SHORT COMMUNICATION

A SIMPLE DESIGN FOR A FORCE-PLATE TO MEASURE GROUND REACTION FORCES

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This paper describes an inexpensive force-plate that can measure ground reaction forces in two planes and can be built to a size or sensitivity suitable for nearly any biological application.

An ideal force-plate should: (1) be able to resolve the vertical, forward and lateral components of the force; (2) have low 'crosstalk' between the measured components of the force; (3) have sufficient sensitivity and resolution for the subject of interest; (4) have a linear response; (5) have a response independent of where on the plate surface the force is exerted; (6) have a high natural frequency of oscillation; (7) have sufficient safety margin to protect both the plate and the subject from damage due to failure; and (8) be simple and inexpensive.

Many plates have been described in the literature (e.g. Calow & Alexander (1973), Cavagna (1975), and Gola (1980)), but all are lacking in two or more of the above criteria. The suggested design is lacking only in criterion 1: it is sensitive only to the vertical and forward–aft horizontal components of the force.

The suggested design (Fig. 1A) is simply a rigid plate surface suspended at each corner by a transducer element. The transducer element (Fig. 1B) is composed of two strain-gauge instrumented spring blades orientated at 90° to each other; the horizontal blade is sensitive to the vertical force, and the vertical blade is sensitive to the horizontal force. The four blades supporting each end of the plate surface are cut out of one solid bar.

Each spring blade is modelled as if it were two identical cantilevered beams joined at their distal ends (Fig. 1C). The standard formula for beam flexure is: $S = Mc/I$, where S is the stress on any fibre (Nm^{-2}), c is the distance from the fibre to the neutral axis (m), M is the bending moment (Nm), and I is the moment of inertia with respect to the neutral axis (m^4). For a cantilever with the load concentrated at the distal end $I = bh^3/12$, where b is the width and h is the height of the beam (m); $c = h/2$; and $M = Pl$, where P is the load (N) and l is the length of the beam (m).

By rearrangement we obtain the equation:

$$h = \left(\frac{6Pl}{ns}\right)^{\frac{1}{2}},$$

(1)

(A)   Small-animal force-plate

Direction of travel

(B)   Transducer element

Plate surface

Honeycomb

Solid
aluminium
bar

Strain gauge

Spring blade *A*

Spring blade *B*

Mounting
frame

(C)   Cantilevered beam

b

h

Taper
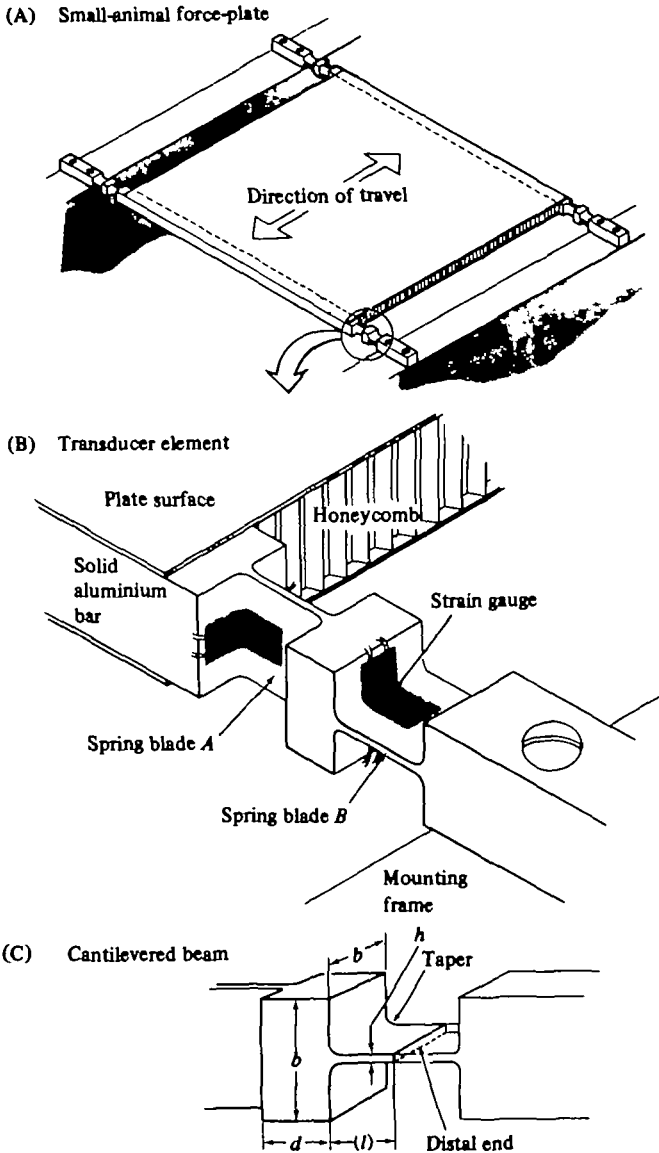
b

d   *(l)*

Distal end

Fig. 1. (A): the suggested design is a rigid plate surface suspended at each corner by a trans-
ducer element. This plate was made from an aluminium honeycomb panel epoxied to two solid
aluminum bars (indicated by the dotted lines) from which the front and back transducer
elements were machined. Many adjacent plates can be mounted on the frame in order to
form a long force-sensitive surface. (B) Each transducer element is composed of two spring
blades orientated at 90 °; each blade is instrumented with two strain gauges (only one shown).
The strain gauges on blade *A* are sensitive to fore-aft horizontal forces, and the strain-gauges
on blade *B* are sensitive to vertical forces; *A* is identical to *B* but turned 90°. (C): each spring
blade is modelled as if it were two cantilevered beams joined at their distal ends. The dimension
d should be 10 or more times the spring thickness *h*; the other dimensions are explained in the
text.

where n is the ratio b/h. The yield strength of the spring material ($S = S_{yield}$), b/h ratio, length of the cantilever, and maximum design load ($P = P_{max}$) can be substituted into equation (1) in order to calculate the spring thickness (h) and subsequently the spring width ($b = nh$). The b/h ratio should be at least 7 in order to keep the crosstalk between the horizontal and vertical signals to a few percent.

The maximum load will generally occur in the vertical direction, and can be calculated as:

$$P_{max} = P_s \, g_{max} + P_p,\qquad(2)$$

where P_s is the subject's weight (N), g_{max} is the peak vertical acceleration measured as multiples of the acceleration of gravity, and P_p is the weight of the suspended portion of the force-plate (N). P_{max} may be multiplied times a safety factor depending upon how accurately g_{max} can be predicted. During normal locomotion g_{max} can attain values of 14 in small (< 100 g) animals, and decreases with increasing size to about 5 in large (~ 100 kg) animals (personal observations).

The deflexion of the cantilever for a given load can be calculated from the equation:

$$y = \frac{4Pl^3}{Ebh^3},\qquad(3)$$

where y is the deflexion (m), and E is the elastic modulus of the construction material. The deflexion of a maximally loaded spring blade is $2y$ when $P = P_{max}$.

The plate surface should be as light-weight as possible while still maintaining rigidity. For many subjects an aluminium honeycomb panel, the structural material of many airplane and race-car bodies, is ideal (honeycomb panels are available from the Hexcel Corporation, 650 California Street, San Francisco, Ca 94108, USA). More than one panel may be bonded together in a stack with epoxy for additional strength.

Once the dimensions of the spring blades and the weight of the suspended portion of the plate are known, the unloaded natural frequency of oscillation can be calculated. The natural frequency of a spring-mass system is given by $f_{nat} = (K/m)^{\frac{1}{2}}/2\pi$, where f_{nat} is the frequency (Hz), m is the oscillating mass (Kg), and K is the spring constant the ratio of the force/deflexion (Nm^{-1})). By evaluating the constants we obtain the equation:

$$f_{nat} = \frac{0.5}{\sqrt{y'}},\qquad(4)$$

where y' is the deflexion (m) under self-loaded conditions; $y' = 2y$ when equation (3) is solved with $P = P_p$.

The sensitivity of a force-plate designed according to this procedure is a function only of P_{max}, the spring blade material and the strain gauges. The peak load strain is given by the ratio of the yield strength to the elastic modulus, and will be approximately 0·0027 for aluminium and 0·0052 for steel. Since correctly bonded strain gauges can measure 10 microstrain, the minimum load resolvable by the plate should be about 0·4% of P_{max} for aluminium and 0·2% of P_{max} for steel spring blades. Strain gauges with a gauge factor of 3 in a two-active-arm Wheatstone bridge will give peak load outputs of about 0·004 V/V for aluminium and 0·008 V/V for steel, requiring only very low amplification for most recorders.

Table 1 contains three examples of force-plates built according to the procedures

Table 1. *Specifications for three force-plates built according to the procedure outlined in the text, and a comparison of the performance of the small animal and horse force-plates*

	Plate 1	Plate 2	Plate 3
Spring blade length, $2l$ (mm)	9·53	10·0	9·53
Spring blade width, b (mm)	9·53	30·0	31·75
Spring blade thickness, h (mm)	0·584	3·00	2·54
Spring material	Al	Steel	Steel
Plate surface dimensions (cm)	25 × 25	65 × 65	75 × 75
Plate surface material	Al honeycomb	Al honeycomb	Al I-beams
Weight of suspended plate, P_p (N)	2·94	88·2	430
Max load on any spring blade P_{max} (N)	26·5	9310	7430
Max. deflexion of any spring blade, $2y_{max}$ (μm)	136	58	62
Minimum load resolvable (N)	0·1	18	14
Predicted minimum unloaded natural frequency, f_{nat} (Hz)	130	680	260*
Measured unloaded natural frequency, f_{nat} (Hz)	170	n.a.	200*
Linearity†	< 2% to 150% of P_{max}	n.a.	< 2% to 70% of P_{max}
			< 10% to 85% of P_{max}
Sensitivity dependence upon position on plate surface‡	< 3% vertical	n.a.	< 5% vertical
	< 3% horizontal	n.a.	< 2% horizontal
Cross-talk§	< 5%	n.a.	< 2%

* Part of the discrepancy between the predicted minimum and measured f_{nat} for the horse-plate is due to a thick, heavy cover on the plate surface (for traction), the weight of which was not taken into account in the predicted f_{nat} calculations.

† Expressed as % deviation from a least-squares fit regression of output vs. load, measured at the centre of the plate.

‡ Expressed as the worst-case deviation from the average output of the plate for a given load, measured at the centre and four corners of the plate.

§ Cross-talk is the output from the horizontal channel for a purely vertical load, expressed as a percentage of the vertical load. The cross-talk was measured at the centre and four corners of the plate surface; the values given are for the worst case.

outlined above. Plate 1 was made for small animals; it has aluminium spring blades and an aluminium honeycomb plate surface (this plate is illustrated in Fig. 1). Plate 2 was made for athletes; the spring material was steel, and the surface was three aluminium honeycomb panels bonded together. Plate 3 was made for horses; it has steel spring blades and a plate surface made from aluminium I-beams welded together edge-to-edge.

Test data for the smallest and largest plates is given in Table 1. The natural frequency of oscillation was measured by rapping the plate and observing the ringing with an oscilloscope. The plates described were all undamped; mechanical damping can be added but at the expense of the natural frequency. A typical record of a kangaroo rat (*Dipodomys spectabolis*) hopping over the undamped small force-plate is given in Fig. 2.

There are a few practical considerations that should be taken into account when designing a force-plate. The length of the spring blade would be very short for optimum performance, but it is difficult to place accurately a strain gauge on a short blade. The blade should be tapered where it emerges from the support so that the metal-foil strain gauge can be mounted over the area of peak strain. The gauges should be centred laterally and orientated parallel to the edges of the cantilever (to minimize cross-talk), and not extend beyond the middle of the spring blade. The plate surface can extend out over the transducer elements and mounting frame, allowing the top of the plate to be mounted flush with the level of the ground in a hole only slightly larger than
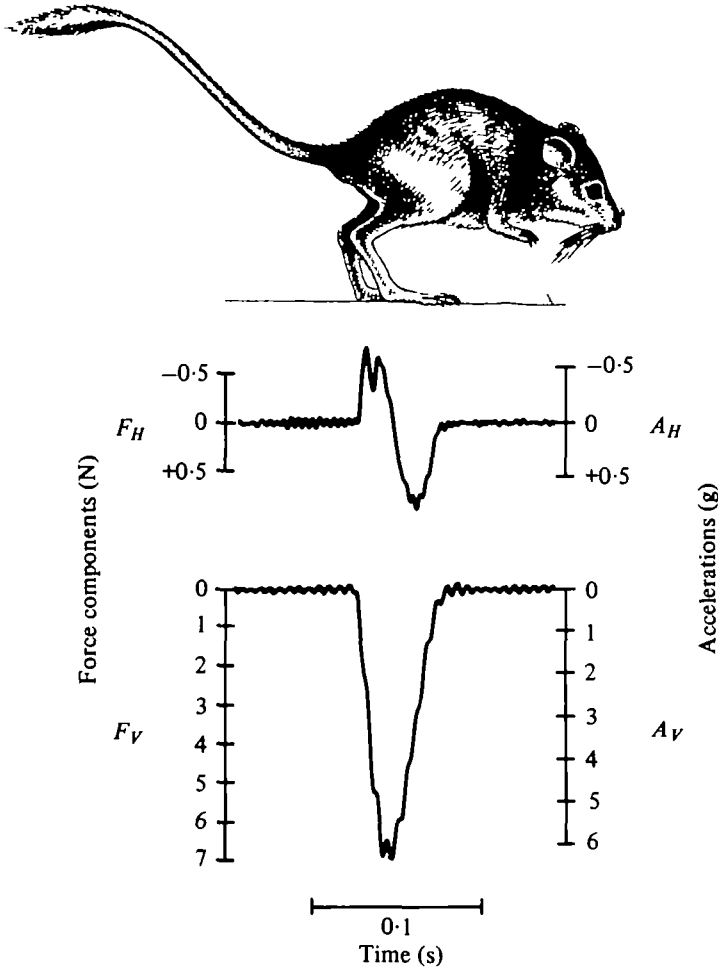
Fig. 2. The fore–aft horizontal (top) and vertical (bottom) forces exerted by a 112 g kangaroo-rat hopping at 2·33 ms⁻¹, as measured by the force-plate shown in Fig. 1. The horizontal force record shows that the animal landed on the hind feet slightly asychronously, exerting a decelerating force, followed immediately by an accelerating force; the peak force in either the forward or backward direction was about 0·7 times P_s. The vertical force record shows a peak force of about 7 times P_s. The ordinates on the right show the acceleration of the animals' centre of mass (ignoring friction) as multiples of the acceleration of gravity (g). The plate was undamped and the electrical signals were not filtered, the recordings were made directly on a Brush Gould model 260 recorder with a flat frequency response from dc to > 60 Hz.

the plate surface itself. Clearance must be allowed for free movement of the plate due to the very small flexion of the spring blades (Table 1). The plate surface can be epoxied or bolted to the two bars containing the spring blades; the two bars can be bolted or clamped to the mounting frame. The important considerations are that the plate surface and mounting frame be stiff relative to the spring elements and that all attachments (surface to bars, bars to frame, frame to ground) be rigid and secure.

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