Experimental Study to Improve "Federica" Prosthetic Hand and Its Control System

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Abstract. Modern 3D printing technologies and wide availability of microcontroller boards allow to make active prosthetic devices in a simple way. This is the case of "Federica", a very low-cost, under-actuated, active hand prosthesis. The five fingers of the prosthesis are moved by a single motor through inelastic tendons. The control system of the prosthesis is proportional to muscle contraction: firstly, EMG was used, then mechanical sensors that measure muscle volumetric variation were successfully utilized. This prosthesis proved to be particularly energy efficient and fast; it provided a general grasp function by adapting the exerted forces, thus allowing to easily catch even deformable objects. This study presents further analyses and design improvements of this prosthesis. In particular, a new, extremely simple but effective conditioning system of a force sensor resistor was presented and tested. In addition, the actual three-dimensional kinematics of a single finger was captured by means of high frame rate cameras and then analyzed. The new sensor conditioning system was characterized. It proved to be as effective as the EMG envelope to proportionally control the hand prosthesis motion, and it allowed an easier connection to common microcontroller boards. Kinematic analysis allowed to accurately reconstruct the actual phalanges motion over time.

Keywords: Underactuated prosthetic hand · Muscle contraction sensors · Kinematic analysis

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1 Introduction

In recent years there have been many developments and improvements in both the design of the hand prostheses and in their control systems, but despite this, continuous re-search is needed to make the use of the prosthesis even easier and more comfortable. Generally, surface electromyography (EMG) signal is used for controlling electrically powered prosthesis [1–3]. However, EMG has some drawbacks, such as: the need of electrodes, biopotential amplifiers and conductive gel for stabilizing the skin/electrode electrical interface; moreover, raw EMG signal needs to be pre-processed to extract its envelope, which estimate the muscle contraction strength. At last, recordings are very sensitive to external electromagnetic interferences and other noise sources (e.g. motion artifacts, crosstalk with other biopotentials) [4–6]. Acquisition problems remain also by using dry electrodes [7–9].

Hence, previous studies [10, 11] proposed prosthesis control signals related to the muscle mechanical variations as alternative to the EMG. Indeed, EMG reflects the electrical events of muscle contraction and it triggers muscular mechanical activity [6]. Recently a conductive, stretchable, carbon impregnated rubber cord sensor, [10] wrapped around the forearm, successfully sensed the volumetric changes of contracting muscles. This sensor was able to proportionally control a 3D printed, under-actuated prosthetic hand named "Federica" [12–14]. However, using this type of sensor, only the volumetric increments distributed over the whole circumference of the arm can be detected, and it is not possible to sense localized and precise variations on certain muscle groups.

A further recent study [11], proposed to use a Force Sensitive Resistor (FSR) [15], placed on skin by means of a mechanical coupler, for sensing the contraction of a specific muscle. Simultaneous recordings of EMG envelope and FSR signals from the same muscle resulted very similar. Preliminary validation tests [11] showed the ability of the FSR sensor to proportionally control the hand prosthesis "Federica", obtaining EMG comparable performances. An op-amp transimpedance amplifier [11] was used as the conditioning circuit of the FSR, ensuring a constant voltage across the sensor. It was demonstrated that commonly used voltage divider [16] is not convenient for FSR conditioning, because it produces relevant drift on the measurements [17].

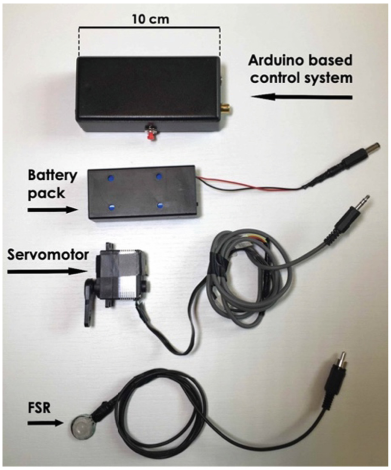
In this study, the use of FSR sensor with a re-designed and simplified control system for hand prosthesis was pro-posed and tested. Moreover, the kinematics of the prosthesis fingers was analyzed in more details.

2 Materials and Methods

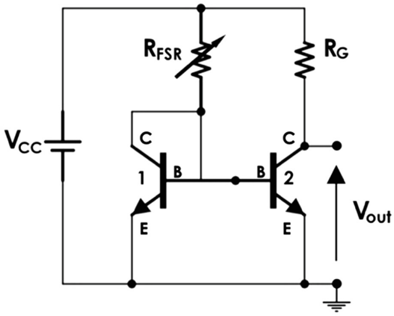
2.1 Modular Control System for "Federica" Prosthetic Hand

The control system was designed as modular and consists of: an Arduino microcontroller, a metal gear servomotor, a 7.4 V battery pack and an FSR sensor (see Fig. 1a).

The Interlink FSR 402 sensor includes two membranes on which electrodes and conductive polymer are printed respectively. The sensor shows a decrease in resistance as the applied force increases [15]. The FSR was placed on a forearm muscle (flexor



(a)



(b)

Fig. 1. (a) Modular prosthetic hand control system; (b) FSR conditioning circuit

carpi ulnaris) by means of a rigid dome [11], in order to improve the force transfer efficiency. The FSR conditioning circuit was re-designed using a simple current mirror (see Fig. 1b), realized by means of a pair of common npn BJT (2N2222), positioned very close to each other.

The circuit replicates the FSR current in the gain resistor R_G (Fig. 1b), providing an output voltage V_{OUT}. The 5 V (V_{CC}) was directly supplied by the Arduino board, and the gain resistor R_G was set to 600 Ω. The output voltage (V_{OUT}) was sampled by the microcontroller to proportionally control the prosthetic hand.

Static calibration of the FSR sensor was carried out to evaluate the relationship between the muscle force and the voltage output V_{OUT} (Fig. 1b). The sensor was placed on a precision electronic scale then different weights were applied on sensor active area perpendicularly to the dome and the corresponding output voltages were recorded.

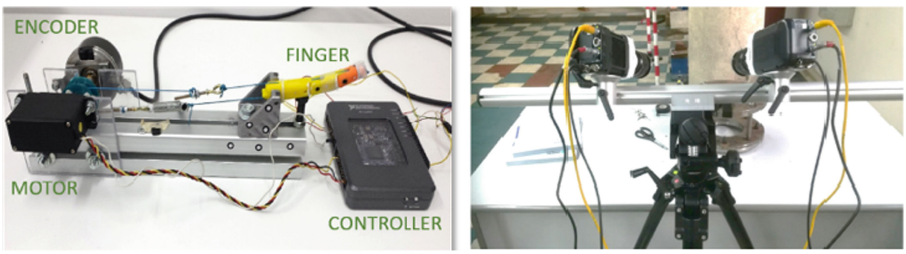
In order to measure the voltage across the FSR and its variation for different applied loads, the collector-emitter voltage (V_{CE}) of the BJT 1 (Fig. 1b) was acquired. Actually, the voltage across the FSR is given by $V_{FSR} = V_{CC} - V_{CE}$. The output signals were acquired at 1 kHz sampling frequency with 14-bit precision by means of an acquisition board (National Instruments NI USB-6009). The latter analysis was motivated by previous studies recommending the use of constant voltage across the FSR [16, 17].

As reported in a previous study [11], EMG and FSR signals were collected simultaneously from the flexor carpi ulnaris, to compare the EMG envelope and the FSR signals.

2.2 3D Reconstruction of Phalanxes Movements

An experimental method to measure the actual finger kinematic with a quantitative approach was developed. It was based on vision technique properly customized to obtain the finger kinematic over time [14]. A geometrical reconstruction algorithm has been employed to build a three-dimensional, skeletal model of the finger and to compute the phalanxes rotations over time.

The experimental setup comprised an underactuated mechanical finger (Fig. 2a) and a vision acquisition instrument based on the Digital Image Correlation (DIC) DANTEC Dynamics Q-450 system [18], operating at 450 fps (Fig. 2b). The DIC system acquired the three-dimensional shape of the finger phalanxes during a flexion movement. A random pattern of markers was applied on each phalanx, then an image correlation technique estimated their motion in space from the camera stereoscopic acquisitions. Then, for each phalanx, clouds of surface points were available at about every 2 ms and fitted to cylindric shape. Finally, the spatial coordinates of the three cylinders associated with the relative phalanxes are available for subsequent analyzes.



(a) (b)

Fig. 2. Experimental test rig: (a) underactuated mechanical finger; (b) vision acquisition instrument

3 Results

Results of the static FSR calibration are showed in Fig. 3. Experimental measurements are represented as circles while linear and exponential regressions are respectively represented as blue and red continuous lines. Considering the weights applied to the sensor as x (kg) and the output voltage from the conditioning circuit as y (V), the equation of the linear regression resulted

$$y = -2.16x + 3.70 \tag{1}$$

with a coefficient of determination R^2 equal to 0.804, whereas the exponential regression resulted

$$y = 0.198 + 5.84\,e^{-2.183x} \tag{2}$$

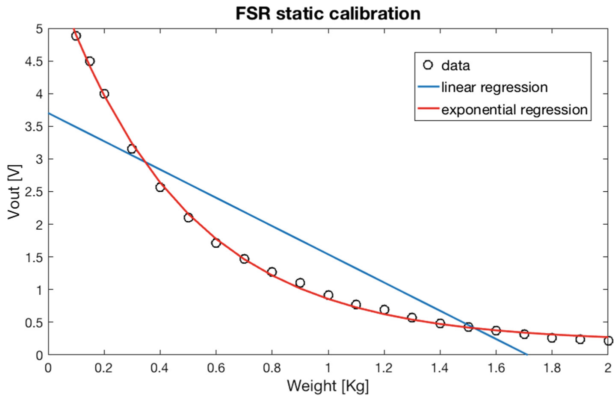


Fig. 3. FSR static calibration: scatter plot of the experimental data (circles), linear regression (blue line) and exponential regression (red line)

with R^2 equal to 0.99. Furthermore, V_{FSR} variations were measured considering different loads between 100 g and 1500 g, mimicking real conditions. The voltage across the FSR changed from 4.43 V to 4.34 V. Hence, the maximum percentage variation was about 2%.

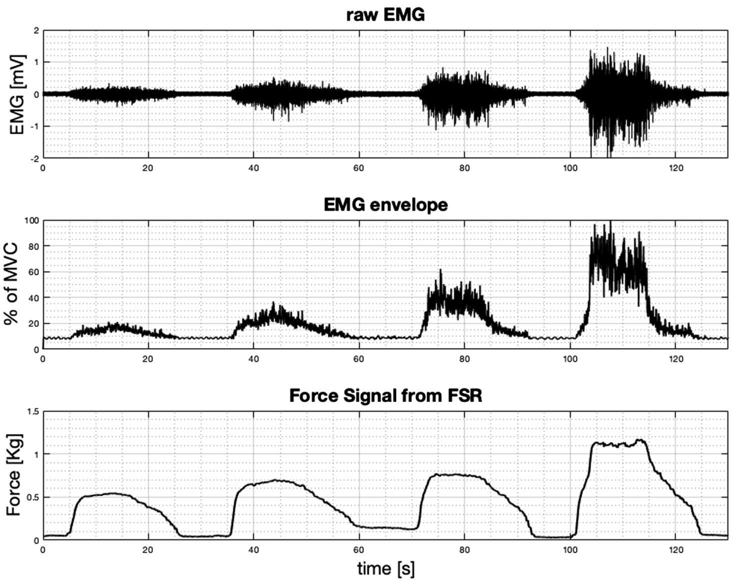
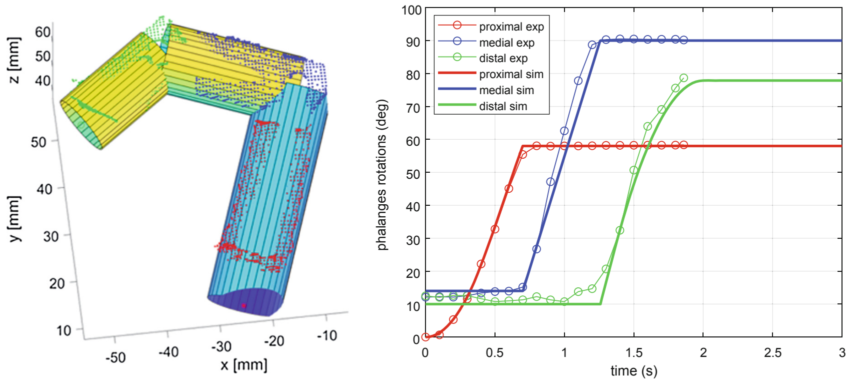


Fig. 4. Simultaneous recordings from flexor carpi ulnaris when performing four grasp actions at increasing strength: (a) Raw EMG signal; (b) EMG envelope; (c) FSR force signal (raw output).

Figure 4 shows an example of simultaneous recordings of EMG and FSR force signal from flexor carpi ulnaris, when performing four grasp actions at increasing strength.

To quantitatively measure the similarity between the EMG envelope and the FSR signal, it was computed the Pearson's correlation coefficient "r" that scored 0.85 (p-value < 0.0001 (two-tailed test)).

As regards the kinematic analysis on the prosthesis finger, the three cylindrical shapes resulting from the fitting of the phalanxes data clouds, at a given time, are shown in the Fig. 5a. Proximal phalanx is depicted in light blue, while the middle and the distal phalanxes are colored in yellow.



(a) (b)

Fig. 5. (a) Finger reconstruction; (b) Phalanxes rotations over time: comparison between experimental (circles) and simulation data (continuous line).

Starting from the cylinder axes, the relative angles be-tween the phalanges over time were computed. Therefore, the actual mechanical behavior of the whole finger was completely known.

These experimental data were compared with the simulated. Figure 5b shows the simulated (continuous- thick line) and the experimental rotations (continuous-thin line and circles) of the three phalanges during a finger closure sequence of 2 s. It resulted that the model enough well fits experimental data. These experimental data allowed to improve the multi-body finger model [19] by taking into account actual friction.

4 Conclusions and Discussion

This study presented further advances in the design of the "Federica" prosthetic hand. The FSR conditioning circuit was much simplified and can be more easily and swiftly connected to any common microcontroller board. The kinematic behavior of the prosthetic fingers was analyzed in detail. The technique developed to measure the kinematic behavior of the fingers, would be of help to improve the "Federica" prototype and to allow more comprehensive mechanical simulations.

Conflict of Interest The authors declare that they have no conflict of interest.

Statement of Informed Consent All subjects gave their informed consent for inclusion be-fore they participated in the study.

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