Experimental Evaluation of Two Commercial Force Sensors for Applications in Biomechanics and Motor Control

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Abstract - *The objective of this work was the comparative analysis of two commercial force sensors, the FSR™ sensors (Interlink Electronics, Camarillo, CA, US) and the Flexiforce™ (Tekscan Inc., Boston, MA, US), that can be attached to the palmar surface of the fingers to study the biomechanics of the hand during grasp and to develop rehabilitative devices such as closed-loop controlled hand neuroprostheses. The performance tests were performed with the sensors mounted on the thumb. The Flexiforce™ sensors showed better performance in terms of repeatability, linearity and time drift when mounted on a rigid substrate, and in terms of dynamic accuracy when mounted on the thumb. The FSR™ sensors showed better performance in terms of robustness.*

Keywords: force sensors, upper limb, tactile, closed-loop control, hand biomechanics, finger, pinch.

1. Introduction

The analysis of grasp forces produced during motor tasks has been widely used in studies concerning the biomechanics of the hand, the hand functional assessment and the design and the development of force closed-loop controlled FES systems for the upper limb [1-3]. In this case, the characterisation of the grasp forces produced by human hand can involve instrumented objects [4] but the sensorisation of all the objects manipulated by the users in their daily activities is not a practical solution for a portable closed-loop controlled FES system. An alternative option is the characterisation of the grasp forces by means of artificial force sensors attached on the surface of the hand. Crago et al. [5] stated that the principal ideal requirements of an artificial force sensor usable for the characterisation of the grasp forces are: 1) operating range between 0.1 and 80 N; 2) resolution of 0.1 N for light load and 1 N in case of heavy load; 3) repeatability; and 4) stability. Also, the ideal force sensor should be light, little, easy to be mounted, not bulky, with few leads and robust. At the moment, no artificial force sensor satisfies at the same time all the previous requirements.

For their good characteristics in term of robustness, flexibility and low costs, the piezoresistive tactile sensors have been often used for measuring external finger forces [6,7]. This kind of sensor has been used to study the external forces exerted during object manipulation [8] and to generate the artificial afferent signals used by the closed-loop controller to regulate the FES of the upper limb [9]. In particular, the FSR™ sensors (Interlink Electronics, Camarillo, CA, US) have been widely studied for these purposes. However, they present several problems in terms of hysteresis, instability and low repeatability. The aim of our study is the performance comparison between the FSR and another piezoresistive tactile sensor, the Flexiforce™ (Tekscan Inc., Boston, MA, US).

This work is part of a long-term effort which is going on in the framework of the European Project GRIP ("An inteGRated system for the neuroelectrIc control of grasP in disabled persons", ESPRIT LTR #26322), whose objective is the developing of an implantable closed- loop FES system to restore hand function in tetraplegics using the sensory information recorded from a glove worn by the patient (see Fig. 1). The aim of this work was to choose the best commercial force sensors to be integrated in the sensorised glove, which will be worn by the patients.

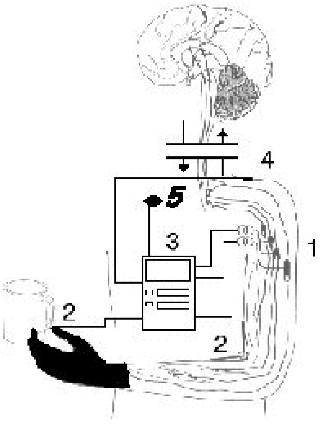

Fig. 1. Schematic of the final demonstrator of the GRIP Project: 1) neural electrodes, implantable stimulator and telemetry system; 2) artificial sensors (position, contact); 3) control system; 4) signals for high level control; 5) system to provide cognitive feedback.

2. Material and Methods

In this study, the FSR sensor and the Flexiforce sensor were compared. The FSR is a thick-film device consisting of two conducting interdigitated patterns deposited on a thermoplastic sheet facing another sheet containing a conductive polyetherimide film. A spacer placed between the plastic sheets permits the two sheets to make electrical contact when the force is applied, but otherwise causes the sensor to have infinite impedance in the unloaded state. As the applied force increases, the two layers compress each other, thus, increasing the contact area and decreasing the electrical resistance.

The Flexiforce sensor is constructed of two layers of substrate, such as a polyester film. On each layer, a conductive material (silver) is applied, followed by a layer of pressure-sensitive ink. The active sensing area is defined by the silver circle on the top of the pressure-sensitive ink. When the sensor is unloaded, its electrical resistance is very high. When a force is applied to the sensor, this resistance decreases.

The sensors selected for the experiments had a 12 mm (FSR) and 10 mm (Flexiforce) diameter circular effective area (see Fig. 2).

To create a sensor that responds to force rather than pressure an epoxy dome and an epoxy plate have been placed over and under the sensing area (see Fig. 3). An adhesive plastic tape was wrapped around each sensor for protection. Some Velcro™ strips were used to apply the sensors to the thumb. The total thickness of the completed sensors was 4 mm.

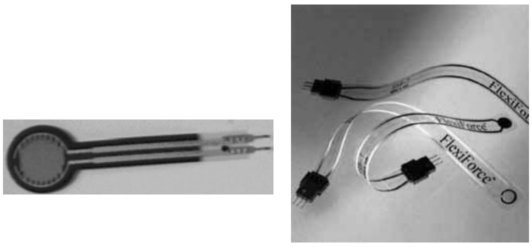

Fig. 2. Force sensing resistor (FSR sensor by Interlink Electronics, Camarillo, CA, US) (on the left) and Flexiforce sensor by Tekscan Inc., Boston, MA, US (on the right).

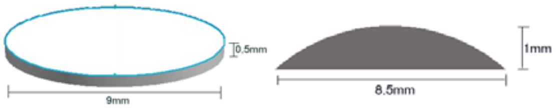

Fig. 3. To create a sensor that responds to force rather than pressure, a method was needed for directing all of the applied force through the effective sensing area. This was accomplished by placing an epoxy dome (on the right) over and an epoxy plate (on the left) under the sensing area.

A monoaxial load cell (produced by Kistler Intrudente AG (Winterthur, CH)), was used to calibrate the sensors mounted on a rigid substrate. A strain gage dynamometer, the Pinch Force Dynamometer (PFD) (Kayser Italia srl. - Italy) (see Fig. 4), was used as a benchmark during testing the performance of the thumb-mounted sensors. The main characteristics of the PFD are the following: 1) range of force measurement from 0 to 270 N; 2) accuracy: ±0.75% full range; 3) 0 to 5 V output from the instrumentation amplifier; 4) operating temperature range from 18.5 to 29.5° C.

Fig. 4. The Pinch Force Dynamometer (Kayser Italia srl, Italy).

Static (calibration, repeatability, and time drift) and dynamic accuracy tests have been performed.

3. Results

Sensor calibration

Each force sensor was calibrated individually on a rigid plane against the load cell. Seven calibration force level (3, 5, 10, 15, 20, 25, and 28 N) were presented in random order on the sensors for three times. The average of the output voltages from the sensors and the load cell were used as static calibration points. The sensor and the load cell outputs were sampled at a frequency of 20 Hz for a period of 2 s.

The static calibration curves of the sensors were compared in case of: 1) absence of substrates and use of a cylindrical indentation point (diameter=10mm) (see Fig. 5); 2) presence of substrates and use of a cylindrical profile indentation point (diameter=3.55cm) (see Fig. 6).

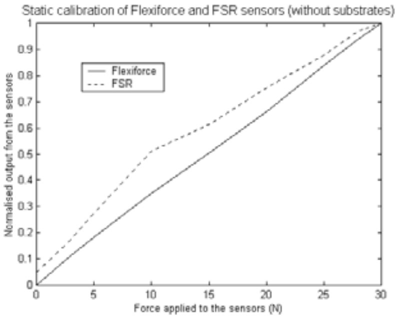

Fig. 5. Typical static calibration curves for Flexiforce and FSR sensors in case of absence of substrates and of use of a cylindrical indentation point (diameter=10mm). The standard deviations in percentage with regards to the full scale of 30N are 4.7% (Flexiforce) and 7.4% (FSR).

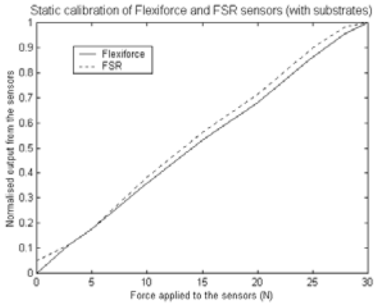

Fig. 6. Typical static calibration curves for Flexiforce and FSR sensors in case of presence of substrates and of use a cylindrical profile indentation point (diameter=3.55cm). The standard deviations in percentile as regards to the full scales of 30N are 1.6% (Flexiforce) and 6.8% (FSR).

Repeatability tests

Experimental protocol used for the static calibration of the sensors in case of presence of substrates and of use a cylindrical profile indentation point (diameter=3.55cm), was repeated during three consecutive days. Fig. 7 and Fig. 8 show, respectively, the performances of the two sensors.

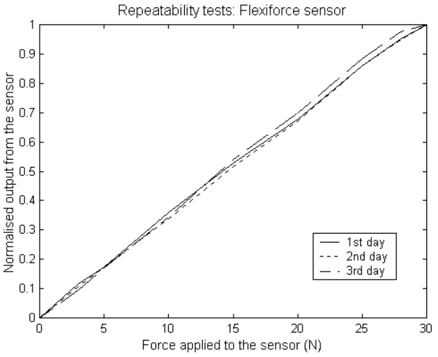

Fig. 7. Static calibration curves of the Flexiforce sensor in three different days.

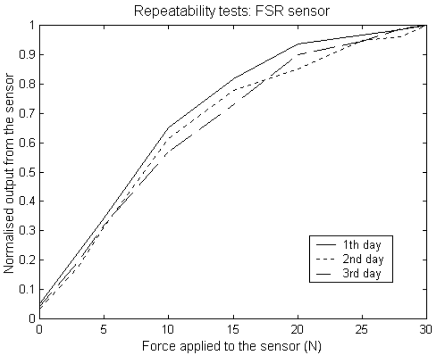

Fig. 8. Static calibration curves of the FSR sensor in three different days.

The maximum percentage errors have been compared (see Fig. 9) showing as, in terms of repeatability error, the performance of the Flexiforce sensor are certainly better than the performance of the FSR sensor.

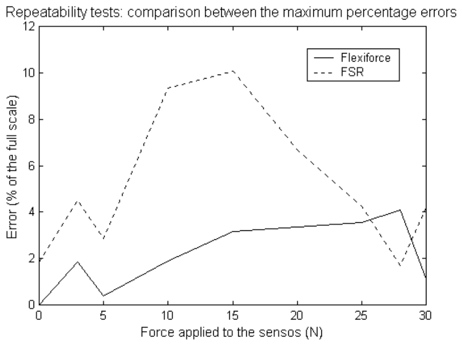

Fig. 9. Comparison between the maximum percentage errors generated by the two types of sensors during repeatability tests.

Time drifts tests

The performances of the sensors during 10 minutes of a constant loaded condition were tested. The substrates were mounted on the sensors and the cylindrical profile indentation point was mounted to the load cell. Each force sensor was fixed on a rigid plane against the load cell. Four static force level (3, 5, 10, and 15 N) were presented in random order on the sensors for three time for 10 minutes. After each trial, the sensors remained unloaded for 30 s. The sensor output was sampled at a frequency of 20 Hz. For each trial, the errors of the sensors output were compared regards to the initial value (see Fig. 10, Fig. 11, and Fig. 12).

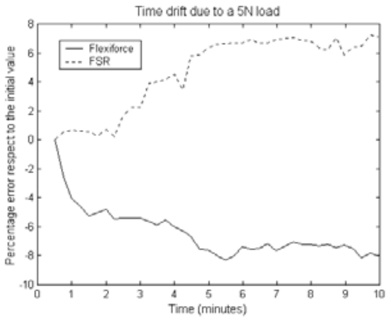

Fig. 10. Comparison between the performance of the two sensors in terms of time drift of the their outputs. A constant load of 5 N was applied on the sensors for 10 minutes.

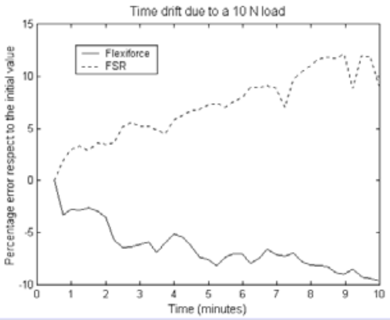

Fig. 11. Comparison between the performance of the two sensors in terms of time drift of the their outputs. A constant load of 10 N was applied on the sensors for 10 minutes.

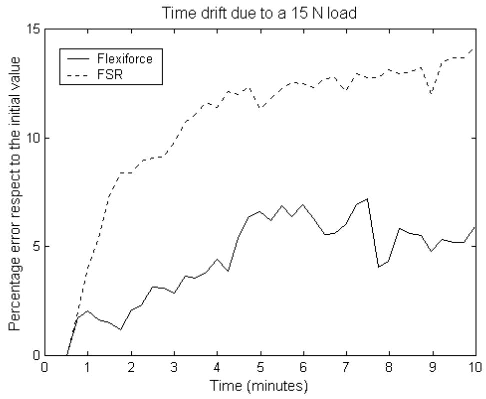

Fig. 12. Comparison between the performance of the two sensors in terms of time drift of the their outputs. A constant load of 15 N was applied on the sensors for 10 minutes.

Dynamic force measurement accuracy

To determine the response of the sensor to slow dynamic loading, they were attached to the thumb and the subject was instructed to pinch the strain gage dynamometer varying the exertion force at a rate of approximately one pinch every 2 s for a period of 10 s. This test was replicated five times over three force ranges including 0-20 N, 0-25 N, and 0-30N. The total error at each force level was computed as the difference between the force measured using the strain gage dynamometer and the force obtained using the sensor output. Table 1 shows the average, maximum, and the standard deviation of the measured error during dynamic force measurements for the Flexiforce sensor and the FSR sensor over each of the three force range tested.

	Force range (N)	**Flexiforce sensor**	**FSR sensor**
Average error (N)	0-20	2.7	4.7
	0-25	3.6	4.9
	0-30	4.6	5.9
Maximum error (N)	0-20	7.4	12.4
	0-25	9.9	13
	0-30	14.2	19.6
Standard deviation (N)	0-20	1.8	3.1
	0-25	2.4	3.7
	0-30	3.6	4.4

Table 1. Comparison between the errors measured for the Flexiforce sensor and the FSR sensor.

4. Conclusions

The results of the experimental evaluation showed that the Flexiforce sensors can overcome some of the common problems of the FSR sensors, especially in terms of linearity, repeatability, and time drift. Moreover, the Flexiforce sensors showed a better dynamic accuracy than the FSR sensors. Thus, the Flexiforce sensors can be considered a good source of sensory information for the implementation of force closed-loop controlled neuroprostheses. They can represent a good trade-off between the "ideal" requirements [5] and the need for easy donning and doffing. Unfortunately, the limit of the Flexiforce sensors, with respect to the FSR sensors, is their limited robustness: the two layers of substrate come detached after a repetitive thumb-mounting of the sensor. So, the aim of our current work is twofold: 1) to design new, more robust Flexiforce sensors; 2) to incorporate these sensors in a sensorised glove to implement force closed-loop controlled hand neuroprostheses [10].

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