2019-01-01

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Hindawi
Journal of Sensors
Volume 2019, Article ID 9181492, 8 pages
https://doi.org/10.1155/2019/9181492

Research Article

Comparison of Performances of Flexible Tailor-Made Force Sensing Resistors Fabricated Using Inkjet and Xurographic Techniques

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Received 13 March 2019; Accepted 16 May 2019; Published 7 July 2019

Academic Editor: Salvatore Pirozzi

The force is one of the parameters very often measured in our life. Force sensing resistors (FSRs) can be successfully used for measuring force, especially that they can be applied in dentistry for measuring bite forces. However, it is very difficult to apply commercial FSRs for accurate measurement of bite forces and to ensure personalized approach to each patient. Because of that, design, fabrication, and characterization of tailor-made force sensing resistors intended for application in dental medicine are presented in this paper. We designed two FSRs, one with two active areas and one with four active areas (for teeth of higher volume–molars). Two different fabrication processes were applied: first additive, using inkjet printer and silver as material for conductive segments, and second subtractive, using cutter, and gold as a material for manufacturing of interdigitated structure of FSR. Performances of these FSRs have been compared, measuring resistance as a function of applied force, using in-house developed experimental set-up with an articulator.

1. Introduction

In many industrial or biomedical applications there is an urgent need for accurate and reliable force measurement, such as measuring compressive force [1], tactile applications [2], robotic applications [3], human postural control [4] or posture recognition [5], and immobilization-device quality-assurance system [6]. Dental medicine is an important field for application of information collected through measuring exact force. It is very significant to determine this value for example in orthodontic treatment or deformities like malocclusion or temporomandibular disorders as well as in assessing the biomechanical properties of masticatory system and the prosthetic treatment [7]. Working principles of bite force measurement can be based on strain gauge transducers, piezoelectric transducers, pressure transducers, force sensing resistors (FSRs) [8], etc. For this purpose many devices have been used and reported in the literature, from very simple to very complex. The bite force recording devices which can be found commercially are digital dynamometer (Kratos IDDK) [9], GM10 (Nagano Keiki) [10], T scan system [11], Flexiforce (Tekscan) [12], FSR no. 151 (Interlink electronics) [13], etc. FSRs are especially appropriate where noninvasive device should be applied for measuring force [14]. Based on the last mentioned FSR no. 151, authors reported in [15] intraoral force-measuring device, tested in conical crown retained dentures. The biosensor designed to be embedded into a safe bite guard, constructed from polymer-based pressure-sensing resistor, produced frequency modulation using the force-measuring circuit to record bite force [16]. A polymer thick film was utilized in [17], as a sensing material for measurement of the axial force and the bending moment, during endodontic therapy, for linear regime with higher load than 0.2 N and with maximum measured axial force equal to 14 N. Khaghaninejad et al. presented in [18] manufacturing and calibration process of bite force-measuring device, but

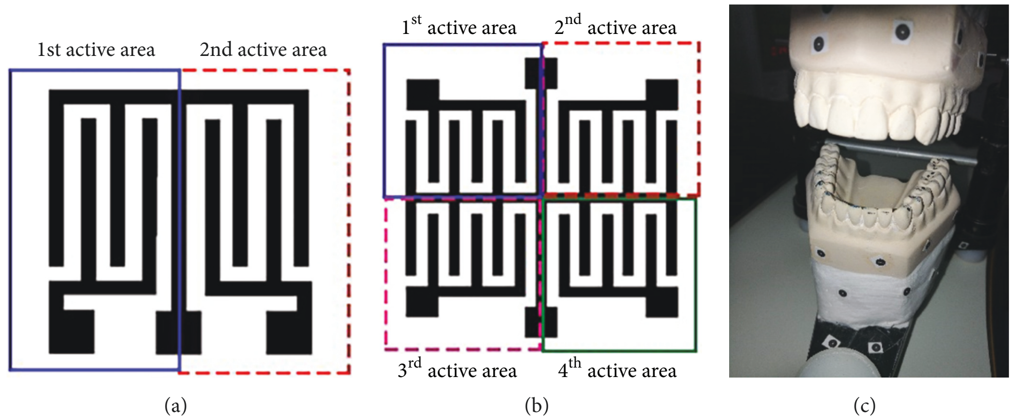


Figure 1: (a) FSR Type 1, (b) FSR Type 2, with labelled active areas, and (c) articulator with marked testing points.

based on FSR-402 commercial sensor (Interlink Electronics). Sensor for measuring human bite force, reported in [19], was manufactured by means of a LaserCNC machine to cut acrylic sheet in which structure a strain gauge was inserted. A circular-shaped commercial FSR no. 402 (Interlink Electronics) was enclosed with steel plates and dental protection to create device for measurement of bite forces produced with posterior teeth [20]. Several studies [21–25] compared characteristics of commercial force sensing resistors (usually from Interlink, FlexiForce and LuSense), but there is a lack of publications which reports performances of custom-made force sensing resistors with properties comparable or better with commercial ones.

This work describes a design of tailor-made force sensing resistors intended to be used in dental medicine (dimensions are adapted for application in oral cavity on the teeth surfaces). These FSRs were fabricated using two different technological process: (1) additive inkjet technique, using silver conductive ink on polyimide substrate, (2) subtractive unconventional xurographic technique, using gold conductive layer (leaf) on Polyvinyl Chloride (PVC) foil. Characterization of the manufactured FSRs was performed using in-house developed test bench with an articulator and appropriate conclusions are given, also based on recorded images from profilometer.

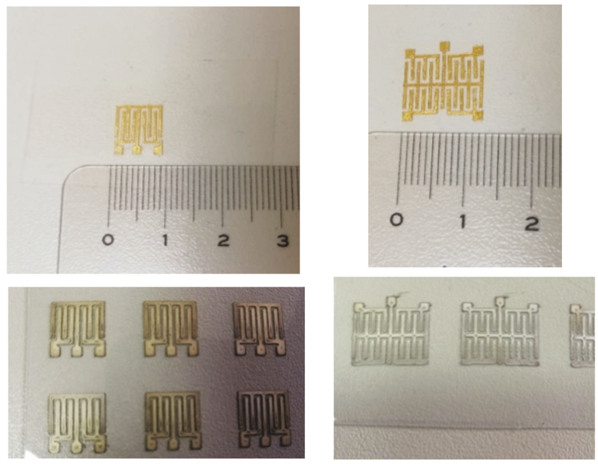
2. Materials and Methods

2.1. FSRs Design and Fabrication Techniques. Two different sizes of interdigitated conductive electrodes of active areas for force sensing resistor were designed and presented in Figures 1(a) and 1(b). Dimensions of the Type 1 of FSR are 8.5 × 9 mm, whereas for Type 2 they are 12.5 × 13.5 mm. Both dimensions are smaller or comparable with commercial FSRs; e.g., FSR402 has overall dimensions 18.24 × 10.80 mm, in order to be adjustable on the teeth surface. The width of conductive segments and spacing between them is 0.5 mm. Design of the structure presented in Figure 1(a) is tailor-made for teeth with two contacts points during biting, whereas FSR Type 2 shown in Figure 1(b) is intended to be applied on teeth of higher size with four contact (bite) points. These points can be seen in Figure 1(c) on articulator which was used in testing phase. To the best of our knowledge, there are no reported such designs in open literature, up to now. Authors of previously reported papers used commercially available FSRs as it is analyzed in the Introduction section. Two different materials were used for fabrication of conductive interdigitated structure of designed FSRs. Silver is a usual material which is applied in inkjet printing process (the gold ink is very difficult to find of-the-shelf and it is very difficult to adjust good printing properties), whereas gold leaves are used for conductive segments in xurographic technique (that is unconventional application of this technique proposed by our group). Both materials, gold and silver, are biosafe and will not cause any health problems if being chewed or eaten, in stated limits.

The above-mentioned designs of FSRs were fabricated using the following technologies: (1) inkjet technique and (2) unconventional xurographic PVC foils-based technique.

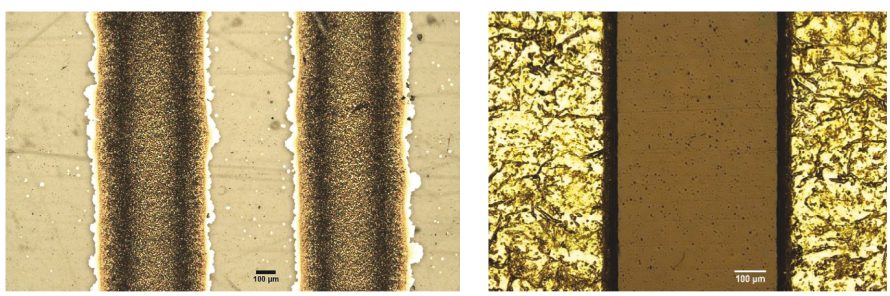
For the first additive method, deposition materials printer DMP-2831 (Dimatix) was used as well as commercial UT Dots silver nanoparticle ink. The Polyethylene Naphthalate (PEN) transparent and mechanically flexible foil (DuPont Teonex Q65 HA), with thickness of 125 μm, was used as substrate. After printing of silver ink, sintering was performed in oven at the temperature of 150°C, for 30 minutes. Thickness of the conductive layer was approximately 250 nm. The minimum droplet diameter was around 36 μm, and spacing between drops was 18 μm, in the case of inkjet printing using silver nanoparticles ink.

The second subtractive method was based on inexpensive and robust plastic foils, which were used as substrate. The gold leaf (with thickness of around 10 μm) was glued on the PVC foil, with thickness of 80 μm. After that the cutting plotter (CE6000-60 PLUS, Graphtec America, Inc., USA) was used to engrave interdigitated segments of active area of FSR. For engraving cutting blade (CB09U) with 45° was applied. After engraving of interdigitated segments, they were positioned manually to form FSR and laminated on the plastic foil (MBL® 80MIC A4 hot lamination foil, Minoan Binding



(a) (b)

Figure 2: (a) Manufactured active area of FSR Type 1 realized by Au (upper image) and Ag (lower image) and (b) manufactured active area of FSR Type 2, using Au and Ag as conductive materials.



(a) (b)

Figure 3: (a) Silver conductive segments, (b) gold conductive segments of FSR interdigitated structure.

Laminating d.o.o., Serbia) supported on the cutting mat (12" Silhouette Cameo Cutting Mat). The motivation for comparing these two techniques lies in the fact that inkjet printing process requires sophisticated and costly equipment as well as experienced personnel, because inks printing parameters set-up is not trivial job. Contrarily, the xurographic technique requires low starting investment, bearing in mind that the price of a cutter is around 5000 EUR and even beginners in the field can use this method for fabrication of tailor-made electronic components.

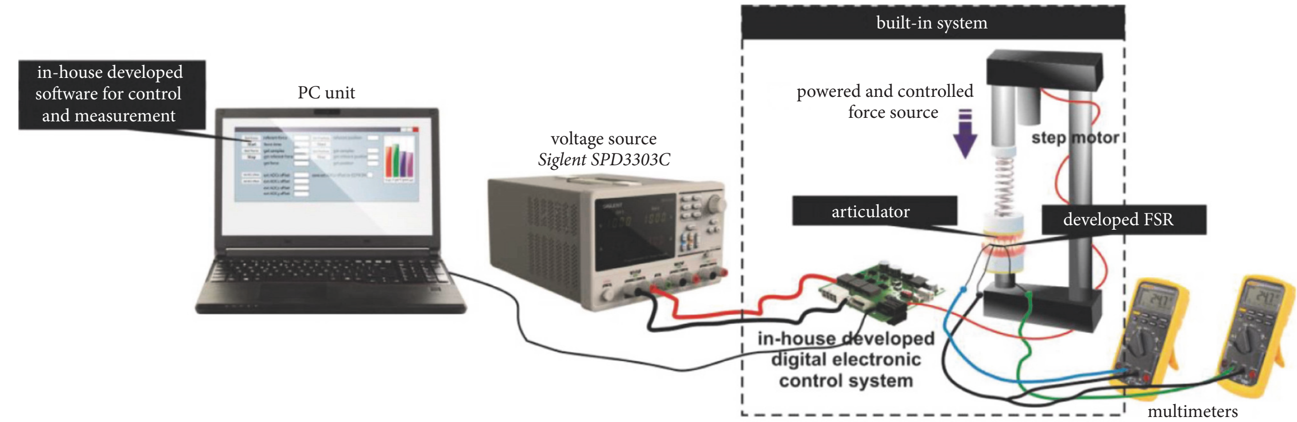
Active areas of FSRs, after fabrication, can be seen in Figure 2.

Figure 3 presents 2D images recorded using optical profilometer (Huvitz microscope with Panasis software).

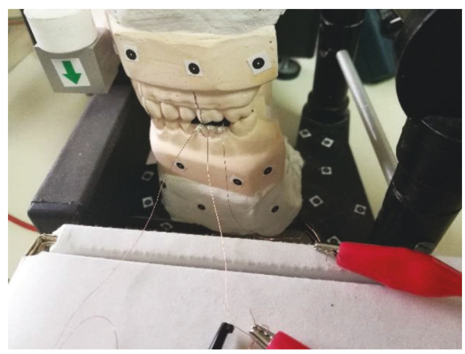
It can be seen from Figure 3 that conductive segments manufactured from silver are uniform and very smooth, whereas Au segments fabricated through cutting of gold leaves have uneven surface structure.

The active (sensitive) layer of force sensing resistors was manufactured by printing of carbon ink by means of RK K printing proofer on 50 μm GTS polyimide film. After fabrication, an active electrode layer and cover carbon layer were attached, using two component epoxy glue (placed only on edges of the FSR active area). Afterwards, wires for terminals from conductive segments were realized, to enable characterization, practically forming a through-hole electronic component.

2.2. Experimental Method. The manufactured FSRs were tested by means of in-house developed measurement set-up depicted in Figure 4(a). It consists of a rigid frame, linear electric actuator with position feedback, spring, actuator sensor holder, articulator, and reference force sensor. The complete system also includes digital electronic system control and operator control software tool, which allows position change and variation of applied force. Resistance (and voltage) of manufactured FSRs was measured using digital multimeter. The fabricated FSRs were tested using an articulator device, which is depicted in Figure 4(b). The articulator is a mechanical device that accurately represents physiological situation in a patient, from whom the impression of the jaw has been taken. Using jaw impression the casts of jaws have been made. It is more adequate to firstly analyze occlusion in vitro in the cast of jaws which are placed in the articulator. Using this device, occlusal contacts between two teeth of the opposite jaws can be measured by proposed FSRs, allowing the optimal creation of long lasting dentures.



(a)



(b)

Figure 4: (a) Illustration of experimental set-up and (b) developed FSR in articulator during testing.

3. Results and Discussion

The resistance as a function of force was experimentally measured and analyzed for FSRs, both Au and Ag, at room temperature and results are presented in Figures 5 and 6.

Both FSRs were tested under the force in the range from 0 N to almost 100 N. There are two reasons for this limit. First one is technological and depends on the thicknesses of the conductive segments of the FSR structure, because this thickness is the limitation for penetration of carbon layer from upper side, under the applied force, among the conductive segments. That means that saturation will be reached and further increase in the applied force will not have influence on decreasing resistance of tested force sensing resistors. The second one limitation has been imposed by mechanical stability of the in-house developed testing system (presented in Figure 4(a)). In normal circumstances humans use force of 90 N to 100 N to perform mastication. The intention was to use this sensor not for maximal forces measurement, but for forces that are necessary to provide occlusion in position of central occlusion of upper and lower jaw. The reason is that this force is applicable when making prostatic teeth, in practice, patient are asked to bite, and they use their average forces, not maximal. In addition, the applied force range in this work is similar like force ranges reported in literature; for example, in [15] the range was from 24 N to around 120 N, for testing occlusal positions, or in [17] where tested force had values from 0 to 12 N, for endodontic experiment. The way to increase the force range of proposed FSRs in this work, from the technological aspect, is to print multilayer structure using inkjet printing process, when one layer of silver is sintered and after that to print another layer, in order to have ticker structure of silver conductive segments, which means more space for penetration of carbon layer and larger force range. As force is applied, there is increased shunting of FSR's conductive layer and consequently its resistance decreases. The carbon layer is not infinitely compressible, so the resistance (R) or conductance (G) will saturate. The equation for conductance, which takes into account also this effect of saturation, can be expressed as follows:

$$G = a \cdot \frac{F}{(b + F)} \tag{1}$$

where G is conductance, F is applied force, a is the maximum of conductance, and b is the force at which half of the maximum of conductance is achieved. It is obvious that conductance is directly proportional to the force, which means that resistance is inversely proportional to the applied force. As can be seen in Figures 5 and 6, all FSRs are showing the same behaviour, the resistance decreases with the increase of

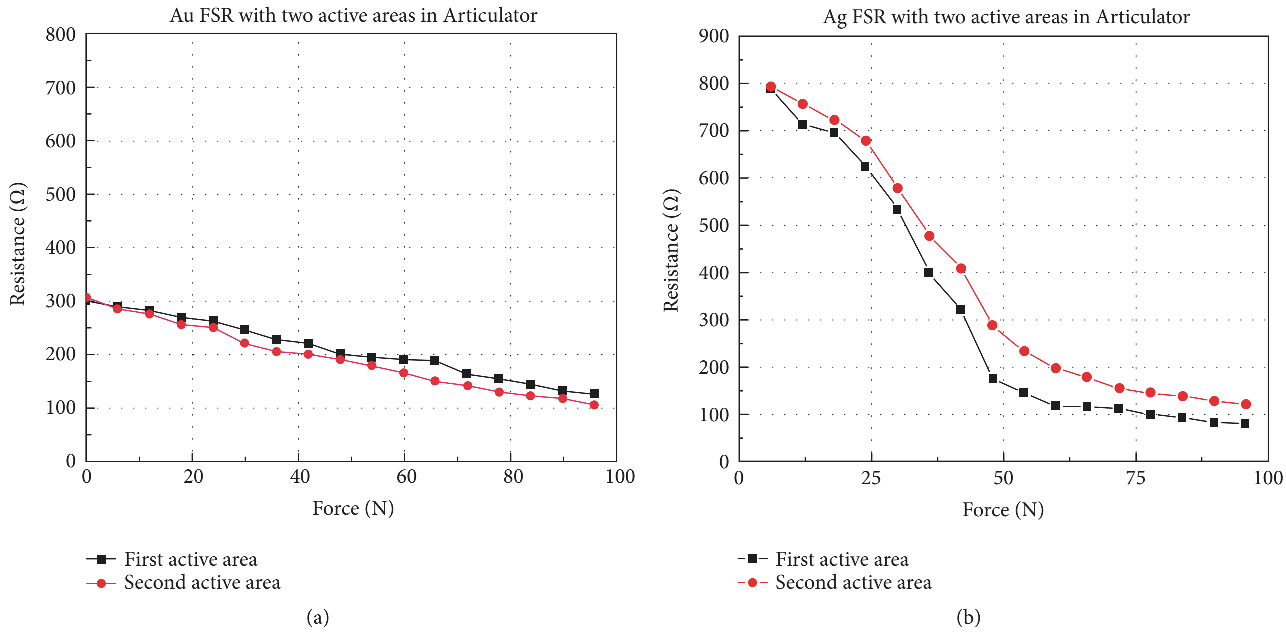


Figure 5: Resistance as a function of applied force for (a) Au FSR with two active areas and (b) Ag FSR with two active areas, in the presented articulator.

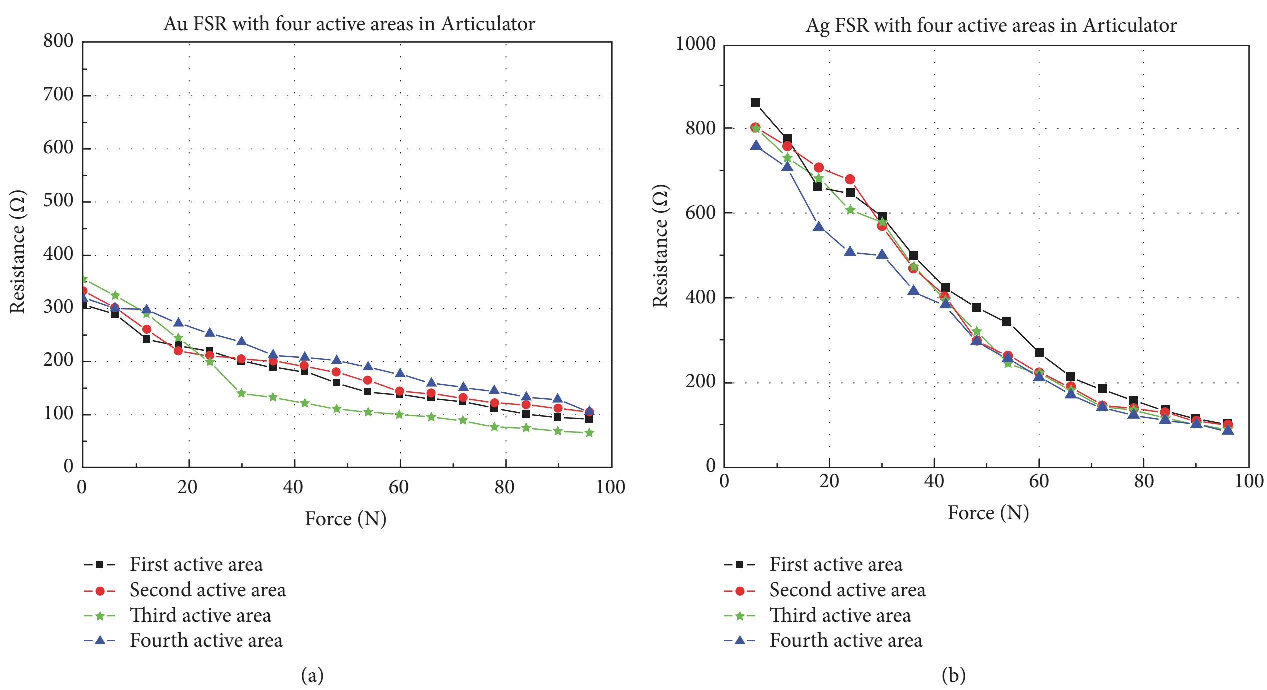


Figure 6: Resistance as a function of applied force for (a) Au FSR with four active areas and (b) Ag FSR with four active areas, in the presented articulator.

applied force (the exact force was additionally measured with commercial force meter as a checking/reference instrument). The sensitivity of sensors can be calculated using following equation:

$$S = \frac{\Delta R}{\Delta F} \qquad (2)$$

where ΔR is the FSR's change of resistance and ΔF is the force variation.

The sensitivity of sensors with two active areas is 2.15 Ω/N for Au and 8.56 Ω/N for Ag, whereas for sensors with four active areas sensitivity is 2.23 Ω/N for Au and 8.45 Ω/N for Ag electrodes. For all sensors only one active area was considered for sensitivity calculation. The resistance of

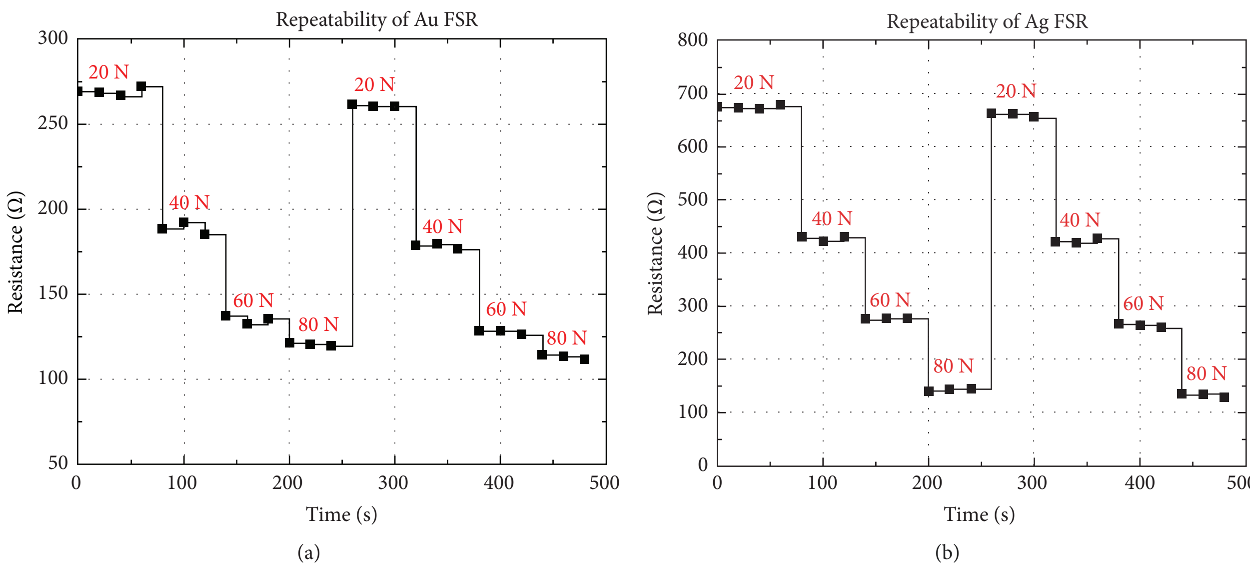


Figure 7: Resistance as a function of time and different applied forces (20, 40, 60, and 80 N) for (a) Au FSR and (b) Ag FSR.

conductive segments of the fingers of FSR structure can be expressed as $R \approx \rho / t$, where ρ is specific electrical resistivity of silver or gold, while t is their thickness. Thickness of the silver layer is much lower than for gold layer which result in higher resistance, but also higher changes in the resistance range ΔR, whereas ΔF is the same for both tested FSRs, silver-based, and gold-based, leading to the larger sensitivity of the silver-based FSR, according to (2).

All obtained results are directly related to sensors structure, thickness, and roughness of the Ag and Au layers. When force is applied on active (sensitive area) from upper side of the complete FSR structure, that force causes that carbon layer enters in the space between conductive segments (fingers of the interdigitated structure). The range of protrusion depends on the applied force, but also depends on the thickness of finger made from silver or gold segments. When carbon layer penetrates dipper between the fingers, that means when higher force is applied; as a result the resistance measured at terminals of interdigitated structure is lower, which can be seen in Figures 5 and 6. Additionally, for both types of FSRs can be noticed linear behaviour, most commonly used for sensing applications, where resistance linearly depends on the force difference. It can be seen from Figures 5 and 6 that FSR made from silver reaches saturation for forces higher than 80 N, while FSR manufactured from gold shows relatively linear behaviour in the whole tested range. This is a consequence of the thickness of silver layer fabricated by means of inkjet printing process and this layer is approximately 250 nm thick, when one layer of silver nanoparticles is printed. That means that carbon layer has the space (height) of approximately 250 nm to penetrate among the fingers in the FSR structure, when the force is applied and the force around 80 N is enough to reach this saturation for silver-based FSRs. In another case, the thickness of the gold layer is much higher than for silver conductive layer and because of that gold-based FSRs demonstrate linear behaviour even for applied forces higher than 100 N.

Figure 7 illustrates repeatability results of presented FSRs.

The repeatability of the FSRs was tested by exposing the FSRs to two alternating force cycles for four different values of force, 20, 40, 60, and 80 N. During these cycles, the resistance response was highly repeatable demonstrating the advantage of the proposed FSRs in possible applications in dental medicine. Related to the FSRs hysteresis behaviour, the resistance returns to almost its initial value upon releasing the applied force. The maximum difference of resistance upon returning is 7.38% for silver-based FSRs and 6.11% for gold-based FSRs, according to the experimental testing. The presented FSRs can be used many times. The limitation on the number of usage is imposed by the mechanical endurance of the material (PEN foil) which is placed from bottom and the material from upper side (Kapton film) of the proposed FSR structures. The PEN and Kapton film foils are basis for flexible and printed electronics development. They have excellent electrical and mechanical properties over a wide temperature range as well as they have excellent chemical resistance, enabling real application of presented FSRs in oral cavity. The FSRs can be used bilaterally, thanks to the applied working principle, which is based on the level of penetration of carbon layer among the fingers of conductive materials realized on transparent and mechanically flexible foil. The presented FSRs could be used to identify position of occlusion and anticipate the perfect bite in patient who has missing teeth. Furthermore, this device can help clinician in the phase of planning prosthetic therapy. It will be easy to recreate the position and bite, using this information. The possibility of providing tooth that is made irregularly will be minimized and that has a great impact on human health. Using presented technology it is possible to anticipate perfect occlusion which makes clinical phases of occlusion reconstruction easier.

The commercially available FSRs have typical (standard) designs and dimensions and cannot be applied for personalized approach which is necessary in dental medicine, because of that we have proposed, in this study, two tailor-made FSRs, with two different dimensions: one for teeth with two contact points and one for teeth with four contact points. These are reasons for existing two or four active areas in presented FSRs, which is an important advantage (it is possible that only one are detect force or all of them). Other advantages are possibility of choosing sophisticated but additive technology such as inkjet printing or cost-effective xurographic technique which is in the same time subtractive method. Both presented methods enable individualized design and fabrication of FSRs which can be adjusted to the needs of dentists as well as patients.

4. Conclusions

In everyday practice in dental medicine, it is necessary to apply simple and cost-effective devices which are able to instantly provide the clinicians with the measured data about bite force at different individuals or teeth models in articulator. We designed, fabricated, and tested two force sensing resistors, with two and with four active areas. Two manufacturing processes were applied. One is additive inkjet printing technique which uses silver as conductive material. The other one is subtractive cutting technique which uses gold as a conductive material. Carbon printed on Kapton film was used as a sensitive layer. All applied substrates are flexible and very easy can be applied in oral cavity, for measuring bite force. The mechanical properties of the manufactured FSRs were experimentally characterized, using in-house developed test bench with articulator. The graphs of resistance as a function of applied force demonstrated the expected behaviour that resistance decreases with increasing of the applied force. The presented force sensing resistors are reusable, are robust, and have huge potential for accurate measurement bite force in dentistry, implementing customized approach.

Data Availability

The raw measurement results, graphs and photos data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work is partly funded by Provincial Secretariat for Higher Education and Scientific Activities in the framework of Project 142-451-2457/2018-01/02 and this project partly has received funding from the EU H2020 Research and Innovation Programme under MSCA Grant Agreement no. 690876, MEDLEM. Within the project with acronym PELWNC inkjet printing was supported. Authors would like to thank Dr. Damir Krkljes for construction of system for FSRs testing.

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