SENSOR OF FORCES IN SMALL VOLUME CONTRACTING TISSUES

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Key words: sensor of forces, strain gauge, physiology, contracting tissue

Abstract: A single-channel sensor intended for measurement of forces in small volume contracting tissues within the range of mN was designed, developed and experimentally tested. The force sensor was made up of a Wheatstone bridge composed of four semi-conductor strain gauges bonded on a specially designed cantilever with a handle and metallic cover to protect them. The natural frequency of the sensor is 350Hz while the compliance is $5.7X10^{-6}$m/mN. The sensor represents a very linear dependence of the output voltage upon the load. The sensibility of the sensor, at a bridge excitation voltage of 5V, is 0.5mV/mN and the nominal range of the sensor is 0-70mN. Results show that the sensor enables almost isometric measurements of forces in contracting tissues. The results also show that the sensor measures forces with a frequency of up to 300Hz with appropriate accuracy. Finally, the sensor is suitable for isometric measurements of forces in all types of contracting tissues.

Senzor sile za meritve krčenja drobnih mišic

Ključne besede: senzor sile, strain gauge, fiziologija, kontraktilna tkiva

Izvleček: Izdelali in testirali smo enokanalni mehansko-električni pretvornik za meritve moči krčenja drobnih mišic. Senzor sile je izdelan iz štirih polprevodniških strain-gaugov povezanih v Wheatstonov mostiček, pritrjenih na rigidno merilno ročico ter zaščitenih s kovinskim oklepom. Naravna frekvenca senzorja je 350 Hz in podajnost 5.7 x 10^{-6} m/mN popolnoma ustreza za meritve skoraj izometričnega krčenja drobnih mišičnih tkiv (<5 N, <50 Hz). Občutljivost senzorja z napajanjem 5 V je v razponu 0-70 mN linearna, 0.5 mV/mN. Testiranja so pokazala, da je mogoče s senzorjem zadovoljivo meriti tudi krčenja s frekvenco blizu 300 Hz. Merilec je primeren za meritve sile izometričnega krčenja različnih krčljivih tkiv.

Introduction

In basic research related to the physiology of muscles and other contracting tissues, especially in studies of contraction mechanisms, measurements of elicited forces are very important /1, 2, 3, 4/. Transducers made of strain gauge bridges give the opportunity to develop highly sensitive and reliable force sensors /5, 6, 7/. The development of sensors to measure muscle or vein contractions has a history at least 30 years long and many devices are now commercially available [Axon Instruments (USA), Experimentaria (HUN), 8, 9]. The force sensor should fulfill the following requirements: a) it should be able to evaluate the force elicited by contraction of the muscles and most other contracting tissues, b) electrical response should be as linear as possible in the whole range of expected forces, and c) nevertheless, the sensor should react fast enough to be able to follow a contraction as reliably as possible /10, 11/. The goal of our work was therefore to develop a force sensor that would fit all of the above-mentioned requirements and be easy to manipulate, as a part of the device, especially when testing muscles that are difficult to access.

Material and methods

In the majority of cases of measuring forces of muscle tissues *in vivo* the force sensor should be able to approach the desired contracting tissues at desired angles. Therefore, we designed the cantilever and its holder in such a way that it could move linearly and rotate within a limited space. However, in some cases of measuring forces *in situ* the sensor should be able to be mounted in any position required according to the protocol measurements especially for pharmacological purposes. To obtain adequate characteristics of the force sensor the measurements should be obtained in the way in which the tissues are attached to the force sensor always perpendicularly to the direction of the measured contraction. The cantilever, shown in Fig. 1, was made of highly tempered stainless steel ribbon machined out of the stainless steel bar that acts as the handle of the force sensor at the same time. The dimensions of the section of the cantilever that could be bent upon the applied force were defined according to the request of the gauge's manufacturer (Celesco, USA) and our request to develop the force sensor that would be enough sensitive to measure the elicited forces.

The force sensor itself was made up of a Wheatstone bridge composed of four semi-conductor strain gauges (Celesco, P05-02-500, resistance in ohms: 500.0 ± 0.3%), bonded on a section of the cantilever where bending is of the highest degree. Strain gauges were actually bonded according to the procedure described by both the manufacturer of the strain gauges and the producer of the adhesive (Micro Measurements, M-Bond 610). The mechanical tension produced by the force within the nominal range elicits elastic deformation of the cantilever, thus resulting as a change of the output voltage that could be amplified and connected to the A/D converter and IBM Compatible PC.

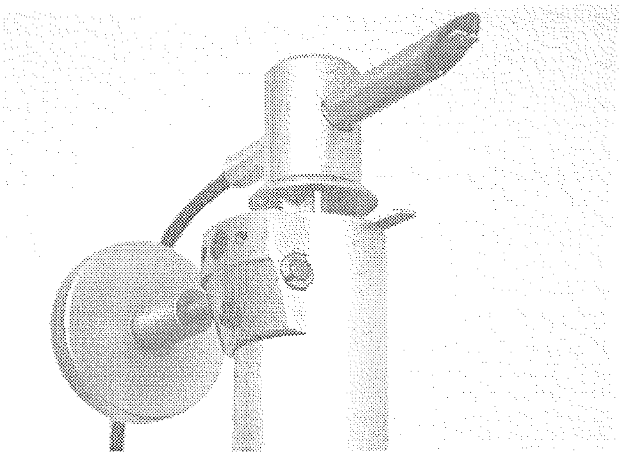

Figure 1. A force sensor mounted within the vice.

The static characteristic of the force sensor was obtained by mechanical connection of the reference force sensor (*ITIS d.o.o., Slo*) to the cantilever of the developed force sensor perpendicularly to the level that is supposed to be the acting point of the measured forces. Then the same manual force was applied to both sensors, exciting them to elicit corresponding voltage signals at the outputs. The output voltage of the developed force sensor was fed to the X input of the X-Y oscilloscope while output voltage of the reference force sensor was fed to the Y input of the oscilloscope. When the applied force reached a nominal value of 70mN, the developed force sensor force was removed. In this way the static charasteristic in both directions was obtained. The compliance of the cantilever was also measured during the recording of the static charasteristics. For this purpose a laser beam was directed to the cantilever and the distance between reflexions when the force sensor was loaded and unloaded was measured. Dynamic behavior of the sensor was defined by eliciting mechanical vibration of the cantilever by striking it with a finger. The output signal of the Wheatstone bridge was amplified at a gain of 100 and fed to a DigiPack 1200 (Axon Instruments) acquisition system and sampled at 2kHz. The recorded data was analyzed using a (*Matlab*) software package enabling Fourier analysis. The dynamic behavior of the force sensor was also tested by a sharp thrust of force applied on the force sensor generated when a weight of 2.75g was dropped on the cantilever of the force sensor from a height of 5cm.

Results

Fig. 2 shows the static characteristics of the force sensor. Considering the data obtained in the aforementioned characteristics and amplification of the output signal, the sensitivity of the force sensor was calculated. Calculations showed that over the nominal range of 0-70mN the sensibility is 0.5mV/mN. The results also showed that the compliance was about 5.7x10^{-6}m/mN. Furthermore, from Fig. 3, showing the dynamic characteristics of the force sensor, the natural frequency and the data describing a behavior of the force sensor below the natural frequency was obtained. The corresponding natural frequency of the force sensor is 350Hz.

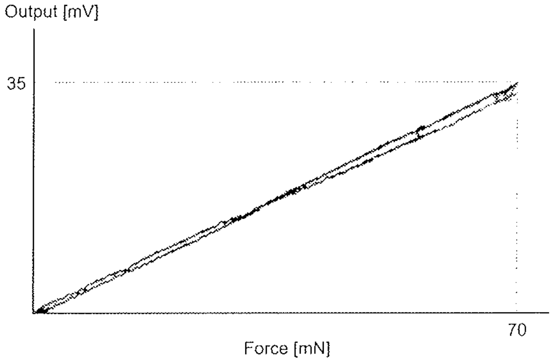

Figure 2. The static characteristic of the force sensor.

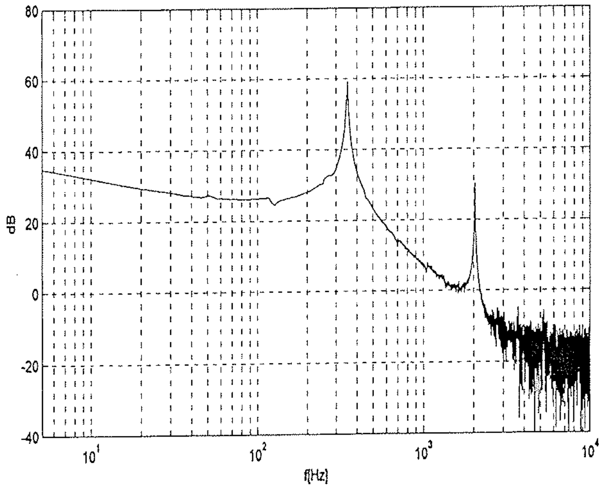

Figure 3. The dynamic characteristic of the force sensor.

Figure 4, however, represents the record of sharp thrust of force applied on the force sensor. It coud be seen that the time from zero to peak force when a weight of 2.75g was dropped on the cantilever of the force sensor from a height of 5cm was 55.23ms.

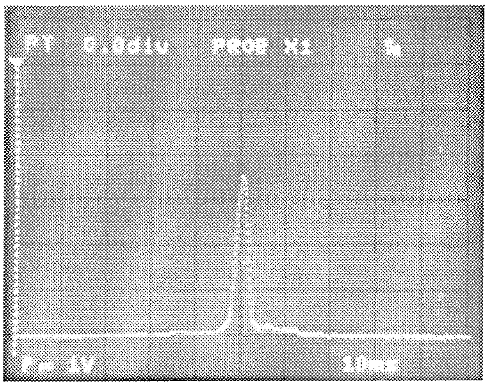

Figure 4. *A record of sharp thrust of a force applied on the force sensor.*

Discussion

According to the requirements determined in the methods section we can conclude that all of the requirements defined at the start of the development of the force sensor were met. Namely, as can be seen in Fig. 2, the force sensor shows a highly linear dependence of the output voltage upon the load within the whole nominal range of applied forces. However, the different slopes in the trajectories (Fig. 2) arising in opposite directions of the applied force were attributed exclusively to mechanical sliding that occurred at the contact between the two sensors when mounted within the vice. By sliding, the length of the reference sensor was slightly changed. This could be confirmed by the intersection of the two trajectories which is settled exactly at the middle between the points representing zero and maximum load. Moreover, it could be seen in Fig. 3, showing the frequency spectrum contained in the response of the force sensor on the strike applied to the cantilever, that the natural frequency of the sensor is equal to 350Hz. At frequencies below the natural frequency of the force sensor the curve is relatively linear, enabling accurate measurements of forces. Since the natural frequency and sensitivity of the force sensor are relatively high one could conclude that the force sensor is able to record fast changes that could be expected in muscle contraction, also of only a few muscle fibers, without any deformation. In Fig. 4. representing a record of sharp thrust of force applied on the force sensor, one can see that the rise time of 55.23ms corresponds to a frequency of 18Hz, which is far below the natural frequency of the force sensor. Accordingly, the force sensor is also suitable for recording sustained tonic contractions of a muscle. The limitation of the force sensor is that it is designed to measure contractions of 70mN maximum. This sensor with a compliance of $5.7\text{x}10^{-6}$m/mN enables the recording of forces in a predominantly isometric mode. However, the higher the force, the more isotonic the contraction appears. The important advantage of the force sensor is that it could be orientated in space to reach any point of the hemisphere with a diameter of 15cm from the vertical handle. Because of that the measurements of contracting tissues could always be perpendicular to the axis of the measured muscle contraction. Our force sensor is relatively simple, reliable and is sold at an acceptable price.

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