depth (D), pocket horizontal length (H) and web thickness (T)

Principle strain (ϵ) is obtained using the equation:

$$\epsilon = \frac{VQ}{2ITG} \qquad \ldots (4)$$

when the shear modulus (G) is computed from Young's Modulus (E) and Poisson's Ratio (υ) using the relationship:

$$G = \frac{E}{2(1+\upsilon)} \qquad \ldots (5)$$

which is dependent on the material used. Consequently the responses for the four strain gauges (R_1, R_2, R_3, R_4) are described by the equation:

$$\frac{\Delta R_1}{R} = -\frac{\Delta R_2}{R} = \frac{\Delta R_3}{R} = -\frac{\Delta R_4}{R} = \frac{VQ}{2ITG} S_g \qquad \ldots (6)$$

When used in a Wheatstone bridge the relationship between the input voltage (E_i), output voltage (E_o) and shear load V becomes:

$$E_o = \frac{4VQ}{2ITG} S_g E_i = \frac{2VQ}{ITG} S_g E_i \qquad \ldots (7)$$

The sensitivity (S) of this transducer is therefore given by:

$$S = \frac{E_o}{V} = \frac{2QS_gE_i}{ITG} \qquad \ldots (8)$$

Use of template and dynamometer construction

The dynamometer was machined by creating a 25·4 mm pocket for locating the strain gauges on the neutral axis of a metal beam (see Fig. 1). The web thickness used was no thinner than 0·25 mm due to machining limitations of the particular equipment used. A thinner web thickness can increase the dynamometer sensitivity. The pocket height was fixed at a height of 25·4 mm since that height was considered the smallest size practical for access when mounting the strain gauges. Any pocket height smaller in size would make mounting the strain gauges extremely difficult.

The strain gauges were configured as a full Wheatstone bridge. A Daytronic 9178 strain gauge conditioner was used, but any conventional strain gauge amplifier is suitable. Placement of the strain gauges is critical. The strain gauges must be centred on the neutral axis of the web with the grid lines oriented at 45° to the neutral axis. Strain gauges packaged as rosettes make this alignment easier. Micro-Measurements type N2A-13-T031H-350 strain gauges were used for this purpose. The gauge resistance (R) was rated at 350·0 Ω ± 0·2%. It is important that the selected strain gauges are compensated for the particular material used (i e, aluminium, steel, etc). Type 2024-T81 aluminium is a preferred material for strain gauge instruments.

A mounting hole was provided so that the dynamometer can be bolted to a face plate. Any rigid mounting may be used, however. The dynamometer should be fastened securely to prevent excessive deflection under load.

This transducer is designed for measuring transverse force applied in a single axis in the plane of the side view shown in Fig. 1. For measuring grip compression force as a handle, the transducer should be used in conjunction with a parallel reaction arm. The reaction arm may be constructed similarly to the transducer beam. The two bars can be mounted along a track so that the distance between dynamometer arms can be adjusted continuously, creating a variable handle span. The reaction arm may also be instrumented with strain gauges if reaction forces cannot be considered equal and opposite, depending on the free body forces for the specific dynamometer application. If the reaction arm is not fitted with strain gauges, the pocket and web are not necessary.

The limiting conditions for the dynamometer design include: (1) it must not fail under maximum force; (2) the grip size must conform to the application desired; and (3) it must have sufficient sensitivity in the desired force range. These dynamometers are therefore designed based on the maximum expected force and the gripping geometry; given these constraints, sensitivity is maximised by altering the remaining non-critical parameters.

Equations for computing transducer sensitivity and load limits given particular dynamometer dimensions, forces and materials were entered into a spreadsheet. Fig. 2 shows the spreadsheet input and output cell contents. A complete spreadsheet listing, including the equations used for computing dynamometer characteristics, is given in Appendix 1. Spreadsheet range names are in Appendix 2. The spreadsheet was run using Lotus 1-2-3 on an IBM PC/AT microcomputer and also using Microsoft Excel on a Macintosh microcomputer. Appropriate syntax changes may be needed for the particular spreadsheet package used.

The top portion of the spreadsheet (See Fig. 2) is where the desired geometry (L, W, D, T, H from Fig. 1), material, force measurement range and ultimate load data are entered. The lower portion of the spreadsheet contains the resulting output, including strain, sensitivity and failure load. The output section also indicates if selected input values and resulting design parameters are within practical ranges. These include a check if the resulting strain is within practical strain gauge limitations (should be $> 0{\cdot}001$), if the maximum load is moment limited or shear limited, and if the voltage range ratio at maximum shear is as large as possible (should be > 4). It is our experience that the voltage ratio at maximum shear rarely is as large as four, but it is desirable to maximise this parameter.

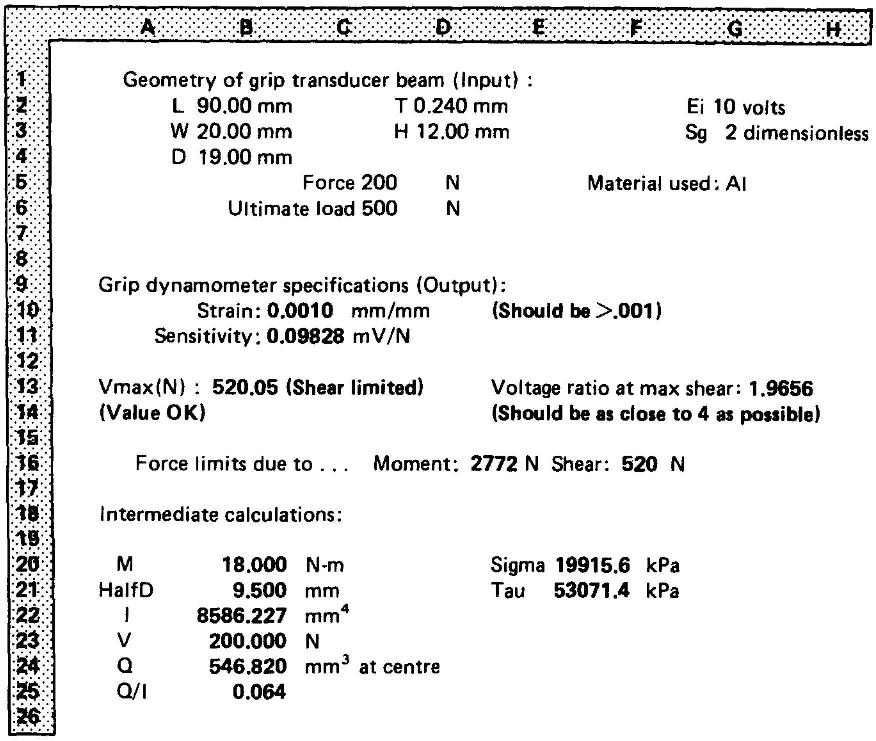
Material constants used in the equations and results from intermediate computations are contained in another section of the spreadsheet shown in Fig. 3. The materials table may be expanded to include other metals if desired by inserting additional lines into the table (in alphabetical order) and adjusting the relative table range (see Appendix 2).

This spreadsheet may be used for iteratively determining dynamometer dimensions and design limitations for particular hand force and sensitivity requirements for designing transducers for particular ergonomics applications. Using a spreadsheet, a particular dimension in the template shown in Fig. 1 can be varied and the sensitivity magnitude of a resulting change observed. At the same time, failure stresses are calculated to insure the dynamometer's integrity. The instruments developed using this technique are then machined based on these calculations and resulting dimensions for specific design specification objectives.

Applications

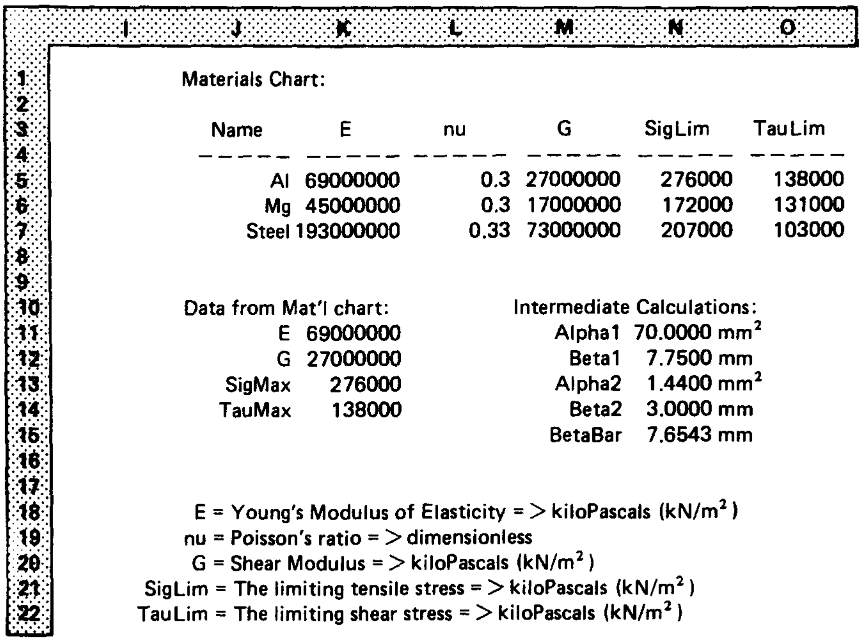
Dynamometer calibration

The dynamometer was calibrated by fastening the beam horizontally to a rigid vertical surface and suspending various load weights within the intended range of use.



```
      A        B        C        D        E        F        G        H
 1     Geometry of grip transducer beam (Input) :
 2        L 90.00 mm              T 0.240 mm                  Ei 10 volts
 3        W 20.00 mm              H 12.00 mm                  Sg  2 dimensionless
 4        D 19.00 mm
 5                  Force 200     N                 Material used: Al
 6          Ultimate load 500     N
 7
 8
 9   Grip dynamometer specifications (Output):
10          Strain: 0.0010  mm/mm        (Should be >.001)
11       Sensitivity: 0.09828 mV/N
12
13   Vmax(N) : 520.05 (Shear limited)      Voltage ratio at max shear: 1.9656
14   (Value OK)                            (Should be as close to 4 as possible)
15
16     Force limits due to . . .  Moment:  2772 N  Shear:  520  N
17
18   Intermediate calculations:
19
20     M         18.000  N-m                Sigma  19915.6  kPa
21   HalfD        9.500  mm                 Tau    53071.4  kPa
22     I       8586.227  mm^4
23     V        200.000  N
24     Q        546.820  mm^3 at centre
25    Q/I         0.064
26
```

Fig. 2 Spreadsheet input/output display. The top portion of the spreadsheet contains input variables including dimensions and force ranges. The lower portion of the spreadsheet displays sensitivity and design limitations. Cells containing equations are presented in bold



```
      I        J        K        L        M        N        O
 1        Materials Chart:
 2
 3          Name       E          nu        G        SigLim     TauLim
 4        -----     -----     -----     -----     -----     -----
 5             Al  69000000     0.3   27000000    276000    138000
 6             Mg  45000000     0.3   17000000    172000    131000
 7          Steel 193000000     0.33  73000000    207000    103000
 8
 9
10        Data from Mat'l chart:          Intermediate Calculations:
11                  E  69000000                 Alpha1  70.0000 mm^2
12                  G  27000000                  Beta1   7.7500 mm
13             SigMax    276000                 Alpha2   1.4400 mm^2
14             TauMax    138000                  Beta2   3.0000 mm
15                                             BetaBar   7.6543 mm
16
17
18          E = Young's Modulus of Elasticity = > kiloPascals (kN/m^2)
19         nu = Poisson's ratio = > dimensionless
20          G = Shear Modulus = > kiloPascals (kN/m^2)
21     SigLim = The limiting tensile stress = > kiloPascals (kN/m^2)
22     TauLim = The limiting shear stress = > kiloPascals (kN/m^2)
```

Fig. 3 Materials and properties section of the spreadsheet. Cells containing equations are presented in bold

Fig. 4 contains response characteristics for a dynamometer used for measuring forces up to 80 N. Least squares linear regression was used for producing a calibration curve and for determining the dynamometer load sensitivity. The resulting force sensitivity for the dynamometer calibration curve shown in Fig. 4 was 2 mV/N. The average resulting coefficient of determination for three different dynamometers calibrated in this manner was 0·999. These results validate the predictions of a linear response made by the modelling equations.

As part of the calibration procedure, the dynamometer was tested for insensitivity to point-of-force application by suspending load weights at various locations along the length of the beam. Fig. 5 illustrates the dynamometer response using load weights between 0·5 kg and 8 kg suspended at points along a distance of 100 mm. The results, showing that output level did not change for loading at different points and loads, verify that the instrument was insensitive to the location of the forces applied.

Grip dynamometer

A common use for a grip dynamometer is for measuring grip compression strength for a power grip. Strength is the maximal voluntary exertion level an individual can produce

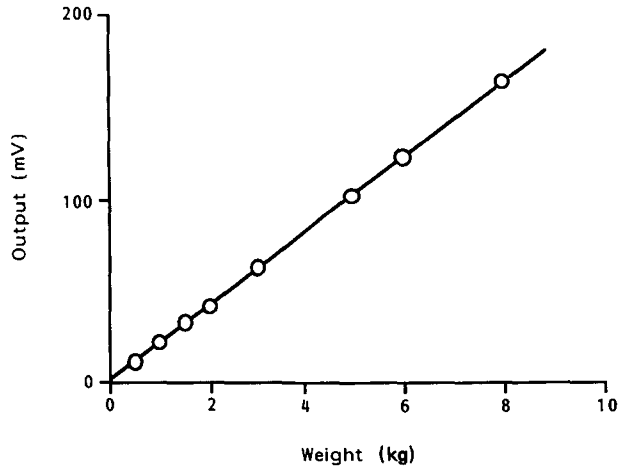


Fig. 4 Dynamometer calibration curve

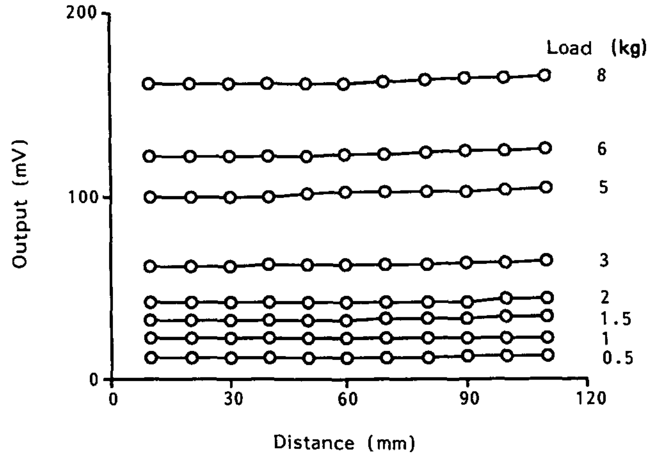


Fig. 5 Output voltage plotted against distance along the length of the dynamometer

for a given grip posture and handle size. Hence the dynamometer was designed for an average force of 250 N and an ultimate load of 1000 N force. The handle length used was 145 mm in order to accommodate hands of various sizes.

Since forces produced during power grip are applied equally and opposite against two bars in the direction of the resultant compressive force, the strain gauge dynamometer may be constructed using one active beam instrumented with strain gauges opposing a parallel reaction beam without strain gauges (See Fig. 6). This instrument may be used for comparing strength data obtained using a conventional spring grip dynamometer since force is measured in a single axis through the fingers and palm. In order to provide variable grip span, the beams were mounted on a track so that they were capable of being separated arbitrary distances. Aluminium caps may be attached to both beams for producing a cylindrical surface as shown in the illustration. Rectangular plates were also attached to the two beams for measuring five-finger pinch force.

This configuration was also used in a number of ergonomics studies involving submaximal exertion levels. Weights of various sizes were suspended from the dynamometer using a wire for measuring forces exerted during manual lifting and carrying tasks (Radwin *et al*, 1991). Another version of this instrument was attached to an electromagnetic shaker stage for directly measuring forces exerted during vibration exposure (Radwin *et al*, 1987), and for providing grip force feedback when controlling vibration transmission to the hand and arm.

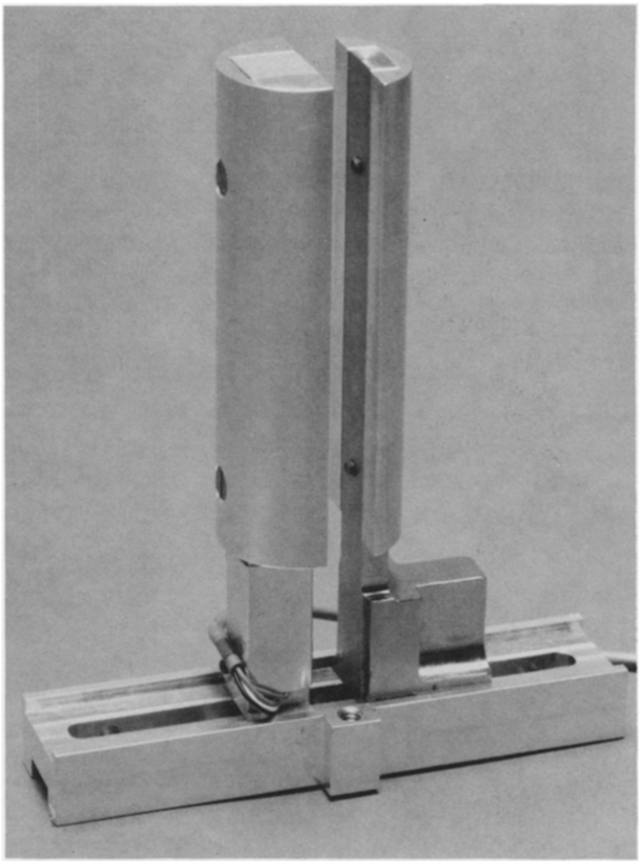


Fig. 6 Dynamometer for measuring strength for a power gripping a cylinder. Aluminium caps were attached to the dynamometer beam for producing a cylindrical surface

Pinch dynamometer for hand rehabilitation

A dynamometer was constructed for particular use in clinical applications for measuring pinch force. This dynamometer consisted of two opposing active dynamometer beams for independently measuring forces exerted by the thumb in opposition to one of the four fingers. This instrument had a 85 mm length and was designed for an average force of 10 N and an ultimate force of 200 N.

Fig. 7 illustrates this instrument. The dynamometer beams were mounted on an adjustable track so that the span between the two beams can be adjusted for accommodating thumb opposition to any of the digits and for controlling pinch span. Since the dynamometer is insensitive to point of application, this instrument was useful for clinical evaluations where it may be difficult to control the location where the fingers apply forces against the bars, particularly when using different fingers. It also allows the clinician to select an unlimited variety of hand postures, accommodate hands of different sizes, and is useful for patients having physical disabilities that limit the range of motion.

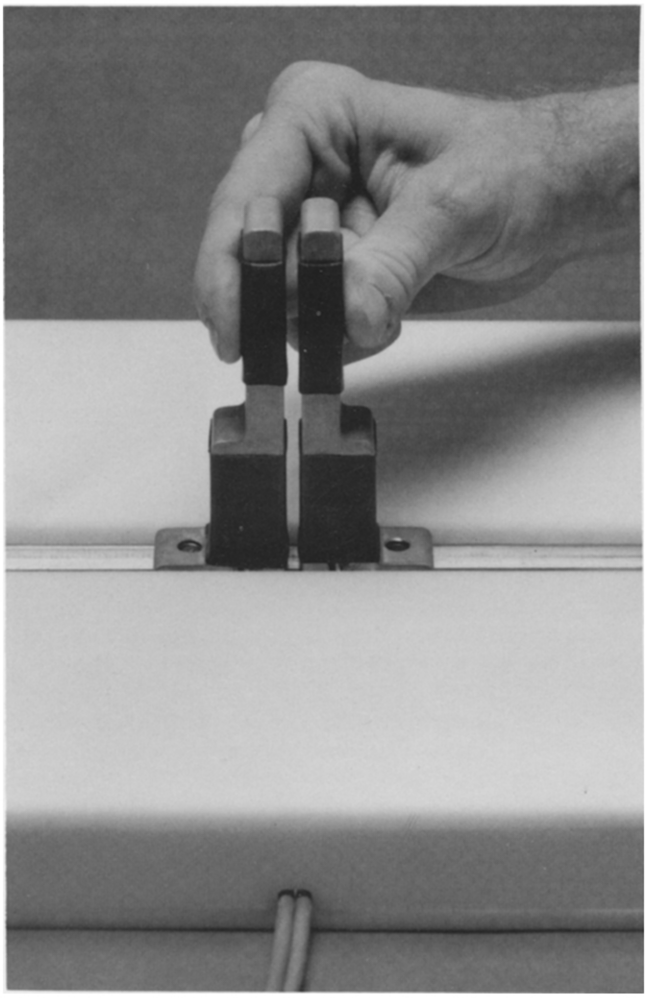


Fig. 7 Two opposing dynamometer beams for measuring index and thumb pinch force

Hand dynamometer for tool ergonomics investigations

A similar dynamometer design was used in an ergonomics study conducted for investigating the forces involved when operating a pneumatic pistol-grip power hand tool. Two instrumented beams were constructed for simulating the handle of a pistol-grip nutrunner. In order to measure palm and finger forces directly, the dynamometers were mounted on a track and attached using a bracket to an in-line power tool for simulating a pistol-grip configuration. This apparatus is shown in Fig. 8.

The tool simulation was completely operational and capable of measuring palm feed force and finger exertions during power tool operation tasks. Plastic caps for the finger and palmar dynamometer bars were constructed and attached for providing a handle resembling the grip of a power tool. A trigger for activating the power tool was integrated into the finger dynamometer cap. The trigger was actually a leaf spring and switch for activating a relay and solenoid valve that controlled the air supply to the tool. The spring tension was adjusted by changing the leaf spring thickness for simulating various triggers on a conventional pistol-grip power tool. Because the dynamometer was capable of linearly adding applied forces, the finger forces exerted when activating the tool and maintaining control of the tool during bolt fastening were summed into the finger force measurements.

Discussion and conclusions

The dynamometer design described in this paper is based on the grip strength dynamometer originally described by Pronk and Niesing (1981). The dynamometer template presented in this paper has been found useful for producing a number of intruments ranging in size and force requirement: The purpose for this article is to present the fundamentals for designing and constructing strain gauge dynamometers for ergonomics applications. The spreadsheet is provided solely as a vehicle for presenting the principles used in the design.

Actual machining of the dynamometer was performed in a professional model-making shop using just the drawing shown in Fig. 1. The machining process for one of these instruments took approximately 8 h. The most difficult aspect was controlling the web thickness. Strain gauge mounting was particularly tedious, requiring a highly skilled technician having great experience in strain gauge applications.

The dynamometer was useful for force measurements for a variety of ergonomics applications. Response characteristics obtained for these dynamometers were proven independent of point of force application, were linear, and they did not fail after repeated use for a variety of force ranges and uses. Several of these dynamometers are currently being used for research projects in our laboratory and for ergonomics evaluations in the field.

Acknowledgements

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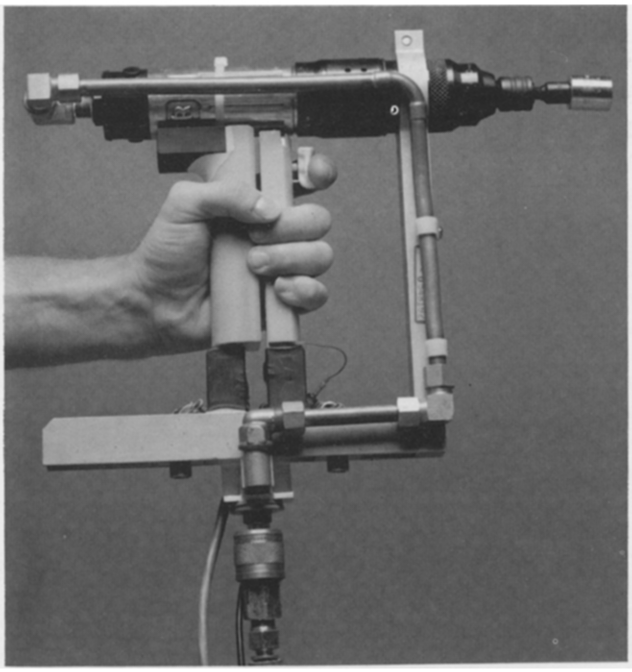

Fig. 8 Dynamometer used for measuring finger and palm forces exerted when operating a completely functional simulation of a pistol-grip pneumatic power hand tool

dynamometer prototypes are also acknowledged. This work has been funded in part by grants from the Ingersoll-Rand Company, the National Institutes of Health (NS26328) and the US Department of Veterans Affairs.

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Appendix 1: Spreadsheet listing

Cell	Contents
C10	+TAU/ (G*2)
E10	@ IF (STRAIN<0.001, "(Should be > .001)", "(Value OK)")
C11	+Q*SG*EI/ (2*G*I*T) *1000^2
B13	@MIN (E16, G16)
C13	@ IF (E16<G16, "(Moment Limited)", "(Shear Limited)")
H13	(V*Q*SG/ (2*G*I*T)) *1000^2
A14	@ IF (VMAX<D6, "(Can't carry the Ultimate Load of "& @STRING (D6, 0) &" N)", "(Value OK)")
E14	@IF (H13<4, "(Should be as close to 4 as possible.)", "(OK)")
E16	+SIGMAX*I/ (L*HALFD) /1000
G16	+TAUMAX*I*T/Q/1000
B20	+FORCE*L/1000
F20	+M*HALFD /I*1000^2
B21	+D/2
F21	+V*Q/ (I*T) *1000
B22	(W*D 3) /12– ((W–T) *H^3) /12
B23	+FORCE
B24	(ALPHA1+ALPHA2) *BETABAR
B25	+Q/I
K11	@VLOOKUP ($MATERIAL, $MATTAB, 1)
N11	((D–H) /2) *W
K12	@VLOOKUP ($MATERIAL, $MATTAB, 3)
N12	(H+D) /4
K13	@VLOOKUP ($MATERIAL, $MATTAB, 4)
N13	(H*T) /2
K14	@LOOKUP ($MATERIAL, $MATTAB, 5)
N14	+H/4
N15	((ALPHA1*BETA1) + (ALPHA2*BETA2)) / (ALPHA1+ALPHA2)

Appendix 2: Spreadsheet range names

Name	Range
ALPHA1	N11
ALPHA2	N13
BETA1	N12
BETA2	N14
BETABAR	N15
D	B4
E	K11
EI	G2
FORCE	D5
G	K12
H	E3
HALFD	B21
I	B22
L	B2
M	B20
MATERIAL	H5
MATTAB	J5 . . 07
Q	B24
SG	G3
SIGMA	F20
SIGMAX	K13
STRAIN	C10
T	E2
TAU	F21
TAUMAX	K14
V	B23
VMAX	B13
W	B3