34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

# Static and Cyclic Performance Evaluation of Sensors for Human Interface Pressure Measurement

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***Abstract*— Researchers and clinicians often desire to monitor pressure distributions on soft tissues at interfaces to mechanical devices such as prosthetics, orthotics or shoes. The most common type of sensor used for this type of applications is a Force Sensitive Resistor (FSR) as these are convenient to use and inexpensive. Several other types of sensors exist that may have superior sensing performance but are less ubiquitous or more expensive, such as optical or capacitive sensors. We tested five sensors (two FSRs, one optical, one capacitive and one fluid pressure) in a static drift and cyclic loading configuration. The results show that relative to the important performance characteristics for soft tissue pressure monitoring (i.e. hysteresis, drift), many of the sensors tested have significant limitations. The FSRs exhibited hysteresis, drift and loss of sensitivity under cyclic loading. The capacitive sensor had substantial drift. The optical sensor had some hysteresis and temperature-related drift. The fluid pressure sensor performed well in these tests but is not as flat as the other sensors and is not commercially available. Researchers and clinicians should carefully consider the convenience and performance trade-offs when choosing a sensor for soft-tissue pressure monitoring.**

## I. INTRODUCTION

Measurement of interface pressures between human soft tissues and mechanical devices can be useful for several research and clinical applications. For example, measuring pressure distributions on the interior surfaces of prosthetics sockets, orthotics or shoe soles can provide valuable information that can evaluate fit quality or diagnose potential loading complications such as blisters or pressure sores [1]. These measurements are often taken with commercially available tactile sensors, such as Force Sensitive Resistors (FSRs), which are inexpensive, thin and require only simple signal conditioning. While these features make them very convenient to use in research and clinical settings, they have well-known performance limitations [2], [3]. Several other types of tactile sensors exist that could also be used for these applications but most are either not commercially available or are more expensive. In the present work, we aim to provide a summary of some important performance characteristics for several tactile sensors types so that researchers and clinicians can evaluate the important trade-offs in performance and cost when choosing a sensor for human interface pressure measurement.

*Manuscript received March 15, 2012. This work was supported in part by the U.S. Army Telemedicine and Advanced Technology Research Center and the Congressionally Directed Medical Research Program.

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Several types of tactile sensors have been demonstrated, including some based on load-related changes in resistance, capacitance, fluid pressure, or optical reflection and transmission. Cutkosky et al. provide a review of tactile sensor technologies and considerations for a broader set of applications [4]. There are several performance characteristics that may be of interest to a designer or researcher, depending on the desired application, including sensitivity, linearity, spatial resolution, noise, dynamic response, hysteresis and drift. For the present set of applications, some of these, such as dynamic response and spatial resolution are generally less important (i.e. most pressure sensors will easily meet the application requirements in those areas). In most human interface pressure measurement applications, loads are applied at relatively low frequencies (from DC up to several Hertz) over long periods of time. Sensitivity, linearity, hysteresis and drift are all important in these situations. Of these, we believe that hysteresis and drift are the most problematic. Due to the repetitive nature of most loads in these applications, hysteresis may be able to be addressed with modeling. Drift, however is very difficult to accommodate and should be minimized as much as possible at the sensor hardware level. We tested three commercially available (two FSRs and one capacitive) and two custom-developed (fluid pressure and optical) sensors in order to characterize several important sensing performance characteristics, particularly hysteresis and drift.

## II. METHODS

### A. Description of Sensors

The sensors evaluated are shown in Figure 1. The Flexiforce (A401-25,Tekscan, South Boston, MA) sensor is a commercially available piezoresistive sensor, with a 25.4mm diameter sensing area and 0.2mm thickness. The Interlink FSR (402 FSR, Interlink Electronics, Camarillo, CA) is another commercially available piezoresistive sensor, with a 12.7mm active sensing diameter and 0.45mm thickness. The Pressure Profiles Systems (PPS, Los Angeles, CA) ConTacts C500 sensors are 25mm square, 0.7mm thick, flexible capacitive sensors with an integrated signal processing unit. These commercial sensors are being evaluated against novel sensors developed at Sandia National Laboratories. The bubble sensor [5] is a Sandia developed MEMS-based diaphragm pressure sensors encapsulated in a fluid-filled bubble about 16x9x5 mm in size. Pressure on the external surface of the bubble is transduced to internal fluid pressure which is measured by the MEMS diaphragm sensor containing piezoresistive traces. Signal conditioning electronics are fully

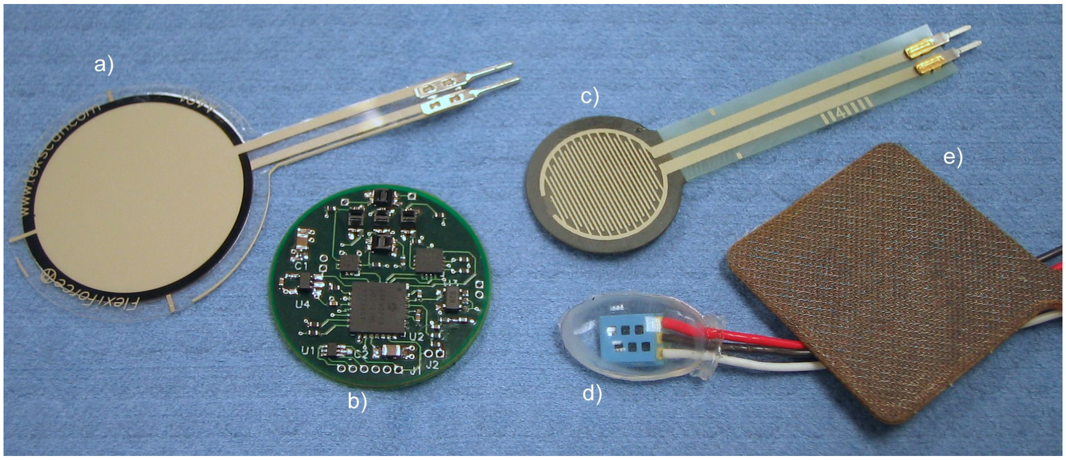


Fig. 1. Photograph of the sensors tested. a) Tekscan Flexiforce A401-25 FSR. b) Sandia Optical 3D force sensor. c) Interlink 402 FSR. d) Sandia Bubble sensor. e) Pressure Profiles C500 capacitive sensor.

integrated into the bubble. The optical 3D force sensor [6] utilizes light emitting diodes (LEDs) and phototransistors to measure reflected light intensity through a transparent elastomer and can measure both normal and shear loads in two directions. The sensor board shown in Figure 1 contains signal conditioning electronics and analog to digital conversion on-board. This sensor has been shown to be more sensitive to shear loads than normal loads [6] but in the present work we show results only in the normal direction to facilitate comparison with the other sensors under test.

The bubble and optical sensors contain on-board signal conditioning electronics. The Tekscan and Interlink sensors were conditioned using a simple filter/amplifier circuit recommended by their respective vendors and configured with gains to optimize the appropriate output range. The PPS sensor included custom electronics to condition the output signal. The optical sensor data were sampled with a 16-bit National Instruments DAQ board (NI-PCI6229, National Instruments, Austin, TX). All other sensors were sampled with a custom, 10 bit, analog to serial converter which converted their native voltage outputs to counts.

### *B. Test Description*

Two sets of tests were performed for each sensor, a static drift test and cyclic loading test. The static drift tests were conducted by setting a mass on the sensor for a period of 13-20 hours while sampling at 1 Hz. The load was applied through a 5mm layer of 20 shore A silicone to help ensure a uniform load application across the sensor surfaces. For the Bubble, Tekscan, and Interlink sensors, a 38.3kg load was applied through a 63.5mm diameter aluminum load block. Due to various geometric constraints and load capacity, the optical sensor was loaded with a 6.8 kg mass through a 25.4mm square aluminum block, and the PPS sensor was loaded with an 8.8kg load through the same square aluminum block. Additionally, the bubble sensor was embedded in a 7mm thick layer of 20 shore A silicone to prevent damage to the bubble, and to approximate a use case where the bubble sensors would be embedded in a prosthetic silicone liner or shoe sole. Static drift data were low-pass filtered (5th order Butterworth) with a cut-off frequency of 0.1 Hz.

The cyclic loading tests were designed to better evaluate the characteristics of the sensors when subjected to a periodic load (e.g. to simulate gait). A cyclic loading profile, shown in Figure 2, was applied to each sensor at levels necessary to achieve an applied pressure varying between approximately 30kPa and 140kPa at 0.5 Hz, for 4 hours. The loading profile was applied on an MTS (Eden Prairie, MN) Alliance RT/5 electromechanical load frame with a calibrated 10kN load cell. As with the static drift test, the load was applied through a 5mm layer of 20 shore A silicone, with the same loading blocks used on the static drift testing.

Due to limitations of the test machine control system, the cyclic test was a displacement controlled test. The test setup required finding the proper displacement limits that would achieve the desired range of force to the sensor system. This need to individually adjust the test parameters for each setup resulted in each sensor receiving load conditions which varied slightly from other sensors. Additionally, due to the viscoelastic nature of the silicone used to distribute the load on the sensor surfaces, the amount of pressure experienced by a sensor at a given displacement slowly changed by a small amount throughout the test (but the actual applied loads were measured).

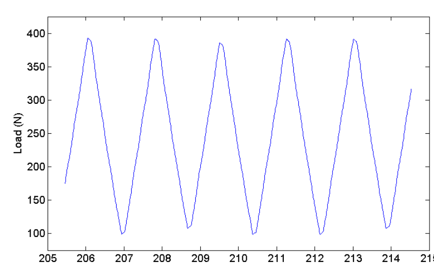


Fig. 2. Representative loading profile for cyclic drift testing

## III. RESULTS

### A. Static Drift Test

The results of the static drift test for all five sensors are shown in Figure 3. The data were shifted (but not scaled) to facilitate comparison. The PPS (capacitive) and Interlink sensors exhibited the largest drift, with the PPS still drifting considerably after several hours. The bubble sensor had the smallest drift. The drift magnitudes are summarized in Table I.

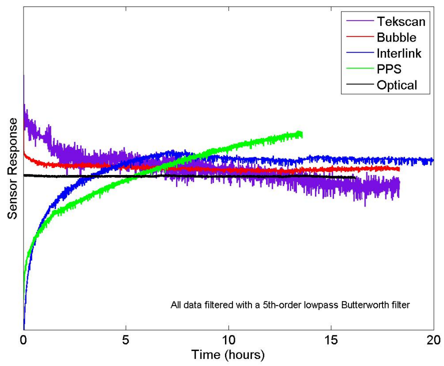


Fig. 3. Static drift performance for all sensors. Data were low-pass filtered at 0.1 Hz and shifted to facilitate comparison.

### B. Cyclic Loading Test

An intuitive way to visualize the results of the cyclic loading tests is to examine a few cycles at the beginning and end of the four hour test. The following plots show ten cycles from the beginning (red) and end (blue) of the tests.

The results for the Interlink sensor are shown in Figure 4. The sensor exhibited substantial nonlinearity, hysteresis (gaps between loading and unloading cycles) and drift (gaps between red and blue curves).

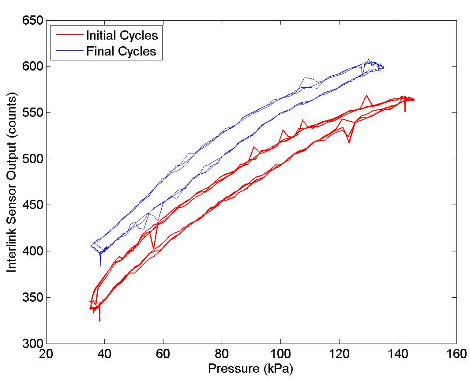


Fig. 4. Cyclic loading response for Interlink FSR. Red curve is ten cycles from the beginning of trial and blue is ten cycles from the end of the trial.

The results for the Flexiforce sensor are shown in Figure 5. At the beginning of the trial, the sensor had reasonable sensitivity and hysteresis but after several trials, the sensitivity decreased to near zero. This effect was repeatable over many trials and may have been due to the fact that the sensor was never completely unloaded. Figure 6 shown the sensor response over the entire four hour trial, showing the gradual loss of sensitivity.

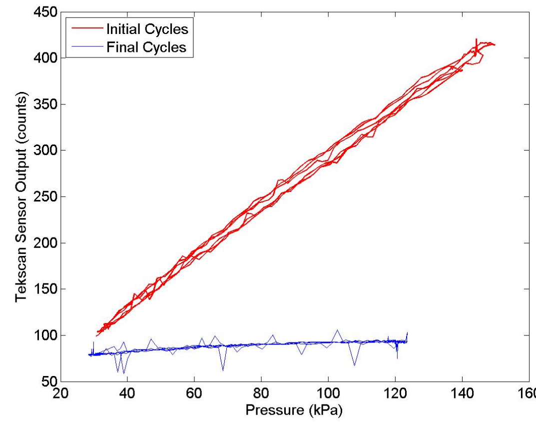


Fig. 5. Cyclic loading response for Flexiforce sensor. Red curve is ten cycles from the beginning of trial and blue is ten cycles from the end of the trial.

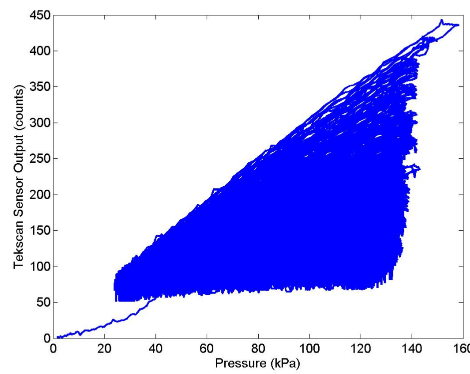


Fig. 6. Cyclic loading response for entire trial for the Flexiforce sensor.

The results for the PPS sensor are shown in Figure 7. This sensor exhibited good sensitivity, linearity and hysteresis performance but had significant drift.

The results for the optical sensor are shown in Figure 8. The sensor exhibited some hysteresis and substantial drift. It was later determined that the drift was due to temperature changes and current versions of the sensor compensate for this [6].

The results for the Sandia bubble sensor are shown in Figure 9. This sensor showed relatively little hysteresis and drift. As discussed previously, the test setup was displacement controlled so some drift occurred in the applied load (horizontal axis), which the sensor accurately tracked.

The results of both tests are summarized in Table I.

## IV. DISCUSSION

The tests described in the present work show some of the relative strengths and weaknesses of various tactile sensor

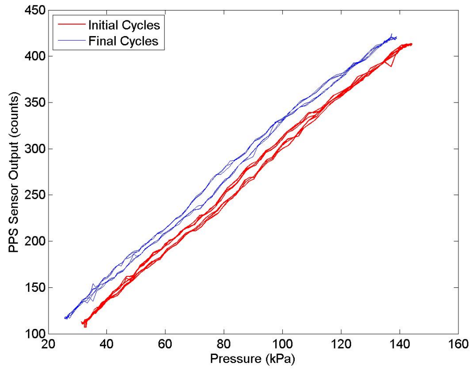


Fig. 7. Cyclic loading response for PPS capacitive sensor. Red curve is ten cycles from the beginning of trial and blue is ten cycles from the end of the trial.

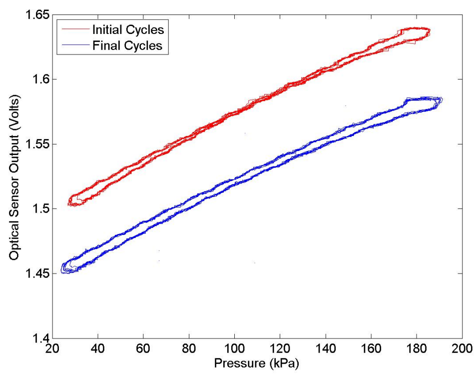


Fig. 8. Cyclic loading response for Sandia optical sensor. Red curve is ten cycles from the beginning of trial and blue is ten cycles from the end of the trial.

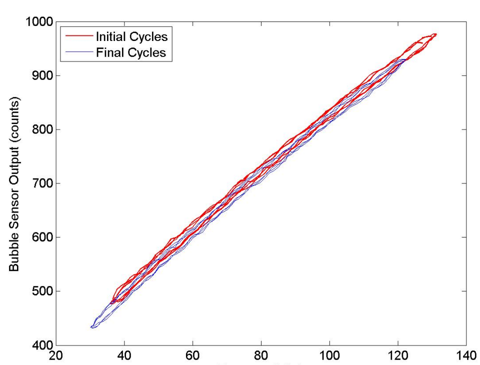


Fig. 9. Cyclic loading response for Sandia bubble sensor. Red curve is ten cycles from the beginning of trial and blue is ten cycles from the end of the trial.

TABLE I

SUMMARY OF SENSOR PERFORMANCE, ALL VALUES PERCENT

| Sensor | Static Drift | Hysteresis | Cyclic Drift |
|---|---|---|---|
| **Interlink** | 21.4 (20 hrs) | 19.8 | 20.9 |
| **Flexiforce** | 6.2 (18 hrs) | 7.4 | n/a |
| **PPS** | 24.3 (13 hrs) | 6.8 | 14.3 |
| **Optical** | 4.7 (10 hrs) | 13.6 | 26.8 |
| **Bubble** | 2.3 (18 hrs) | 2.8 | 1.8 |

technologies for human interface pressure monitoring applications. The FSR sensors (Flexiforce and Interlink) had some substantial performance limitations, particularly when loaded in a cyclic fashion as is the case in many of these applications (e.g. gait monitoring in shoes or prosthetic sockets). While the hysteresis may be manageable with some considerable modeling, the drift is much more difficult to compensate for and will likely require very frequent recalibrations. The ubiquitous and inexpensive nature of these sensors makes them attractive for simple studies but researchers should be aware of and acknowledge the performance limitations.

The capacitive (PPS) sensor is designed primarily for tactile sensing in robotics and has very good sensitivity, linearity, dynamic response (not reported in the present work) and low hysteresis. However, for the present set of applications, the drift may be prohibitive. These sensors are also much more expensive than FSRs. The optical sensor had reasonable performance but exhibits some hysteresis and drift. The main advantage of this sensor is the ability to measure shear, which is not possible with the other tactile sensors. We have found that the optical sensor drift can effectively be compensated for with on-board temperature sensing, while the drift in the other sensors appeared to be systematic (not temperature-dependent). The bubble sensor had the best overall performance in these tests. The low hysteresis and drift make it attractive for many applications. However, it is not flat, which requires some special packaging and is not yet commercially available.

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