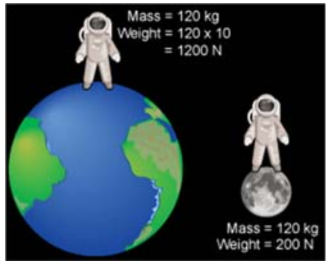
2. Motion and Force

- Motion sensors
  - Displacement sensor
  - Position sensor
  - Velocity sensor
  - Acceleration sensor
- Force sensors
  - Force plate
  - Piezoelectric sensor
  - Load sensor
  - Capacitive sensor

Objects of Measurement

- Linear Motion – time (s) and length (m)
  - Displacement (m)
  - Velocity (m/s)
  - Acceleration (m/s^2)
- Rotation – angle (radian, degree)
  - Rotating angle (rad, deg)
  - Angular velocity (rad/s)
  - Angular acceleration (rad/s^2)
- Force – mass × acceleration ($1N=1kg\ m/s^2$)
  - Mass – quantity of matter (kg)
  - Weight – force acting on a mass under gravity (kgf)
  - Pressure – force exerted per unit area (N/m^2)



Motions by Muscle Activities

Many kinds of body motions generated by muscular activities are objects of motion measurements, while passive motions due to externally applied forces are sometimes also of interest.

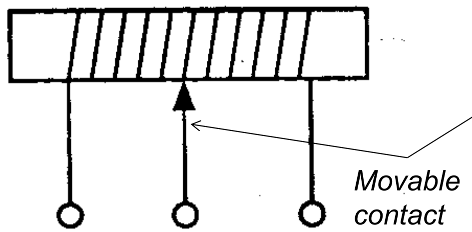
	Contraction Speed (l_0/s)	Change of Length (%)	Tension (kgf/cm²)
Skeletal muscle	4 ~ 24	–40 ~ +80	0.5 ~ 5
Cardiac muscle	1 ~ 2	0 ~ 50	0.4 ~ 1
Smooth muscle	0.1 ~ 3	–60 ~ +80	0.4 ~ 2

Note: l_0 = muscle length at rest.

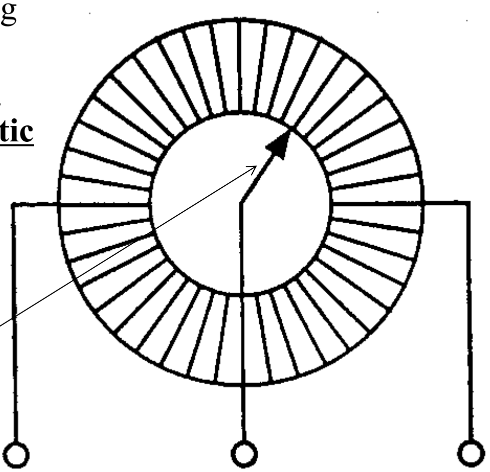
The body motion generated by muscles depends both on the characteristics of the muscle as an actuator and on the mechanical characteristics of the body as the load to this actuator.

Potentiometers

Displacement and rotation of a part of the body can be measured using various types of sensors, such as **resistive potentiometers**, **photo-encoders**, **capacitive** and **magnetic sensors**.



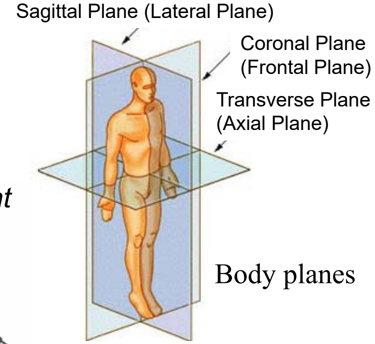
Translational type

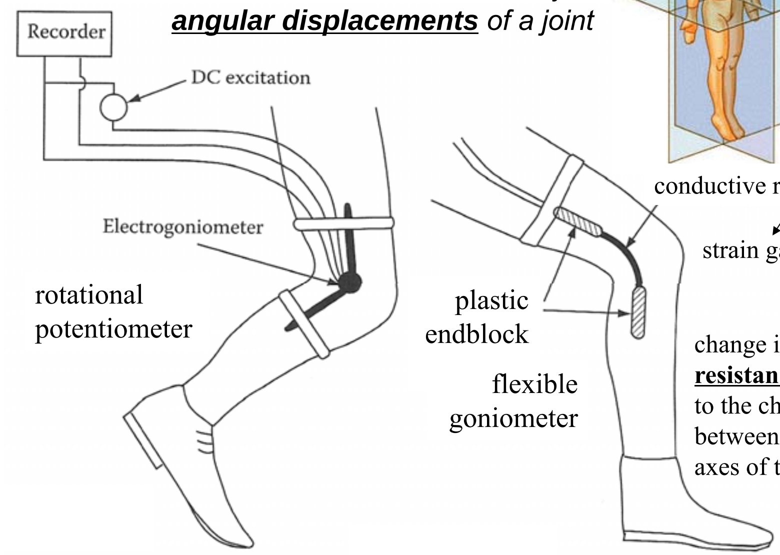


Rotational type

Electrogoniometer

rotational motions *of the body*
angular displacements *of a joint*



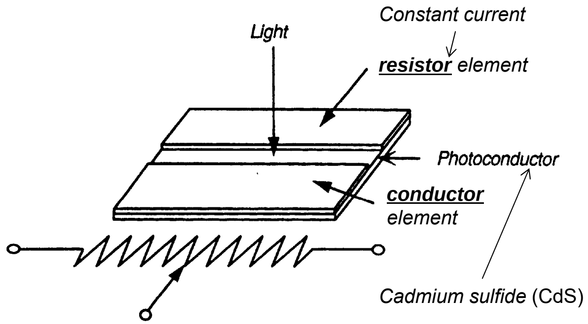


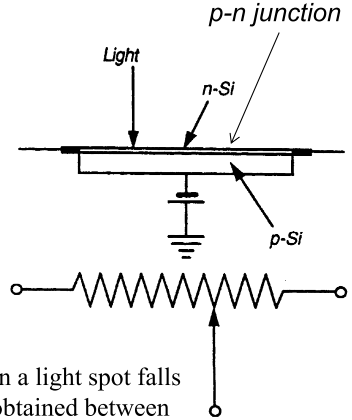
conductive rubber bending
↓
strain gauge deformation
↓
change in **electrical resistance** is proportional to the change in the angle between the longitudinal axes of the endblocks

Photo-potentiometers

A strip of **photoconductive material** placed between a **resistor** and **conductor** elements

The p-n junction is nonconductive when a negative bias potential is applied to the p-type substrate, but the junction becomes conductive when a light spot falls on it.

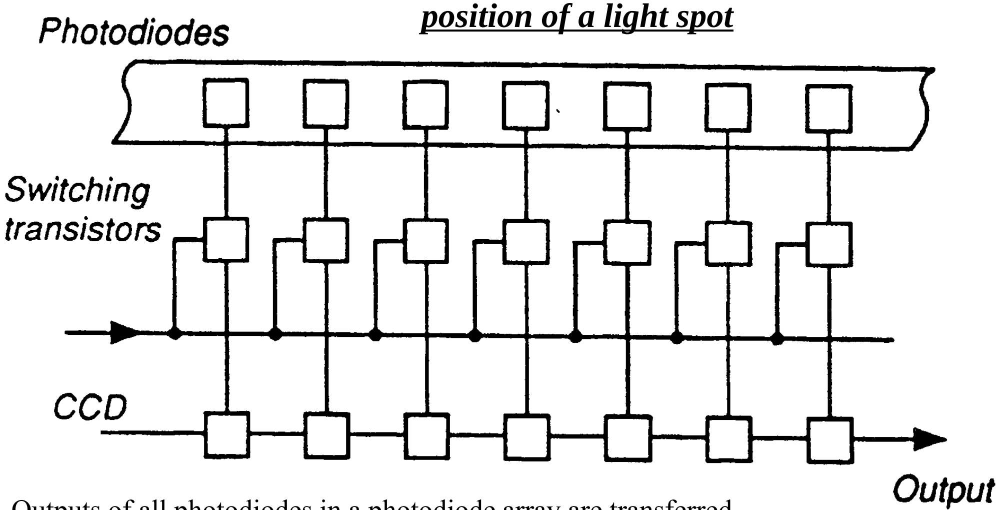




A constant current is applied to the resistor element. When a light spot falls on the **photoconductive strip**, a potential output can be obtained between the conductor element and one end of the resistor element that is proportional to the distance between the light spot and the end of the resistor.

One-dimensional Image Sensor

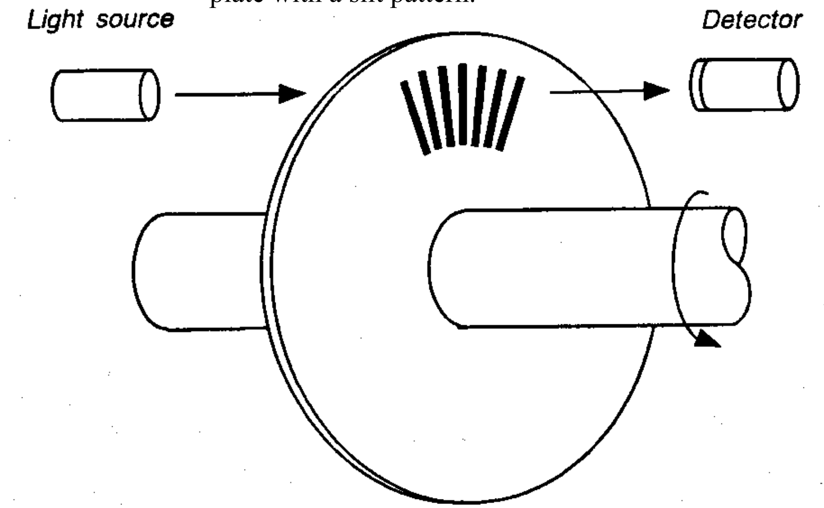
position of a light spot



Outputs of all photodiodes in a photodiode array are transferred simultaneously to CCD image sensor.
CCD transfers the outputs from the photodiodes sequentially to the output port.

Rotary Encoder

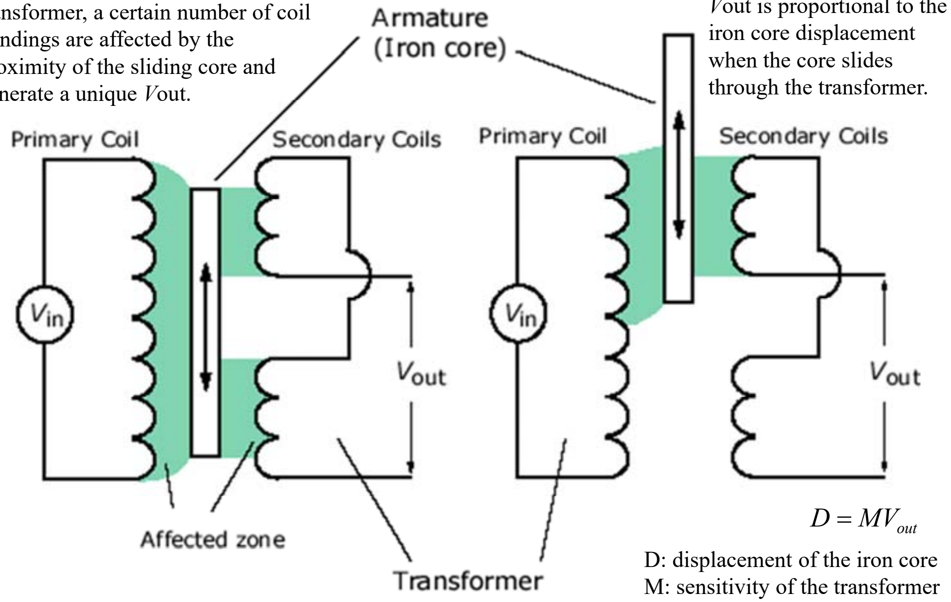
Rotational displacement is converted into a pulse sequence, or a series of coded signals, by interrupting light beams at a plate with a slit pattern.



Differential Transformer

When the iron core slides through the transformer, a certain number of coil windings are affected by the proximity of the sliding core and generate a unique *V*out.

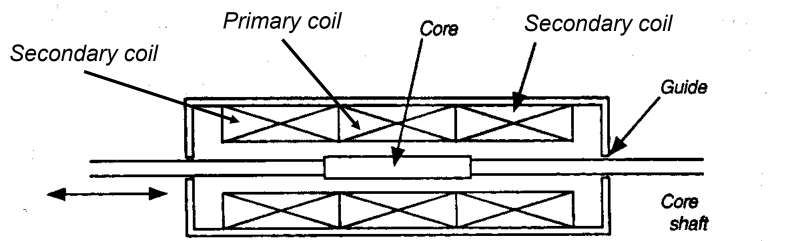
*V*out is proportional to the iron core displacement when the core slides through the transformer.



$$D = MV_{out}$$

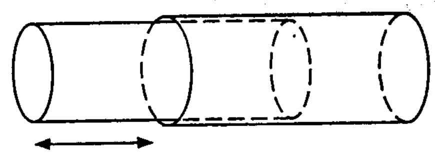
D: displacement of the iron core
M: sensitivity of the transformer

Displacement Sensors



Differential transformer for measurement of small displacements

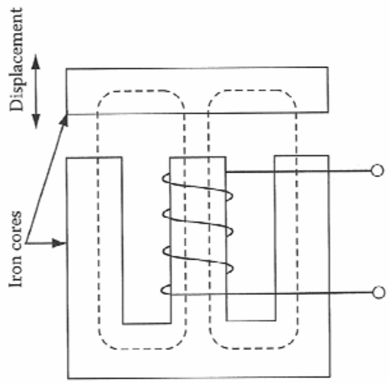
Cylindrical type



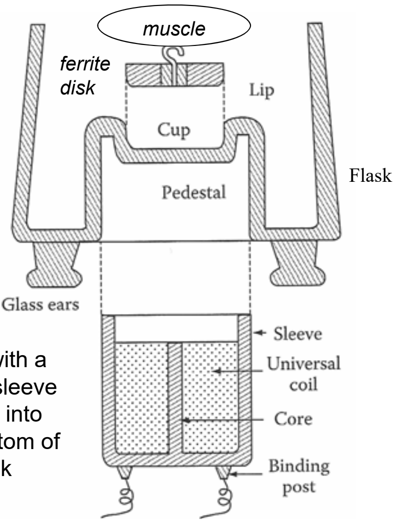
Capacitive sensor for measurement of large displacements

Variable Reluctance Pickup

The change of the **gap** between cores causes a change in **magnetic reluctance** and results in a change in the **inductance** of the coil.



Measurement of
isotonic muscle contraction



A coil with a ferrite sleeve is fitted into the bottom of the flask

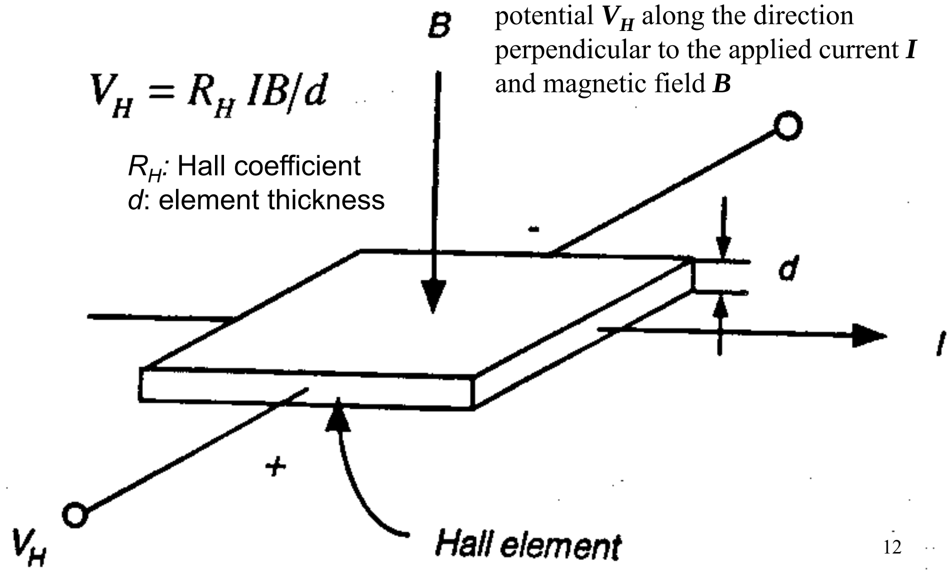
Disk weight produces isotonic load to the muscle. When the muscle shortens, the disk is shifted vertically and the magnetic reluctance is increased.

Hall-effect Sensor

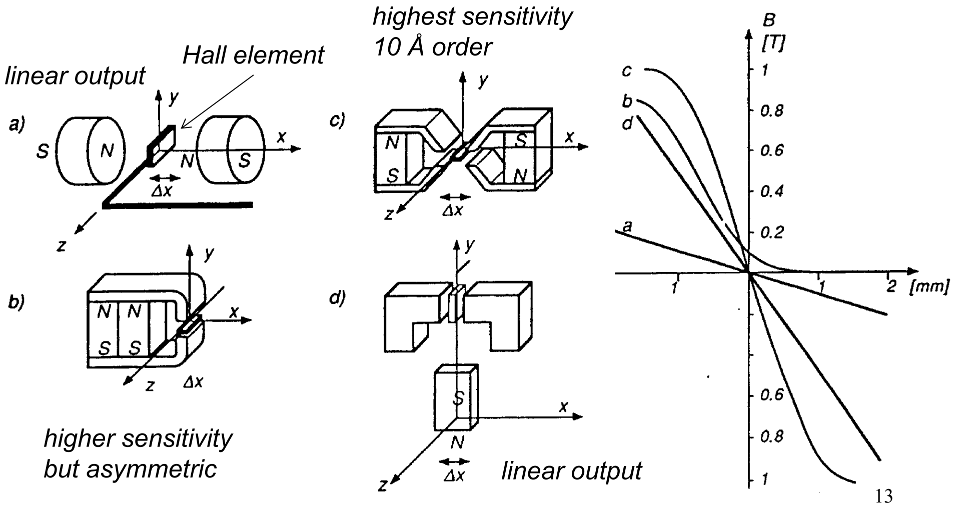
Hall element generates an electromotive potential V_H along the direction perpendicular to the applied current I and magnetic field B

$$V_H = R_H\, IB/d$$

R_H: Hall coefficient
d: element thickness

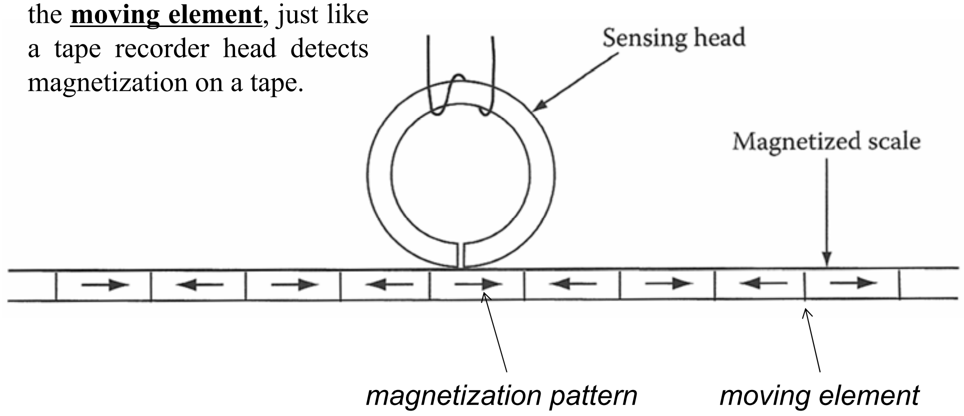


Different Configurations of Hall-effect Displacement Sensor



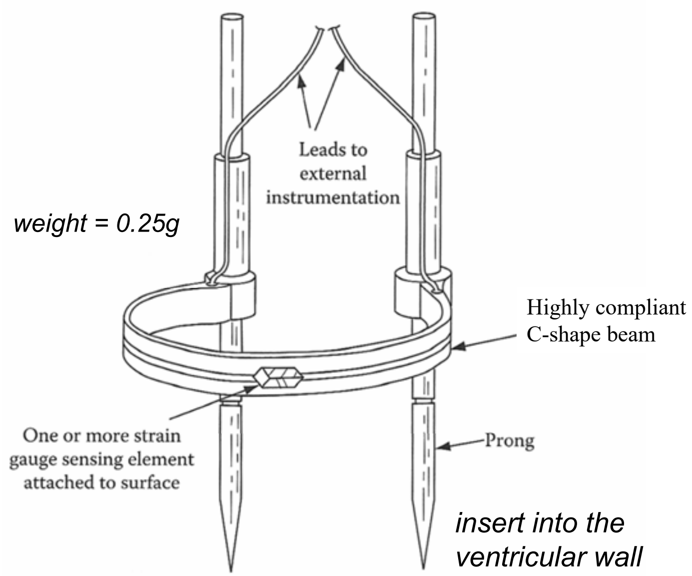
Magnetic Scale

a magnetic head detects the **magnetization pattern** on the **moving element**, just like a tape recorder head detects magnetization on a tape.

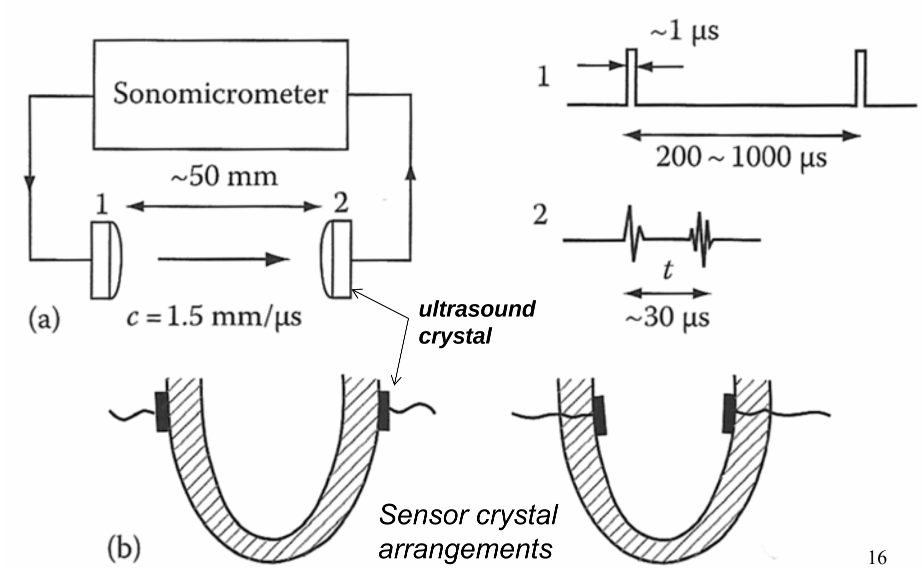


resolution = 0.2 mm
measurement range = 0.2 to 3 m

In Vivo Measurement of Myocardial Contraction

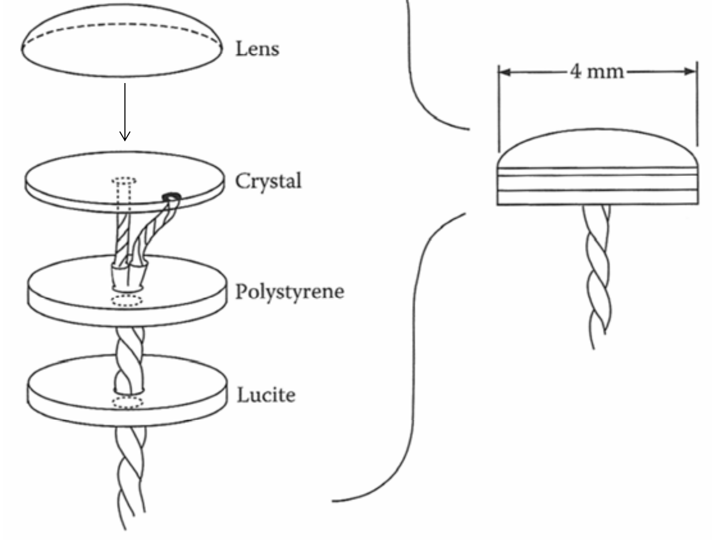


Cardiac Ventricular Diameter

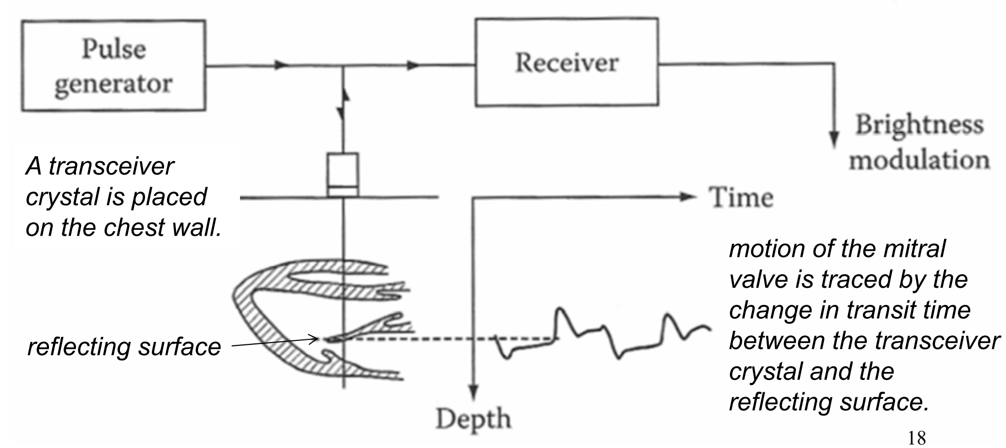


Structure of Sonomicrometer Sensor

glued to the crystal face to diffuse the ultrasonic beam

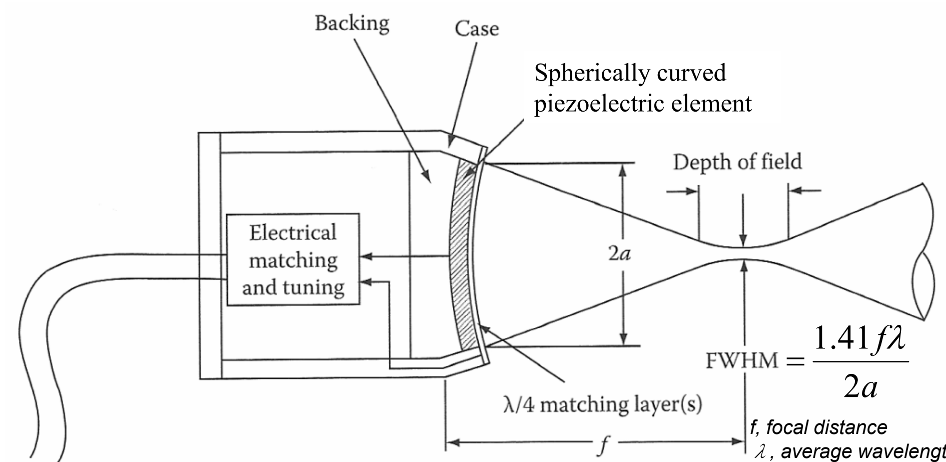


Motion of Mitral Valve



Focused Beam Ultrasonic Sensor

The ***spatial resolution*** *along the ultrasound beam axis is the order of the* ***wavelength*** *of the ultrasound when the* ***beam is narrow*** *and the reflecting surface is perpendicular to the beam.*



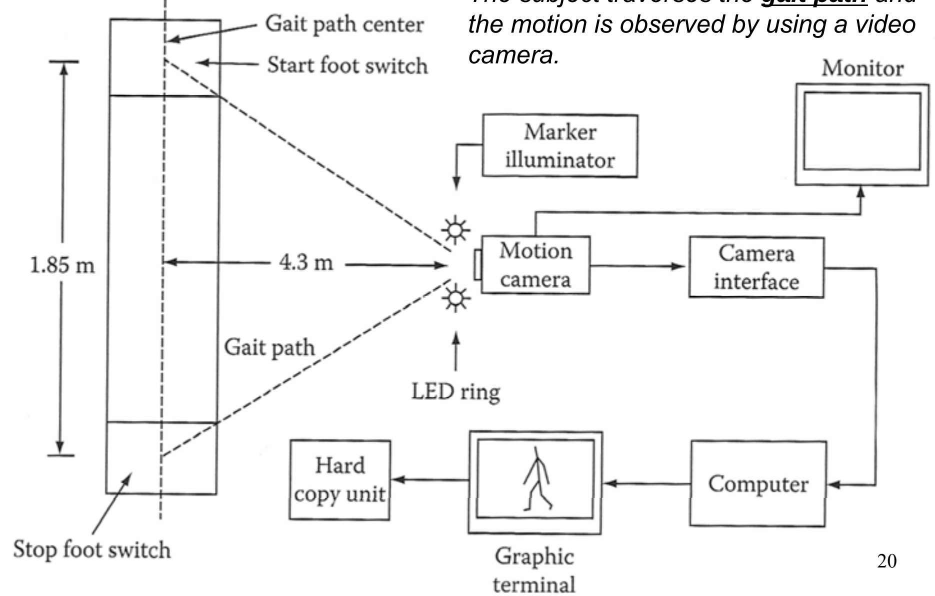
$$\mathrm{FWHM} = \frac{1.41 f\lambda}{2a}$$

f, focal distance
λ, average wavelength
2a, diameter of the crystal

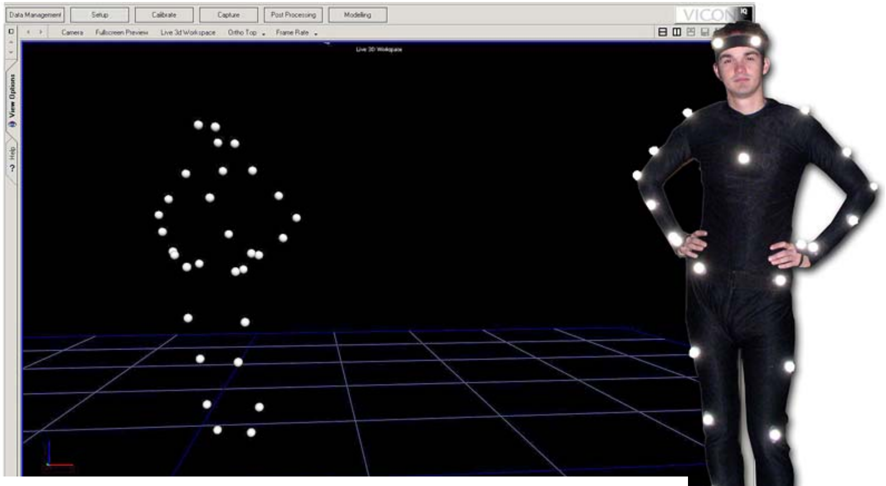
The ***beam width*** *has a minimum at the* ***focal distance*** *f. Where the intensity of the sound is above half of that on the axis is called the* ***full width at half maximum*** *(FWHM)*

Motion Capture System

The subject traverses the ***gait path*** *and the motion is observed by using a video camera.*

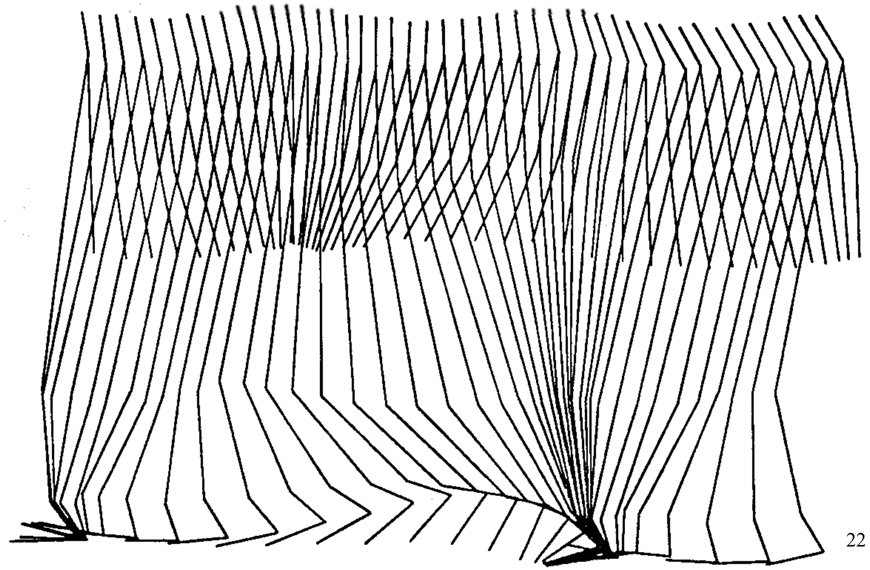


Reflective Markers



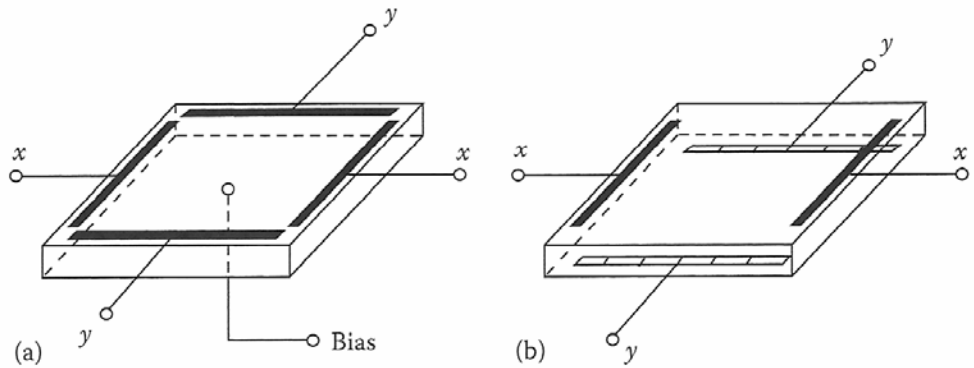
Passive reflecting **markers** are attached to some specific positions of the body, such as neck, shoulder, elbow, wrist, waist, knee, ankle, heel, and toe.
Markers are illuminated by **near-infrared light** so that the measurement can be performed in a room illuminated by fluorescent light.
The position of each marker is determined by a tracking algorithm automatically.

Motion Traces



Position-sensitive Detector

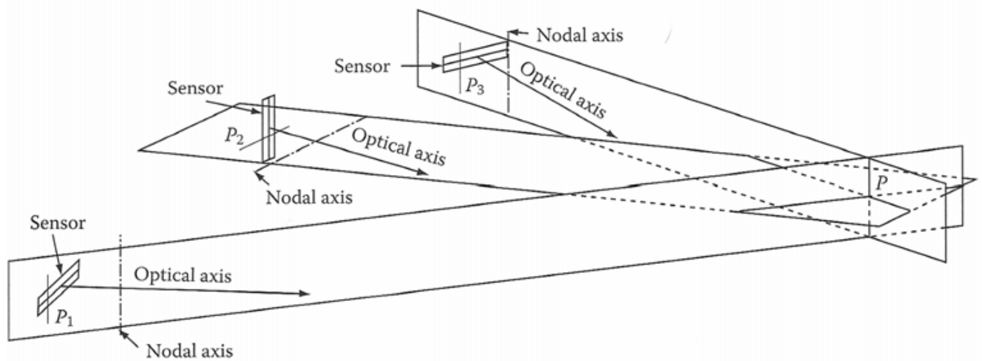
The principle is similar to that of the ***photopotentiometer.***
The position of a ***light spot*** *in a two-dimensional (2D) space can be directly determined by a 2D position-sensitive detector.*



tetralateral configuration
photoconductive layers is formed on one side of the device

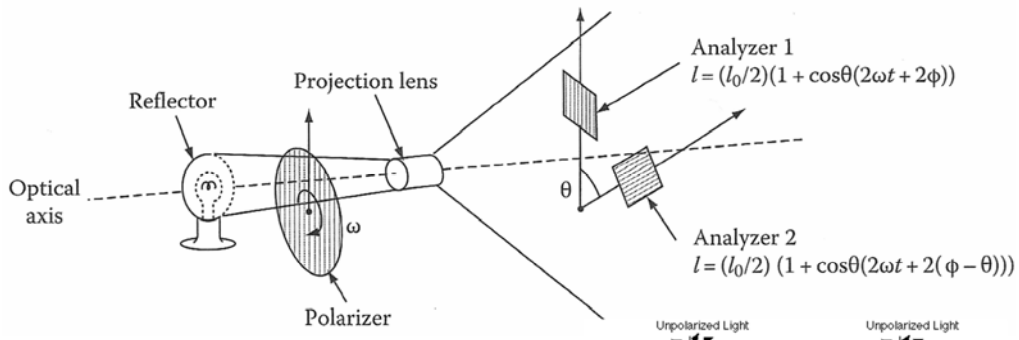
duolateral configuration
two photoconductive layers on both sides of the device

3D Position Determination

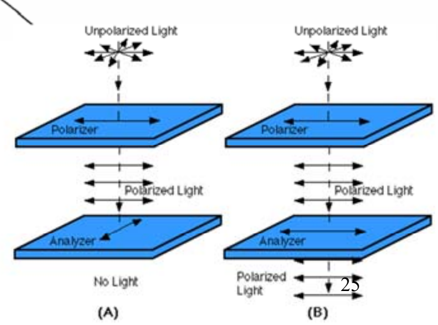


measurement of a position in a 3D space uses three 1D position sensors

Rotational Angle Measurement

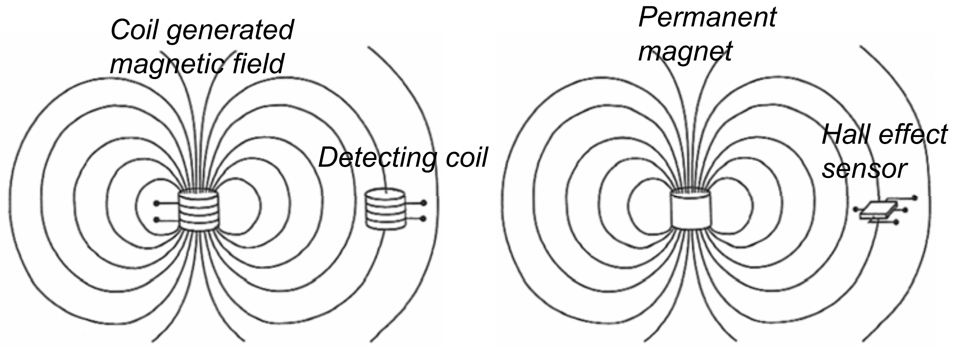


When unpolarized light passes through a polarizing filter, only one plane of polarization is transmitted. Two polarizing filters used together transmit light differently depending on their relative orientation



Displace Measurement by Inhomogeneous Magnetic Fields

If a magnetic pole is attached to an object, an inhomogeneous magnetic field is generated in the surrounding space.
*The **position** of the pole can be determined by the measurement of the **magnetic field distribution**.*

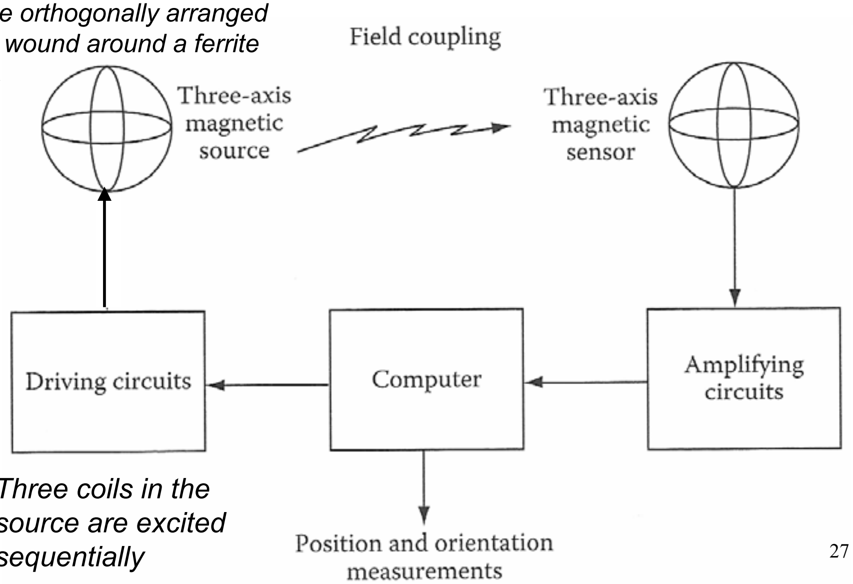


(a) magnetic field is generated by a coil and detected by another coil

(b) a permanent magnet and a Hall effect element

3D Magnetic Source and Sensor

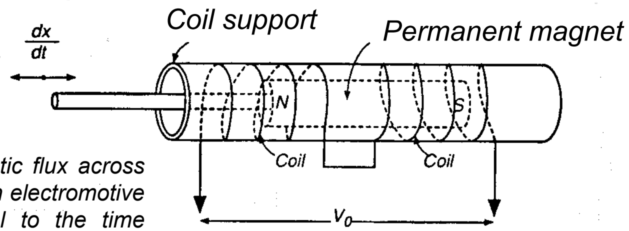
Three orthogonally arranged coils wound around a ferrite core.



Three coils in the source are excited sequentially

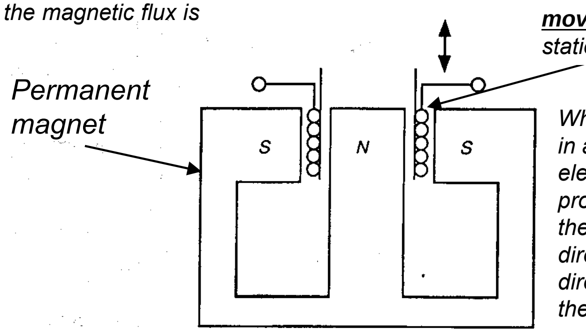
Electromagnetic Velocity Sensors

***moving magnet** in a solenoid coil*



When the magnetic flux across a coil is varied, an electromotive force proportional to the time derivative of the magnetic flux is induced.

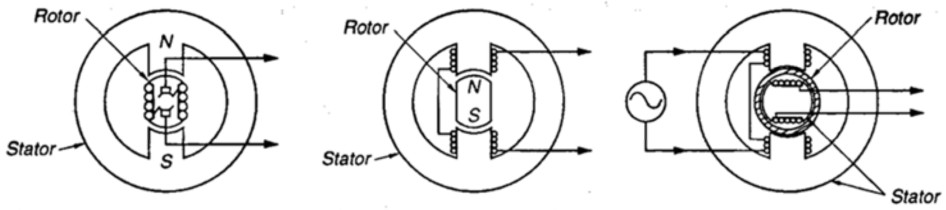
***moving coil** in a stationary magnetic field*



When a conductor is moved in a magnetic field, an electromotive force proportional to the velocity of the motion is induced in the direction perpendicular to directions of the motion and the magnetic field.

Angular Velocity Sensors

angular velocity sensor generates an electromotive force roughly proportional to the rotational speed based on electromagnetic induction



D.C. tachometer

Stator = a magnet
Rotor = rotating coil

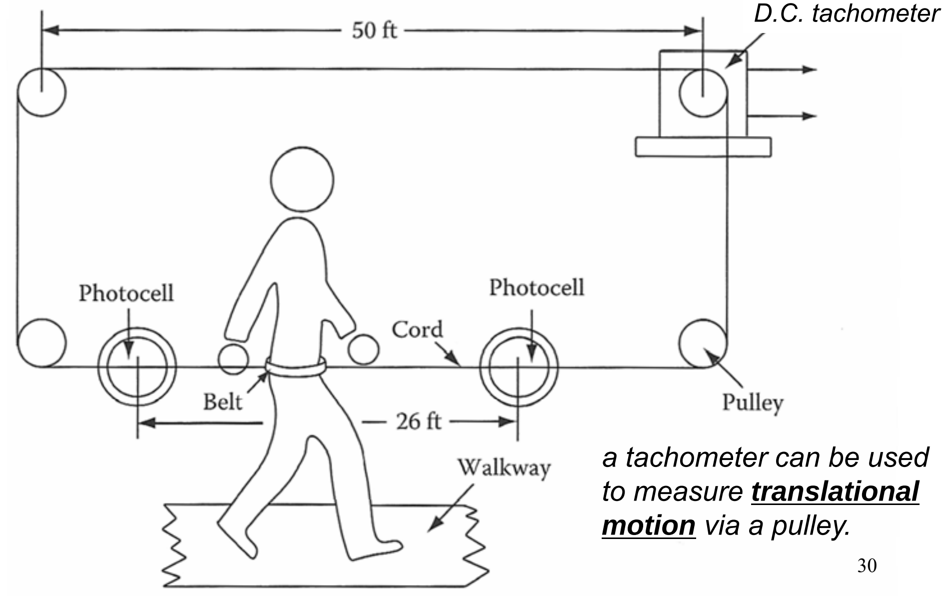
A.C. tachometer

Rotor = permanent magnet
Stator = output from the coil

Drag-cup tachometer

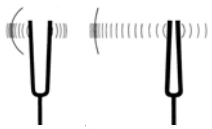
Two stators with coils are perpendicular to each other;
A.C. excitation is applied to a coil, and the output is derived from another coil.
A cup-shaped rotor made from a conductor is placed in between two stators.
During rotation, eddy currents are induced in the cup, the current produces a magnetic field and the A.C. output of the excitation frequency is induced in the second coil.
The output amplitude is proportional to the rotation speed.
The phase is inverted when the direction of rotation of the cup is inverted

Instantaneous Tachometer

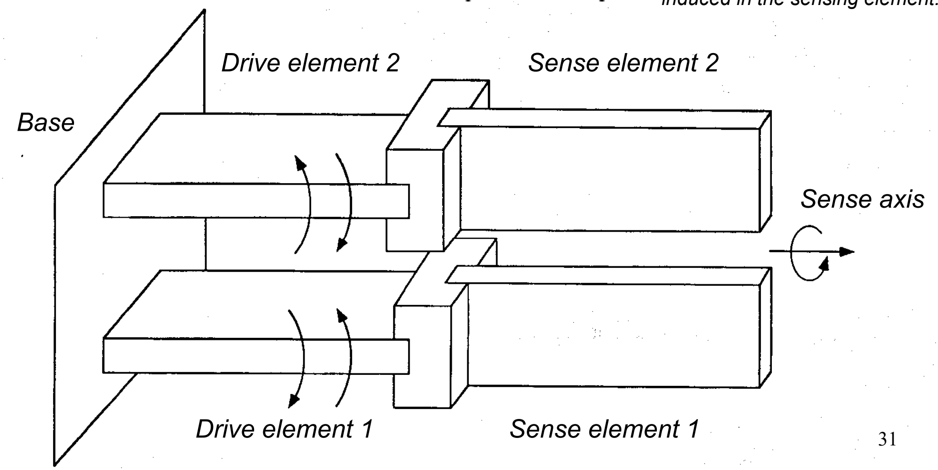


*a tachometer can be used to measure **translational motion** via a pulley.*

Piezoelectric Gyroscope “Tuning Fork”

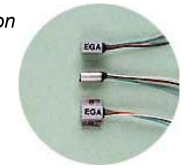


Driving elements bend resonantly through electric excitation, then sensing elements swing.
Under zero angular velocity, the sensing element does not produce a signal.
*When it rotates, a bending motion is induced, due to the **Coriolis force**, and consequently a signal proportional to **angular velocity** is induced in the sensing element.*

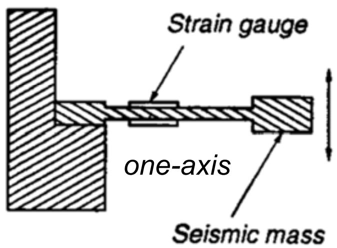


Translational Accelerometer

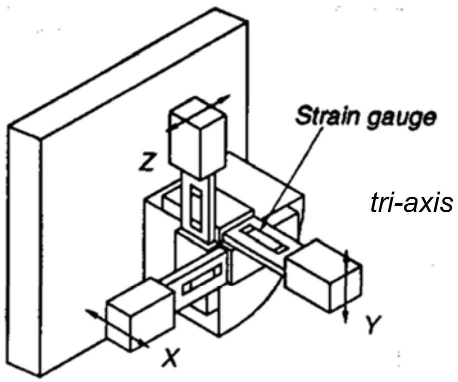
range of ±5g, a dimension of 3.56 x 3.56 x 6.86 mm, and a weight of 0.5 g (Entran Devices, Inc)



The displacement of the seismic mass can be detected by different sensing principles, such as the piezoresistive, piezoelectric, capacitive and semiconductor strain-gauges.



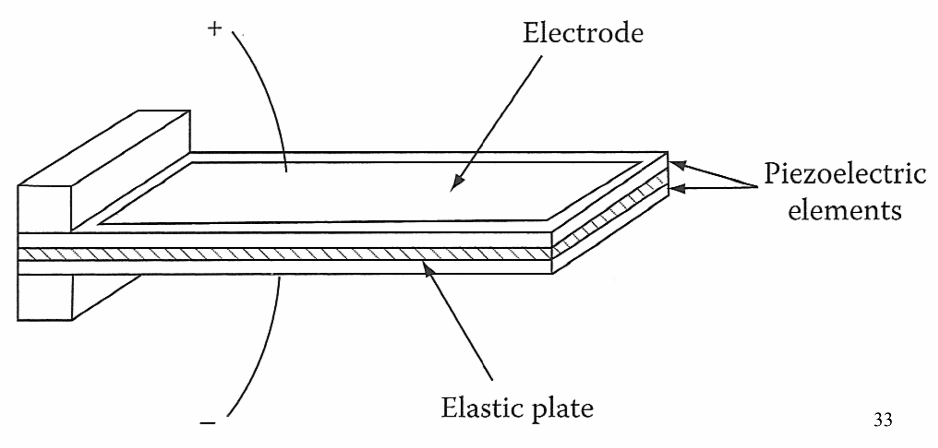
An elastic beam is fixed to the base at one end and a seismic mass.
*When the mass is accelerated, a **force** proportional to the mass times the acceleration appears, and the **beam bends** elastically in proportion to the force.*



Three beams with seismic masses are assembled on a base so that sensitive directions of these beams are arranged perpendicular to each other.

Bimorph Sensor

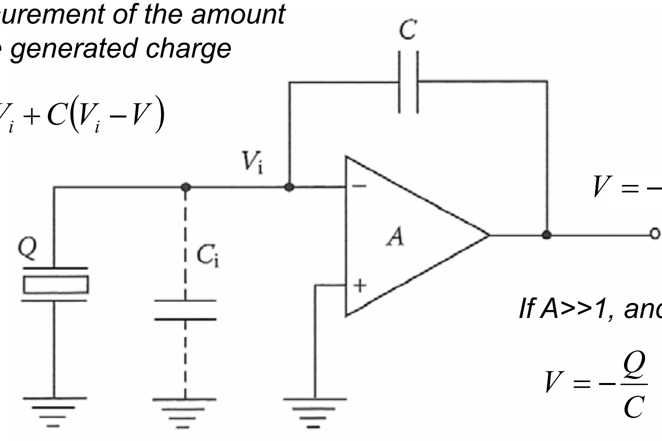
A beam with two piezoelectric elements of different polarities in order to produce a double or differential output. This configuration is called the ***bimorph****.*



Charge Amplifier

Measurement of the amount of the generated charge

$$Q = C_i V_i + C(V_i - V)$$



$$V = -AV_i$$

If A>>1, and AC>>Ci

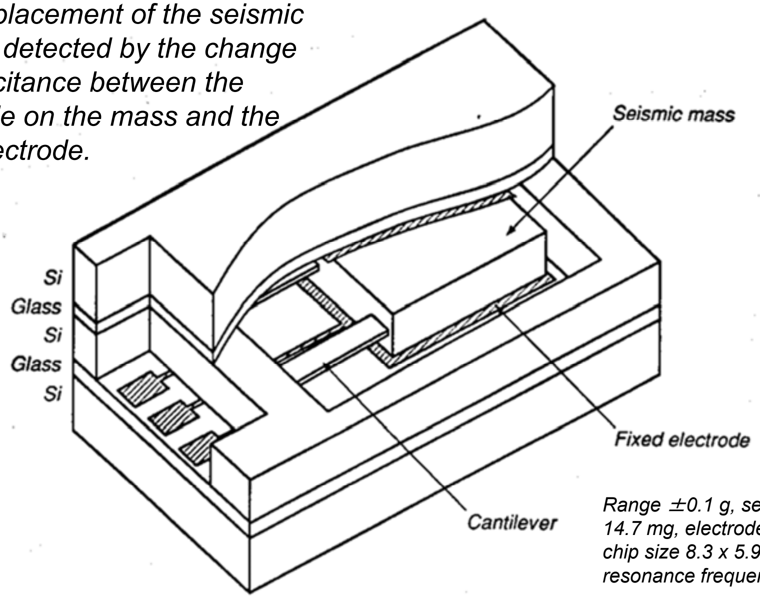
$$V = -\frac{Q}{C}$$

Q: generated charge
C_i: stray capacity
V_i and V: input and output voltages
A: gain of the operational amplifier

Output voltage is proportional to the generated charge regardless of the input capacitance

Capacitive Accelerometer

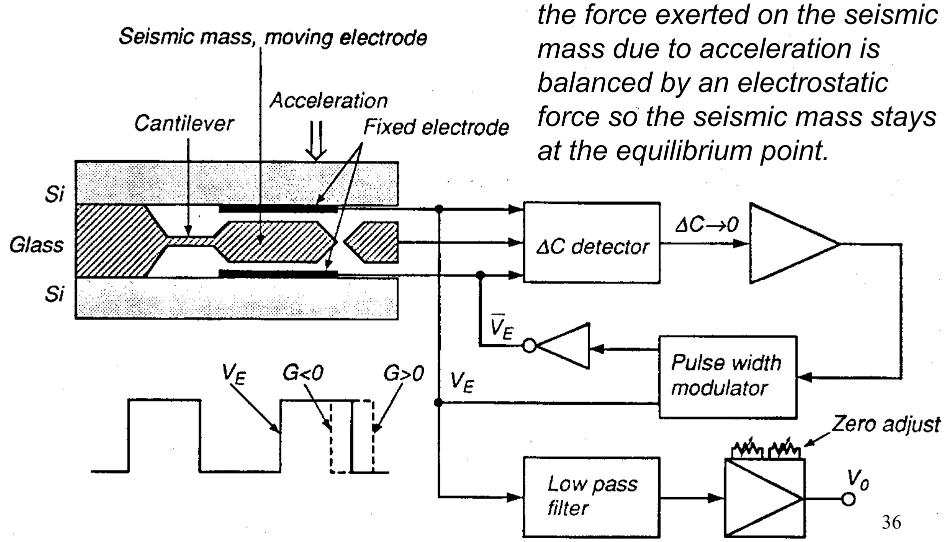
The displacement of the seismic mass is detected by the change of capacitance between the electrode on the mass and the fixed electrode.



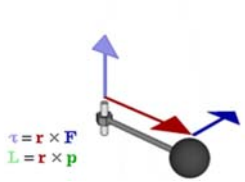
Range ±0.1 g, seismic mass 14.7 mg, electrode gap 7μm, chip size 8.3 x 5.9 x 1. 9mm, resonance frequency 126Hz.

Servo-controlled Accelerometer

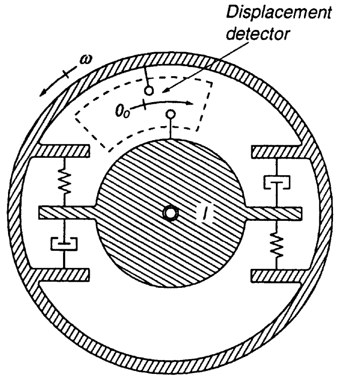
the force exerted on the seismic mass due to acceleration is balanced by an electrostatic force so the seismic mass stays at the equilibrium point.



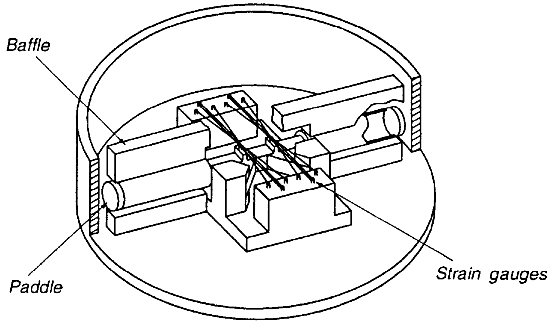
Angular Accelerometers



Angular acceleration is measured by a torque τ and the moment of inertia I around a fixed axis of rotation, i.e. τ/I.



static device used to regulate the flow of a fluid

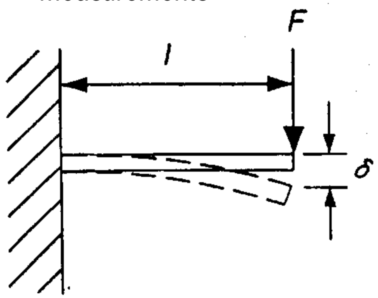


the momentum appeared at a rigid body supported by a shaft is measured by the displacement of the spring connected to it

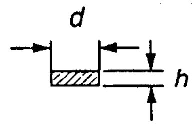
a liquid is used instead of a rigid body, the flow generated by angular acceleration is detected by the force exerted on a paddle

Cantilever Beams

muscle contraction measurements

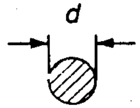


Rectangular cross-sectional beam



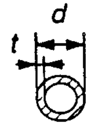
$$\delta = 4L^3 F / Edh^3$$

Circular cross-sectional beam



$$\delta = 64L^3 F / 3\pi Ed^4$$

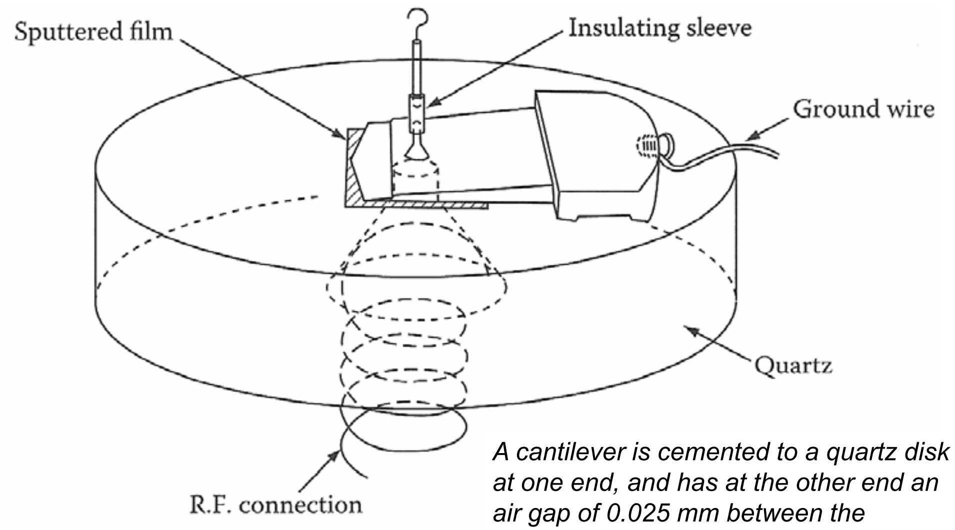
Beam made from thin wall pipe



Young's module E

$$\delta = 4L^3 F / 3\pi Ed^3 t$$

Cantilever Beams

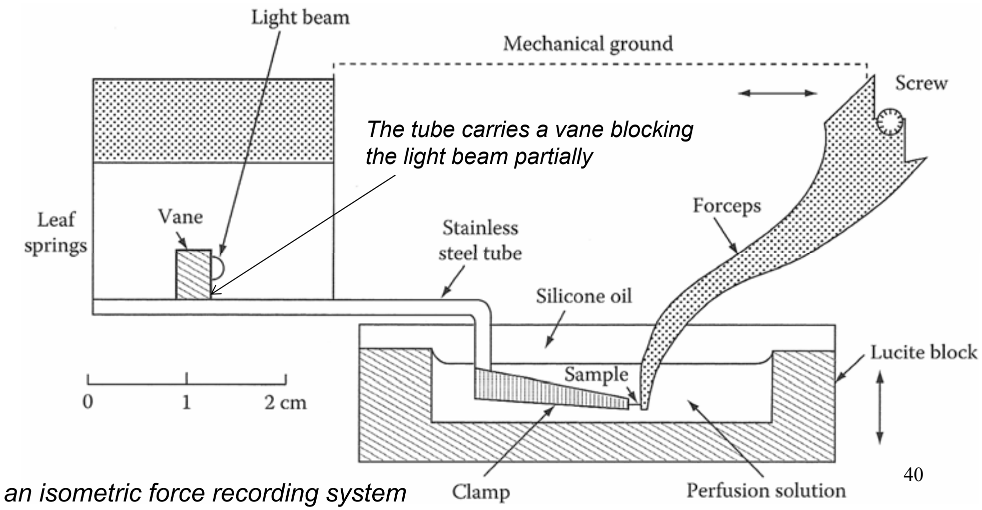


A cantilever is cemented to a quartz disk at one end, and has at the other end an air gap of 0.025 mm between the cantilever and the vacuum-sputtered film on the quartz disk. The displacement of the cantilever is less than 0.25 mm

a form of spring, commonly used for the suspension in vehicles

Leaf Spring

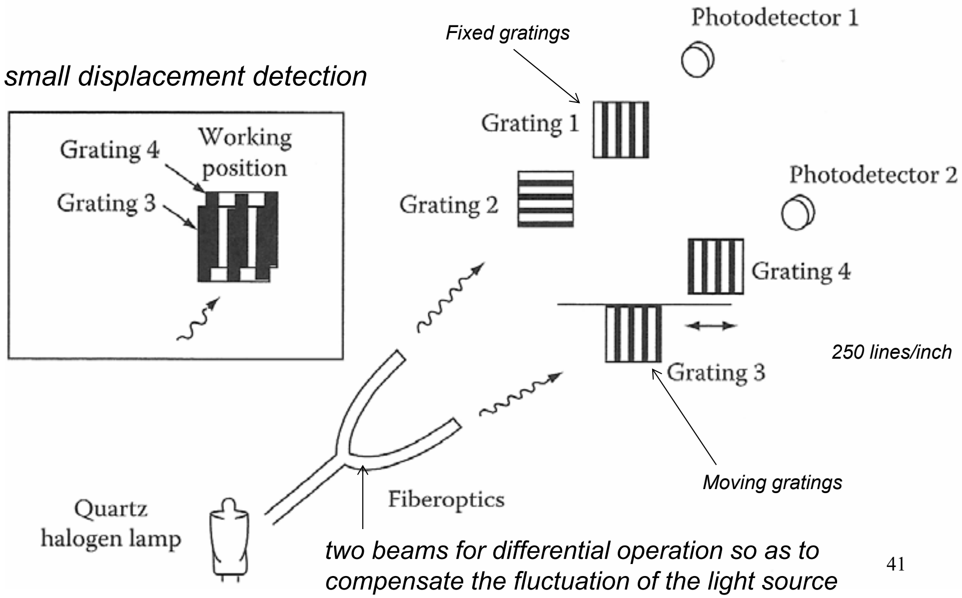
optical method is used to detect a small displacement of a cantilever or spring



an isometric force recording system

Light Beams and Gratings

small displacement detection

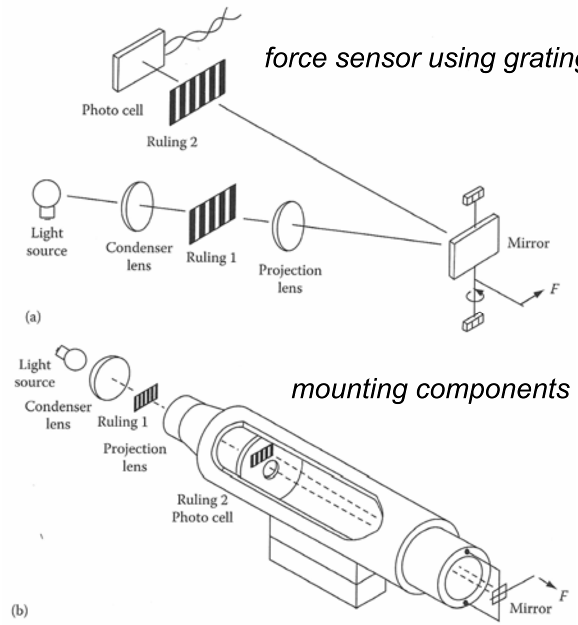


two beams for differential operation so as to compensate the fluctuation of the light source

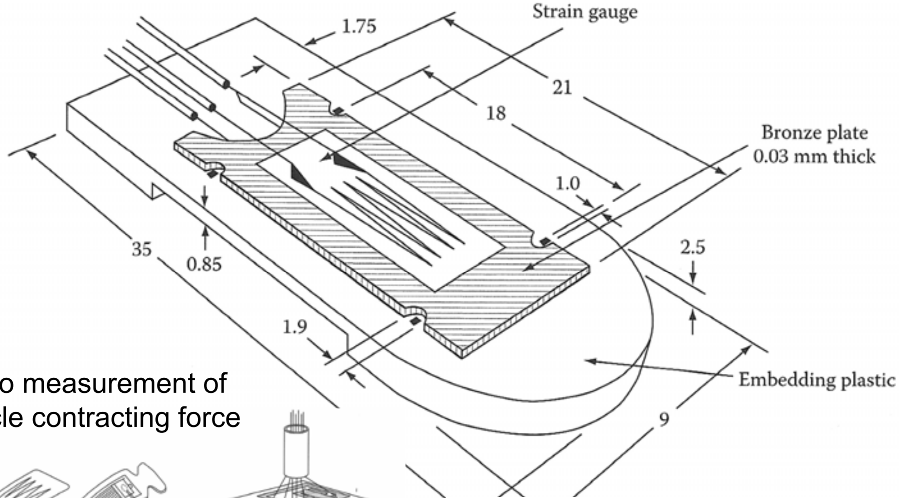
Single Light Beams

force sensor using gratings

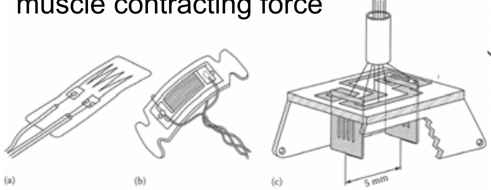
mounting components in a microscope



Implantable Force Sensor



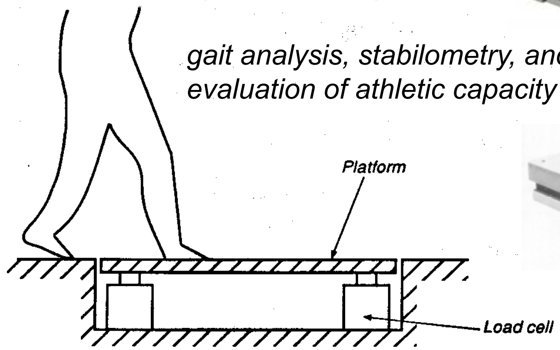
in vivo measurement of muscle contracting force

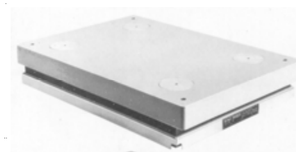


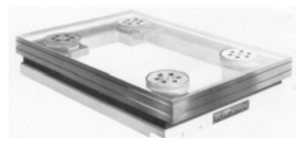
A bonded strain-gauge element is cemented onto a spring bronze plate, and glued with epoxy resin

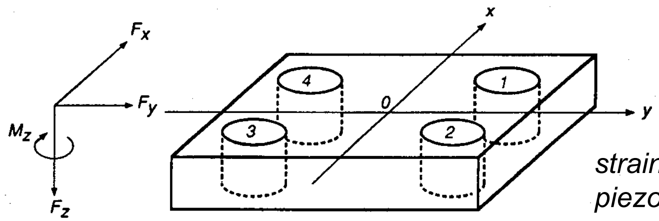
Force Plates

gait analysis, stabilometry, and evaluation of athletic capacity



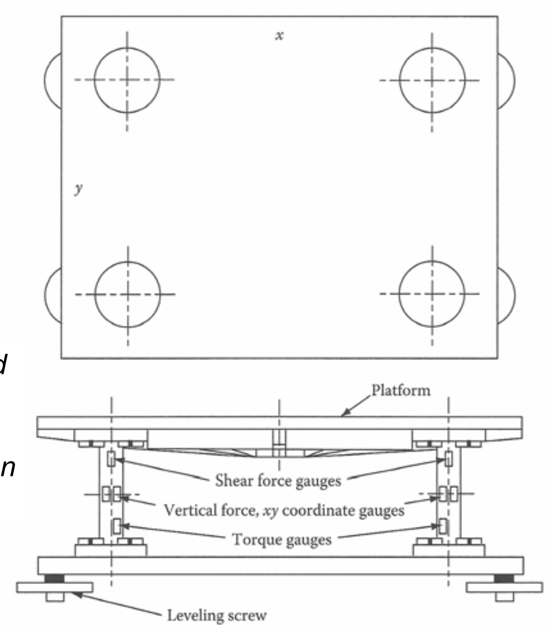






strain-gauge or piezoelectric cell

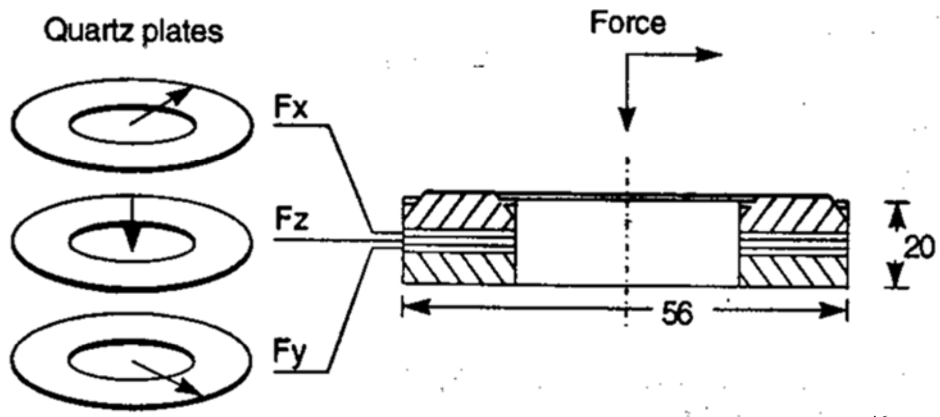
Stain Gauge Force Plate



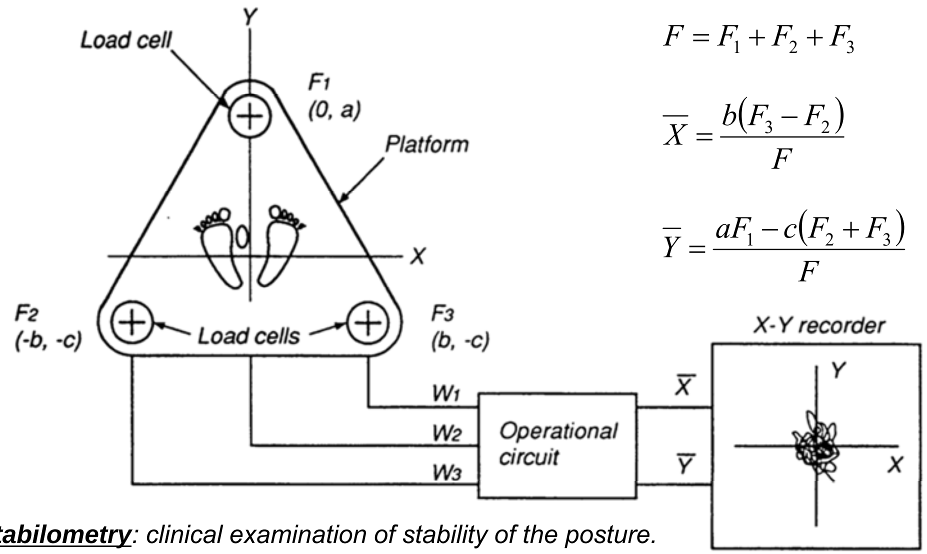
strain gauges are attached on four metal pipe pylons so that the compression, bend, and twist of the pylon can be detected.

Piezoelectric Force Sensor

Each sensor consists of three quartz disks sandwiched between the steel bases and provides outputs corresponding to the three orthogonal components of the applied force.



Stabilometer



$$F = F_1 + F_2 + F_3$$

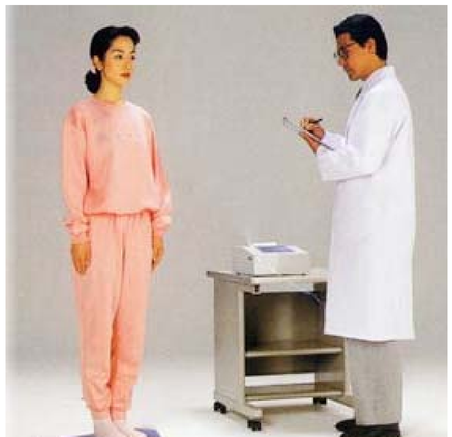
$$\overline{X} = \frac{b(F_3 - F_2)}{F}$$

$$\overline{Y} = \frac{aF_1 - c(F_2 + F_3)}{F}$$

Stabilometry: *clinical examination of stability of the posture.*
Stabilometer: *instruments using such as force plate designed for Stabilometry. It measures the locus of the point of application of the ground force using their triangularly arranged vertical force sensors.*

Stabilometer Report

Subject stands still, the point of application of the ground force stays right below the center of gravity of the body.

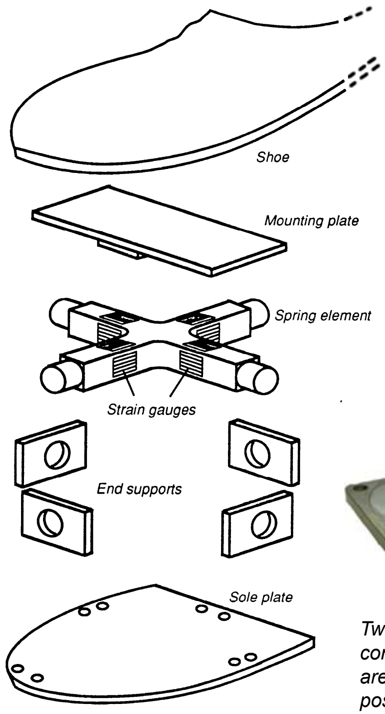


60 sec
Eyes open and close

Normal athlete eye closed
Normal non-athlete eye closed

Perkinson's disease eye open

Shoe with Load Cell

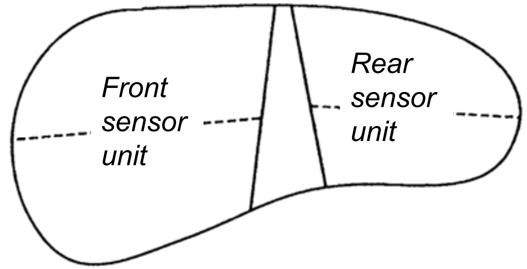


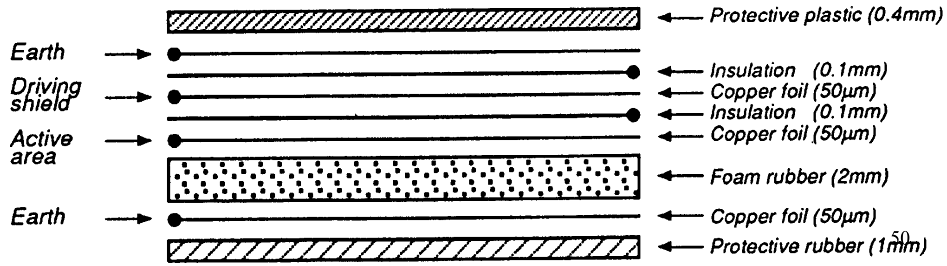
The instrumented shoe measures natural locomotion without restricting the subject to a walkway.

Two load cells are attached at the toe and heel. Each load cell consists of an end support spring element on which strain gauges are mounted and provides outputs corresponding to the anterior-posterior and medial-lateral shears, axial compression, and torque.

Shoe with Capacitive Sensor

A foam rubber sheet was sandwiched between two copper sheets so that the capacitance between the copper sheets varies when the rubber sheet is compressed by the applied load.

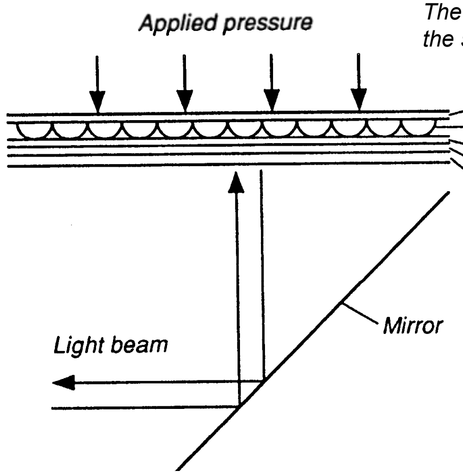


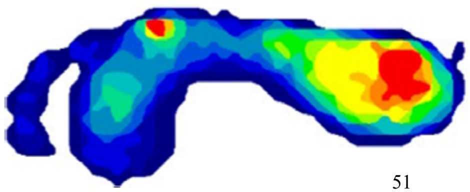


barograph

Direct Visualization of Foot Pressure Pattern

The distribution of the ground force exerted on the sole is called the foot-ground pressure pattern.





A black rubber mat having many small protrusions of pyramidal contours is placed on a glass plate.