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Technical note

Evaluating and improving the performance of thin film force sensors within body and device interfaces

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A B S T R A C T

Thin film force sensors are commonly used within biomechanical systems, and at the interface of the human body and medical and non-medical devices. However, limited information is available about their performance in such applications. The aims of this study were to evaluate and determine ways to improve the performance of thin film (FlexiForce) sensors at the body/device interface. Using a custom apparatus designed to load the sensors under simulated body/device conditions, two aspects were explored relating to sensor calibration and application. The findings revealed accuracy errors of $23.3 \pm 17.6\%$ for force measurements at the body/device interface with conventional techniques of sensor calibration and application. Applying a thin rigid disc between the sensor and human body and calibrating the sensor using compliant surfaces was found to substantially reduce measurement errors to $2.9 \pm 2.0\%$. The use of alternative calibration and application procedures is recommended to gain acceptable measurement performance from thin film force sensors in body/device applications.

1. Introduction

Sensors that measure force and pressure within biomechanical systems are important tools used by designers and researchers to gain insights into these typically complex systems. Compactness and ease of installation of pressure sensors are important considerations so that the biomechanical system is altered and disturbed as little as possible [1]. While there are multiple thin film sensors in the market, such as the Force Sensitive Resistor (FSR) sensor (Interlink Electronics, Camarillo, CA, USA) and the Quantum Tunneling Composite (QTC) sensor (Peratech Ltd, Richmond, North Yorkshire, UK), the advantages of FlexiForce (Tekscan, Boston, MA, USA) over other sensors include better performance in linearity, repeatability, drift and dynamic responses [2–4]. Under controlled conditions, FlexiForce sensors have a low linearity error of $\pm 3\%$, repeatability of $\pm 2.5\%$ of full scale, drift of $< 5\%$ per logarithmic time scale, and hysteresis of $< 5\%$ of full scale [2,5]. Response time is < 5 ms and temperature effects are low at 0.36% per degree Celsius.

Thin film pressure sensors, including FlexiForce sensors, have been broadly utilized in biomedical applications to measure interfacial pressure in mobility assistive technology such as braces, crutches and other orthotic and prosthetic assistive devices [6,7], forces exerted by medical devices such as laparoscopic instruments [8], forces exerted within the mouth and throat [9–12], pressure under a digital tourniquet [13], pressure in compression garments [14], impact forces in helmet [15], as well as plantar foot pressures used in portable gait analysis devices [16]. Thin film sensors have also been used in feedback systems for detecting pressure ulcers and hematomas [17–19], robotic applications [20] and in grip monitoring for prosthetic hands [21] and golf club handles [4]. Despite their broad use in applications involving body/device interfaces, there is limited data about their performance under such conditions and there is no clear agreed upon standard on the application of the sensor within the interface of body/device.

Furthermore, multiple studies using thin film force sensors rely on calibrations performed under controlled conditions which involves applying a known weight on the sensor with rigid and flat surfaces underneath [1,9,10,13–15]. This calibration is based on the manufacturer's recommendations for maximizing sensor performance, and includes adjusting sensitivity to minimize linearity and repeatability errors, adjusting calibration time to minimize drift, and controlling for temperature [2]. Furthermore, to achieve accurate calibration, applied loads should be evenly distributed over the sensing area of the sensor [2].

However, in applications involving the human body where compliant body tissues interface with the sensor, uniform load distributions may not be achieved. A limited number of investigations

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have examined the influence of loading conditions on sensor performance, and few recommendations and guidelines currently exist guiding the effective use of thin film sensors in biological applications. Due to this limited information on sensor placement in the body/device system, the majority of the literature places the sensor directly between the body and the device being investigated [6–8,11–21]. This direct placement of the sensor has the potential to cause multiple inaccuracies in the sensor readings.

One source of error associated with the use of thin film sensors within the body/device interface relates to the sensor bending. Deformation of the sensor may be caused by placing it between two curved surfaces, or two compliant surfaces as is the case in many body/device applications. Ferguson-Pell et al. [5] investigated the effects of curvature on sensor performance, and found that relatively mild bending of the sensor (i.e. radii of 32 mm) can alter sensor readings. While their findings suggest the importance of limiting sensor bending to ensure accurate sensor readings, the applicability of these results to measurements taken at the body/device interface is less clear due to the complexity of the stresses and strains that result at the sensor under such conditions.

Additional measurement uncertainty can be attributed to current sensor calibration protocols. As described above, Tekscan recommends calibrating using conditions that mimic the application to minimize the effects of drift and temperature [2]. Brimacombe et al. demonstrated that the accuracy of Tekscan I-Scan pressure sensors (model 5051) are heavily dependent on calibration technique, and that user specific calibration yielded significant improvements in sensor performance over the manufacturer suggested calibration methods [22]. The physical properties of the materials contacting the sensing surfaces may also influence measurements by altering the load distribution over the sensor. Conventional calibration of FlexiForce sensors is performed by placing the sensor between two hard surfaces [2,5]; however, within a body/device interface one or both of the sides of the sensor may be in contact with compliant surfaces. This potential mismatch of conditions likely affects the accuracy of sensor calibration in body/device applications, although a paucity of information about this currently exists.

The study by Jensen et al. [23] is one of the few studies that looked into the performance of FSR sensors and the associated calibration performance within the body/device. The investigators placed a thin layer of dome shaped epoxy onto the active sensing area, which increased rigidity of the sensor and reduced local pressure concentrations. The sensors were calibrated by pinching a strain gage dynamometer [23]. Since this work was performed on early-stage FSR designs, similar work could be beneficial for the establishment of recommendations for FlexiForce sensor calibration and placement to improve their performance.

The overall objective of this work was to assess the performance of thin film sensors under conditions that are representative of the biomechanically relevant body/device interfaces, and to investigate new calibration techniques and application conditions to improve their performance. Specifically, this study explored the effects of different sensor contact conditions used in calibration and during measurement at the body/device interface.

2. Methods

A set of experiments was conducted to compare the standard manufacturer-recommended sensor calibration procedure [2] against an alternate procedure involving compliant surfaces which are representative of the body/device interface. Similarly, the standard technique for applying the sensors at the body/device interface was compared to several proposed techniques whereby the flexible sensor is provided additional support.

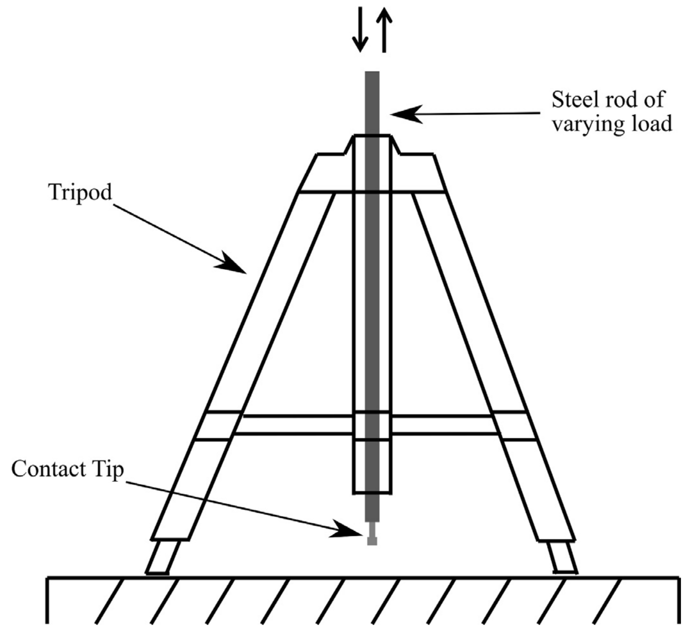

Fig. 1. The testing apparatus for the FlexiForce sensor. The apparatus is constructed from a tripod and a tube used to insert the steel rod with a tip that is the same dimension as the sensing area of the FlexiForce sensor.

2.1. FlexiForce sensor

The FlexiForce sensor is constructed from two layers of polyester film, each with an inside coating of a conductive material and separated by a layer of pressure-sensitive ink; these comprise of the active pressure sensing area which is 9.53 mm in diameter and the thickness of 0.203 mm. When the sensor is unloaded its electrical resistance is very high, and as it becomes loaded the ink is displaced and the resistance decreases. Different sensors exist to measure loads in the ranges of 0–1 lbs, 0–25 lbs and 0–100 lbs. For this study the sensing range of 0–1 lbs was used because it most closely represents the interface pressures reported in biomedical devices [13,14].

As recommended by the manufacturer, the sensor was conditioned at the beginning of each experiment whereby a load of 550 g (i.e. 110% of the highest test load) was applied to the sensor four times for 30 s each [2].

2.2. Data acquisition system

An inverting operational amplifier circuit [2] was used to convert the measured resistance to a linear pressure–voltage relationship [2,5]. The voltage was sampled using an ELF 2 System (TekScan) at a rate of 200 Hz, which also provided the user interface software for sensor calibration and data acquisition.

2.3. Testing apparatus

A custom apparatus was constructed from a commercially-available tripod base and tube to apply discrete loads to the sensor mounted under simulated body/device conditions (i.e. on the arm), and also in conditions for standard calibration. Five 19.05 mm diameter steel rods were precision machined in length to weights of 50 g, 150 g, 250 g, 350 g, and 500 g. The tips of the rods were fabricated to have contact areas of 9.53 mm in diameter. The inner diameter of the tripod tube was slightly larger than the diameter of the rod weights, allowing them to transfer their weight directly downward (Fig. 1). A high accuracy digital scale (Navigator