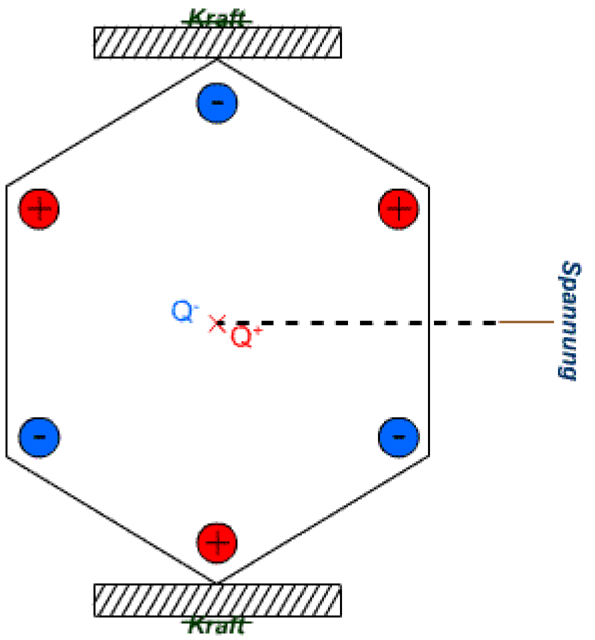
If you want to conduct a biomechanical analysis, be it for scientific research or practical sports, one of the parameters you usually measure is force. In principle, there are two sensor types: Piezoelectric sensors and strain gauges. Although both measure the same physical quantity, they differ fundamentally in their mode of operation. This also affects the application areas of both methods.

In this article you will learn:

1. Technical basics

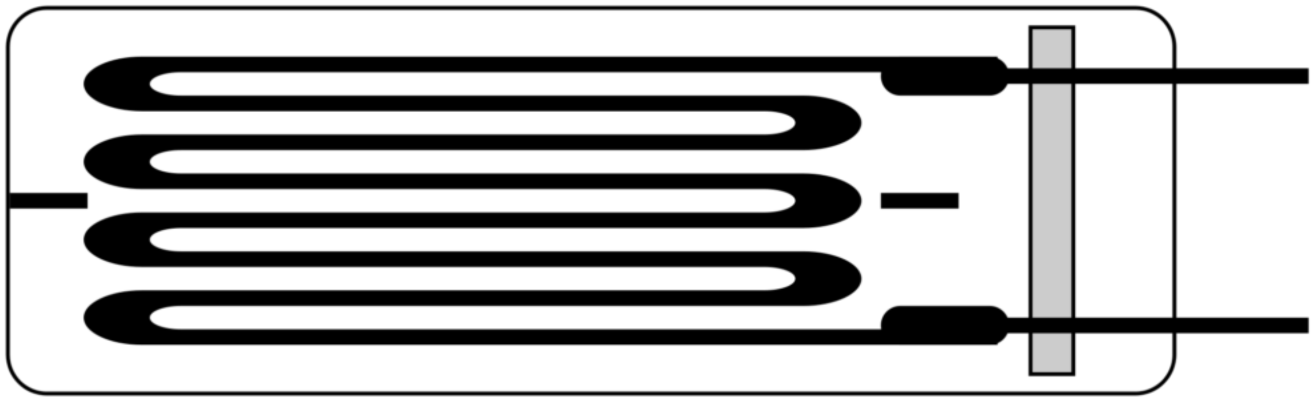
"The piezoelectric effect is the production of electric polarization by application of stress to a crystal."
Richard M. Martin
1972

If a piezoelectric crystal (e.g. quartz or lithium niobite) is deformed under the influence of force, dipoles are formed within the elementary cells and a shift of the charge centres occurs. This polarization leads to a displacement of charge in the crystal lattice. This results in a gradient of electrical potential across the cross section of the crystal. If both surfaces are now connected with a conducting material, electrons are flowing, and a small measurable voltage can be detected with the help of an amplifier. The resulting voltage is proportional to the applied force.



The piezoelectric effect. [Spannung] german for voltage; [Kraft] german for force

In a piezoelectric sensor usually two discs of a piezoelectric material are used, which are built into a housing. An electrode is placed between these discs, which absorbs the resulting charge and passes it on to the connector plug. The housing itself serves as the second electrode. The quality of the whole piezoelectric force sensor is determined by the surface quality of the crystal and housing. Since the voltage is generated by the sensor itself in this measuring technique, no external voltage needs to be applied. One can therefore speak of active sensor elements.



Design of a strain gauge

It is different with strain gauges. They are basically just really thin wires that are glued on top of an element that transduces the forces you want to measure. Even the hardest and strongest materials like steel slightly transform under stress. When the element you want to measure the force in, is loaded, even the slightest deformation is detected by the strain gauge as it picks up the deformation in every winding of the wire. The deformation causes the wire to stretch and this in turn to decrease the diameter of the wire. As this happens multiple times throughout the length of the wire, it gets harder for electrons to pass through at the same time and thus their flowing speed increases (similar to a rapid in a river when two large rocks block the water and it flows faster in between them). In order to measure a force, an external current must therefore be applied, which is why strain gauges are also known as passive sensor elements. The change in voltage is proportional to the applied force.

2. Which Sensor for which application?

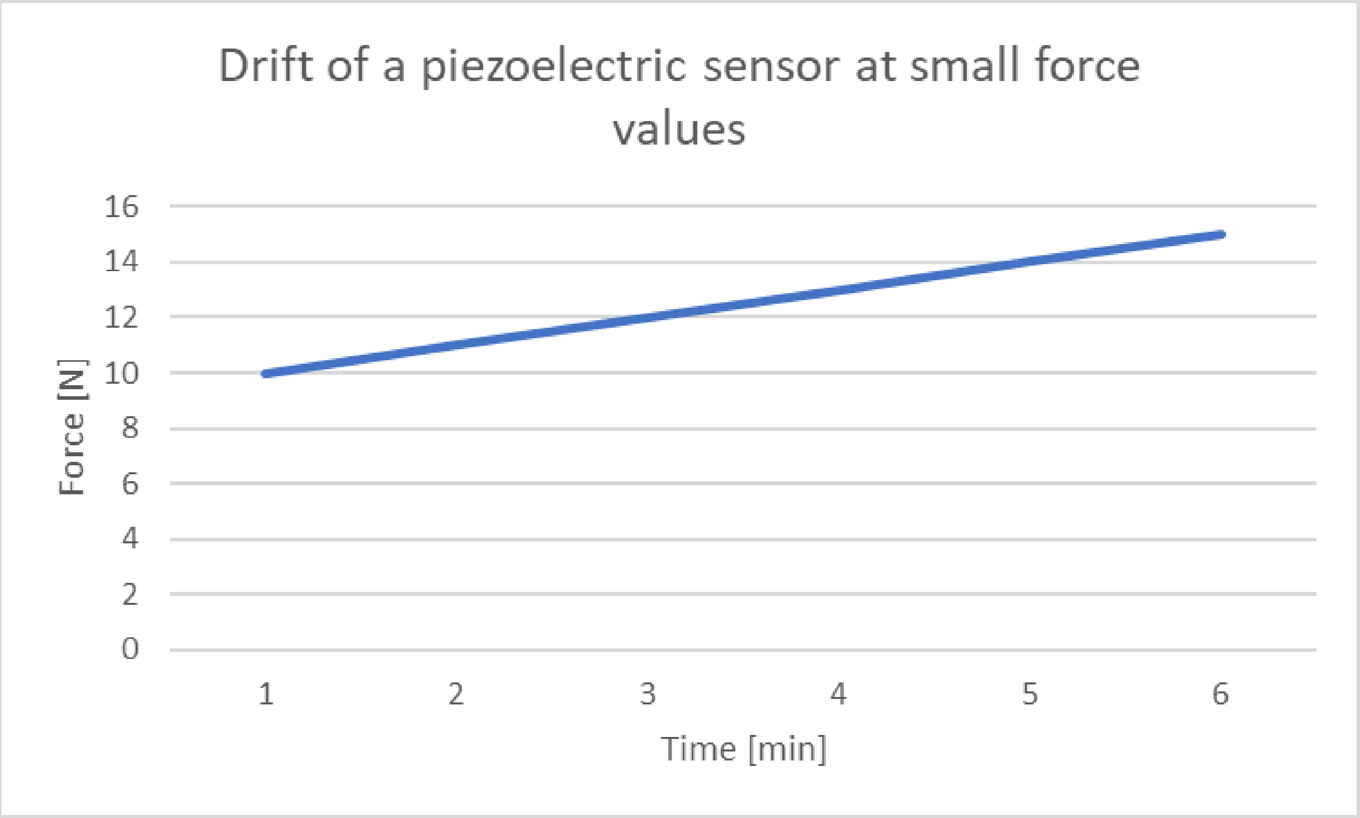
a. Accuracy

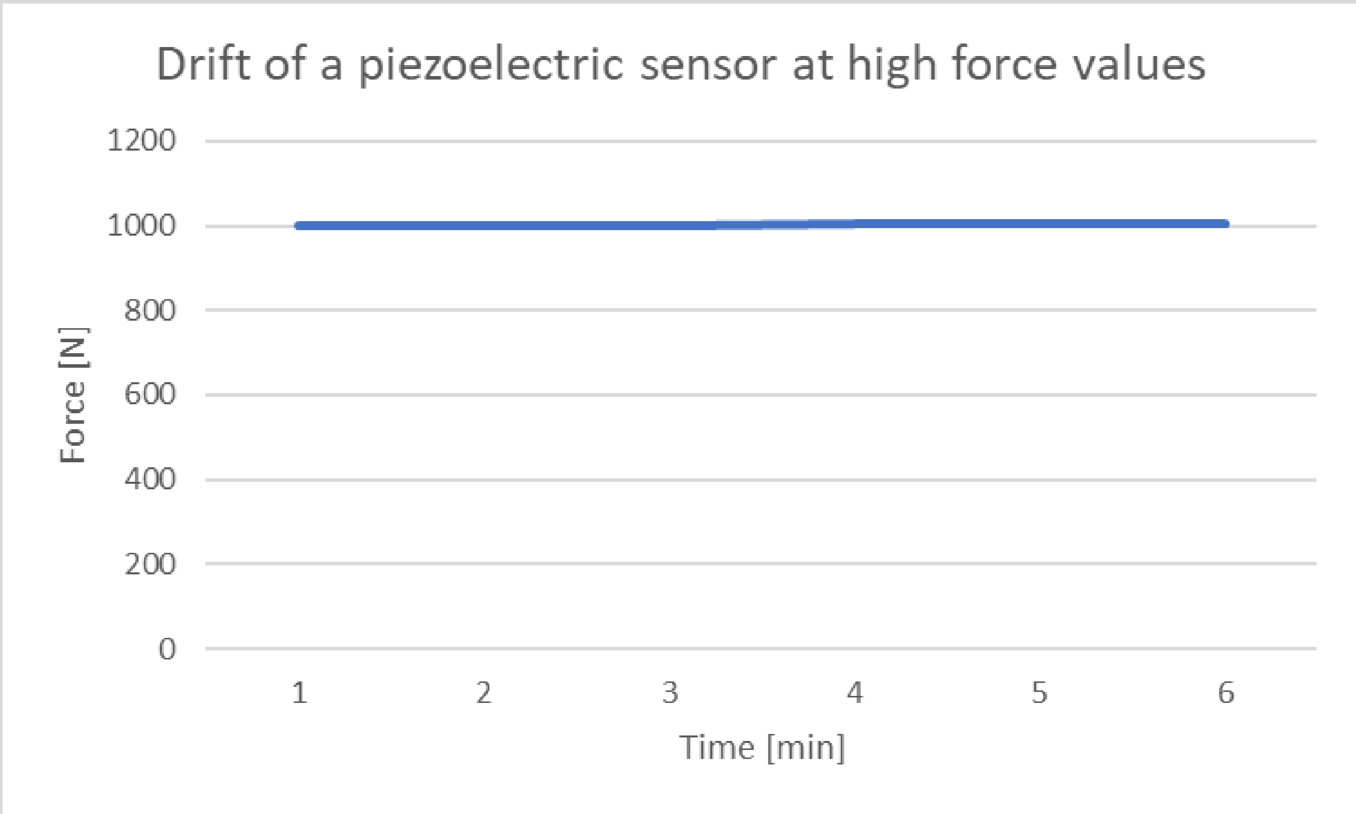
Modern force transducers achieve excellent accuracy values. The strain gauge-based sensors are usually superior in accuracy. In individual cases, these can have relative errors of only 0.01%. Piezoelectric force transducers on the other hand usually have higher relative errors (usually about 0.5%). In general, the accuracy of all force sensors is always dependent on the in-situ calibration!

b. Statics

A big difference between piezoelectric sensors and strain gauge-based sensors is the so-called drift. Piezoelectric sensors exhibit a time-dependent but reversible change in the output signal when statically acting forces are applied. This change is approx. 1N/min and is independent of the magnitude of the acting force. Accordingly, the relative drift is smaller the stronger the forces to be measured are.

Strain gauges, on the other hand, function largely without drift and are therefore preferable, especially for long-term measurements of constantly small forces.





Effect of drift at small and at high force values: At a measurement of 1000 N, longer measurement times are possible because the relative error remains small; at smaller forces, the effect of drift is more noticeable.

c. Dynamics

Even if the material deformation of the piezoelectric crystals under the influence of force leads to the measured charge change, the deformation itself is very small, i.e. piezoelectric crystals are very stiff. This results in a high resonance frequency, which greatly facilitates the measurement of dynamic processes. However, it should be noted that the resonant frequency is not only influenced by the sensor itself, but also by all the mounting parts used. It is therefore important to use light and stiff parts when mounting the sensor.

The resonant frequencies of strain gages depend on the nominal force of the respective sensor: Force transducers designed for smaller force ranges usually use softer springs and have correspondingly low frequencies. Sensors for large forces therefore have higher frequencies. In general: For fast measurements of small forces piezoelectric sensors are preferable; for fast measurements of large forces strain gauges are usually superior.

Since different spring bodies must also be used for different force ranges in strain gauges, the field of application of each individual strain gauge sensor is very limited. If the special application now requires a very large measuring range, piezoelectric sensors are to be preferred.

Excursus: Influence of the resonance frequency at high measuring dynamics.

If a force pulse is applied to a material (here the piezo crystal or the strain gauge including housing and mounting parts), the material deforms within the so-called rise time, which is dependent on the pulse. After this time interval, the material reaches the end position, by which the material then oscillates at the resonance frequency. The shorter the duration of the force pulse, the shorter the rise time. However, the resonant frequency of the excited material determines the minimum rise time t_{min}. So, if the applied pulse is of very short duration, this leads to an increase of the excited oscillation magnitude, but not to a shortened rise time. Think of a drum set as an example: No matter how hard or fast you hit the cymbals, the sound does not change. The tone depends on the resonance frequency of the instrument. If you hit the cymbals harder, the sound only becomes louder, as the magnitude of the oscillation becomes bigger.

The higher the resonance frequency, the shorter is t_{min} and the more suitable is a sensor for dynamic measurements.The resonant frequency can be calculated with the following formula:

$$f_G = \frac{1}{2\pi}\sqrt{\frac{C_{ax}}{m}}$$

Where m is the mass that oscillates (incl. mounting parts) and C_{ax} is the stiffness of the force transducer.

A rule of thumb is that the force transducer should be used up to 20% of the resonant frequency.

d. Environmental conditions

Particularly in biomechanical applications, the installation of force sensors must often not take up much space (e.g. in bicycle pedals or exoskeletons). Here, piezoelectric sensors clearly have the edge: They can be made extremely compact, so that they are sometimes only a few millimetres thick.

In biomechanics, investigations with high preloads are rather rare. If this is the case, however, piezoelectric sensors are to be preferred here as well. If desired, these can be short-circuited under load, so that the input of the charge amplifier is in the same state as at force ‘zero’. Accordingly, it is possible to achieve very accurate results with piezoelectric sensors even under rather unfavourable conditions. With strain gauges, measurement inaccuracies can quickly occur here.

High temperatures can be just as unfavourable as high preloads. Since the electrical resistance is strongly dependent on the temperature of the respective conductor, strain gauges should always be calibrated at the measuring temperature. If there are strong temperature fluctuations, large measurement errors can be avoided using so called wheatstone bridges, which are a special kind of circuit.
The situation is different with piezoelectric sensors. The low temperature sensitivity of this measurement technique allows measurements of up to 300°C with a calibration at room temperature in some models. Possible fields of application at high temperatures are mainly in the field of ergonomics (e.g. in the metal industry).

3. Summary

Both piezoelectric-based and strain gauge-based sensors measure the same physical quantity. However, they differ fundamentally in their mode of operation. This also affects the application areas of both methods.

Piezo sensors are to be preferred for:

- High measurement dynamics and small forces
- Wide measuring range
- Strong spatial restrictions during installation
- Measurements with high preloads
- Measuring at very high or low temperatures

Strain gauges are to be preferred for:

- High demands on the measuring accuracy
- Small measuring range
- Static measurements over a longer period
- High measuring dynamics and large forces

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