Concept Generation and Preliminary Prototyping of a Tailored Smart Glove with Capacitive Pressure Sensors for Force Grip Analysis in Cycling

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Abstract. Design methods for sports engineering allow to improve the world around the athlete. In cycling, a sport device that can be useful to reduce and monitor the risk of injuries is a smart glove equipped with pressure sensors. The literature underlined how the current design methods lack the comprehensive consideration of sensors integration for force analysis at the handlebar. Furthermore, the majority of existing solutions is based on resistive pressure sensors. In this work, we present mainly two advancements with respect to the state-of-the-art: (1) user-centered design methodology for the glove development, which allows to take care about the main design parameters which involve the cyclist, namely her/his anthropometric characteristics and her/his sport gesture analysis (achieved by the pressure analysis on the handlebar) during classic grip position of cycling (i.e., top grip); (2) prototyping of custom-made capacitive pressure sensors instead of classic commercial resistive pressure sensors. The work involves the concept generation, the selection of the optimal concept through Kano and Quality of Function Development as well as the preliminary prototyping of one capacitive pressure sensor, realized using a fabrication process involving additive manufacturing techniques and silicon molding.

Keywords: user-centered design, injury risk, human body scanning, capacitive sensors
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1 INTRODUCTION

Although sports and engineering can appear different worlds, their interaction is strongly increasing over the recent years. Engineering is involved in sport, and it is part of the complex world around the athlete. It answers the requests for reaching the best performance and for preventing injuries of the athletes [2]. In general, sports engineers develop a method, and then apply their skills to many different sports fields. Nowadays, sports engineering allows: (i) to improve the design of sport equipment (and athlete's interaction) in order to increase the performance of the system (equipment plus athlete) and reduce the risk of injuries for the athletes [4]; (ii) to develop tools for the measurement of the athlete's performance in order to assess key performance indices useful to understand and to improve the efficiency of the sport gesture [5]; (iii) to develop products and tools to increase the active engagement in sports for disabled people [2]. Design and development of sports devices should take into consideration the needs of the users, namely athletes, coaches and sport science experts. In order to involve subjective users' needs into the design process, the engineers might use user-centered and user-participatory design methods. In this way the user "becomes part of the design team, an integral part of exploring possibilities for effective technological design" [14]. One of the sports where engineering plays a relevant role is cycling. Here, the assessment of biomechanical parameters is a powerful tool for risk analysis of injuries [6]. In this context, the cyclist's gripping (i.e., sum of force applied on bottom-half-shell of the handlebar) and supporting force (i.e., sum of force applied on top-half-shell of the handlebar) analyses at the handlebar is useful to understand the different changes of the cyclist biomechanics. With this respect, information as trunk posture or how hand-arm absorbs the external vibrations are related to the force at the handlebar [10]. In this context, laboratory equipment as dynamometer to measure forces at the handlebar of the bike are presented in literature [13]. For field analysis, several gloves with pressure sensors have been recently developed, but they are not specific for cycling [1,18]. These gloves use standard, commercially available resistive pressure sensors, which present the following limitations: (i) they mostly act as on-off system, thus are very effective for detection purposes but not very effective for measurement in a continuous manner; (ii) they are rigid and available in predefined size and shape so, it is not possible to customize their specifications according to applications and hand's anthropometric measurements. Recently, easy-to-customize capacitive soft sensors to measure forces for soft robotic applications have been proposed [3]. In cycling, design methods for the development of new gloves for road cycling have been recently developed, including: (i) understanding the hand wear and tool also taking into account users' needs; (ii) the analysis of 3D user's hand (also considering biomechanics); (iii) hand wear and tool product innovation also in terms of materials [16]. However, these approaches present some limitations. The glove is designed without the implementation of any sensors (e.g., pressure sensors), useful for many aims as said before. The sport gesture analysis, in terms of force analysis at the handlebar, is carried out in a qualitative way (i.e., by painting taped bike handlebars to assess the grip contact surface) without acquisition of biomechanical parameters (e.g., gripping and supporting force), which are stated as powerful tools for the design of wearables for sport analysis [7]. In addition, the cyclist's needs are not directly correlated with design parameters, so the users are not involved in the definition of the optimal concept, as suggested in [15]. This paper presents the preliminary design of a novel tailored smart glove with custom-made capacitive sensors for force grip analysis at the handlebar in cycling, developed through a user-centered design approach. The rest of this work is organized as follows. Section 2 presents the proposed methodology. It starts from design parameters definition involving the cyclist, with his digital hand reconstruction (through 3D scanning) and his experimental cycling tests for the analysis of pressure areas on the handlebar (to derivate the force analysis), during classic grip position of cycling. The users' needs analysis is applied to define the best combination of design parameters levels to obtain the final design of the smart glove. Section 3 presents the concept generation with the application of the proposed methodology and the definition of the optimal concept. Finally, section 4 shows the preliminary prototyping of one capacitive pressure sensor, realized using a fabrication process involving Aerosol Jet Printing and silicon molding.

2 METHODOLOGY

The proposed methodology consists in a design generation process where the users are involved two times. First, the users are involved in collecting anthropometric data and sport related biomechanical parameters. Starting from these data, two levels for each design parameter are defined. Secondly, the users are involved again through subjective questionnaires on users' needs related to the product. The collected data are related to design parameters assessing them a rating of importance. Finally, according to the importance rating, the combinations of the design parameters levels selected allows to define the optimal design of the glove. The full methodology (generically applicable for the design of sport devices) is shown in Figure 1. It also includes the prototyping of the system with experimental validation. In the present paper, the work is limited to the preliminary prototyping.

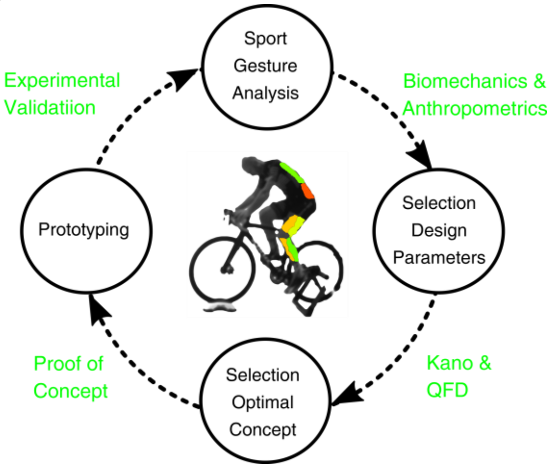

Figure 1: User-centered design method of sports devices.

2.1 Design Parameters Definition: Users' Anthropometric and Sport Gesture Analysis

In order to define the main design parameters of the cycling smart glove, the proposed approach starts by involving the users to capture anthropometric data and biomechanical sport specific data.

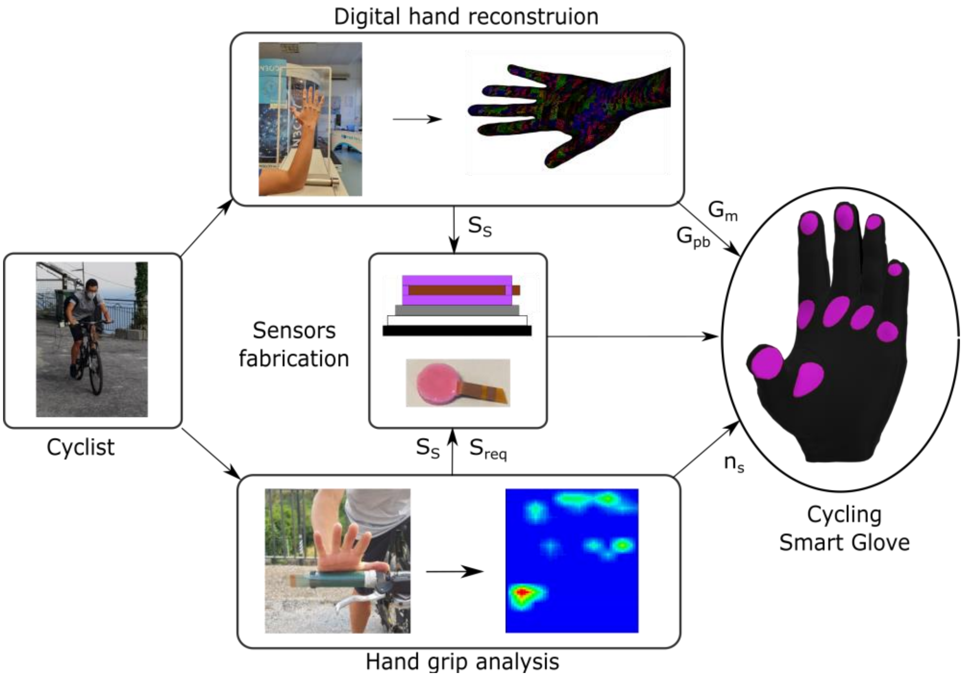

Figure 2: Flow chart of methodological approach for cycling smart glove design parameters definition.

The flow-chart approach for the definition of the design parameters is shown in Figure 2. According to this, we define five design parameters: (i) pressure sensor requirements (S_{req}); (ii) pressure sensors size (S_S); (iii) number of the pressure sensors located on the glove (n_s); (iv) glove pattern block (G_{pb}); (v) glove material (G_m). The digital hand reconstruction allows to define G_{pb} and G_m the force analysis at the handlebar allows to define n_s and S_{req}; indeed, S_S can be defined through both the phases. Each design parameter is defined on two levels. The first one (level 0) related to more simple technical requirements in terms of product design while the second one (level 1) related to more accurate technical requirements in terms of grip analysis.

2.2 Design Parameters Selection: Users' Needs Analysis

Starting from a preliminary list of users' needs, the selection of the main ones is carried out using specific surveys based on the Kano analysis [8]. Finally, the Quality Function Deployment [12], through the realization of the House of Quality, allows to relate the design parameters (defined in the section 2.1) with the users' needs and define the ranking of importance useful for the selection of the best level for each design parameter.

3 CONCEPT GENERATION

In this section we report the application of the proposed methodology presented in section 2 for the concept generation.

3.1 Design Parameters Definition for Concept Generation

In this subsection the definition of the levels of each design parameter is shown based on digital hand reconstruction (section 3.1.1) and pressure analysis at the handlebar (section 3.1.2).

3.1.1 Digital hand reconstruction

The 3D reconstruction of the hand, with related texture, is obtained using a structure scanner (attached to iPad), and the Scan software. The system allows to capture hand shapes with an acceptable accuracy in terms of landmarks recognition [11]. The process for the acquisition required about 30 s. One amateur cyclist participated in this part of the study. He sat in front of a small table (i.e., height 90 cm) rested their dominant elbow on the table while holding their forearm and hand vertically. A plexiglass support allowed to maintain the vertical position. The scanning position required that the cyclist's hand was positioned upright, flat, with open fingers. To detect the required anatomical landmarks, blue-dark washable markers were applied on the hand [11]. A second scan without plexiglass support was carried out to acquire the surface of palm.

3.1.1.1 Glove pattern block (G_{pb})

The glove pattern block is a custom designed basic template of the glove based on hand anthropometric measurements. It is defined at level 0 using 8 parts based on 13 anatomical landmarks and 10 anthropometric measurements, as suggested by [9], and the level 1 using 8 parts based on 34 anatomical landmarks and 44 anthropometric measurements according to [17]. The digital anatomical landmarks are obtained starting from the texture of the first acquisition.

3.1.1.2 Glove material (G_m)

For the glove material, level 0 is related to material that simplifies the product design in terms of sensors printing (i.e., 80% polyester, 20% elastane). Level 1 is related to a more elastic material (i.e., 71% polyamide, 29% elastane) that increases the adaptability of the glove.

3.1.1.3 Sensors size (S_S)– Level 1

The scan without plexiglass is used. Starting from the calculation of the gaussian curvature (k_v) for each vertex (V(x,y,z)) of the surface Ω of interest (e.g., from the first interphalangeal joint to the fingertip for each finger), we assess the matrix of the outlier vertices P on the surface Ω:

$$P \in \Omega, \text{ s.t. } k_\mu - k_\delta < k_v < k_\mu + k_\delta \quad (3.1)$$

where k_μ and k_δ are respectively the mean and standard deviation of k_v for all vertices of Ω. Starting from P, we define a rectangle, on palmar view using the vertices coordinates in P (Figure 3, left). In detail, it is obtained considering the vertices with minimum and maximum x coordinate (i.e., P_{xmin} and P_{xmax}) and minimum and maximum y coordinate (i.e., P_{ymin} and P_{ymax}), as shown in Figure 3, right. Finally, the sensor size is obtained considering the inscribed ellipse in the rectangle (that becomes a circle in the particular case of square). The application of these steps for each area of interest allows to define the size of the sensors as reported in Table 1.

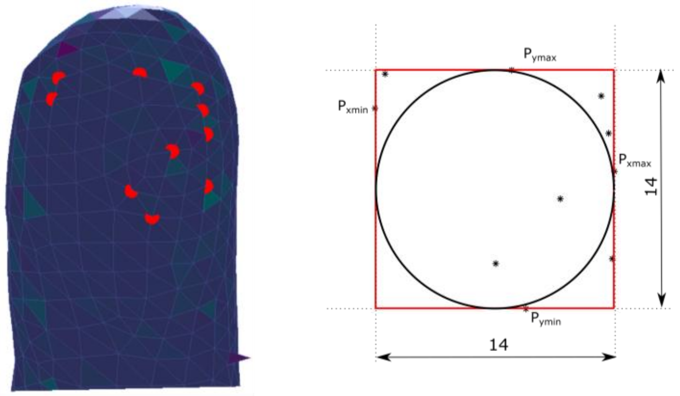

Figure 3: Left: the 3D reconstruction with color map of gaussian curvature of the fingertip 4. The red circle points represent the outlier vertices. Right: palmar view with the * that represents the outlier vertices. The circle (black bold line) inscribed in the square (red bold line) represents sensors size. The measurements are expressed in mm.

Area	*Size [mmxmm]*
Fingertip 1	13X16
Fingertip 2	14x16
Fingertip 3	14x22
Fingertip 4	14x14
Fingertip 5	13x10
Metacarpal	74x24
Metacarpal head 2	15x18
Metacarpal head 3	16x18
Metacarpal head 4	16x14
Metacarpal head 5	15x14
Thenar Eminence	22x22

Table 1: The defined areas of pressure with related size (horizontal axes x vertical axes). For the metacarpal zone is reported also the assessment of the single area.

3.1.2 Pressure analysis at the handlebar

The force analysis at the handlebar is evaluated by pressure distribution analysis equipping the bicycle (MERIDA Big Seven Team XX1 Carbon MTB) handlebar with a Force Sensitive Resistors (FSRs) matrix (MS9724 by Kitronyx). The matrix was composed of 160 FSRs flexible sensors (on 16 rows and 10 columns) with a sensitive total area equal to 128x80 mm (8x8 mm for each sensor) set at sampling frequency of 100 Hz. After 5' of warm-up, the subject performed three trials of 200 m each on three different road surface tarmac, gravel, and cobblestones in Agerola (Naples), at self-controlled speeds, applying a typical cycling grasp (i.e., top grasp) around the handlebar.

3.1.2.1 Number of sensors (n_s)
Considering the main loaded areas, n_{sens} is defined at the level 0 equal to 7 (simplified version that considers only one big area 64x16 mm for the metacarpal zone, Figure 4 right) and at the level 1 equal to 10 (see Figure 4 left).

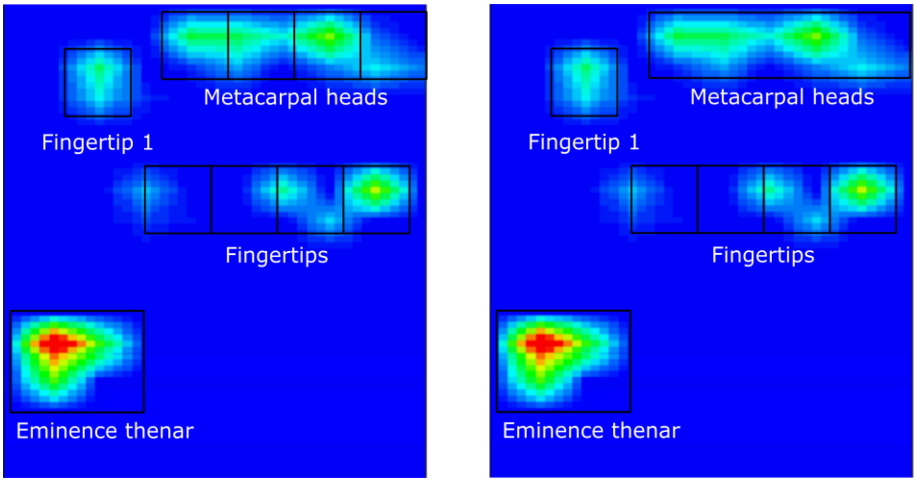

Figure 4: Left: colored pressure map during the top grip with the identification of the main ten areas of pressure. Right: a simplified version with seven areas.

3.1.2.2 Sensors requirements (S_{req})
In addition, the sensors requirements in terms of dynamic range are defined according to collected data reported in Table 2. For the definition of the level 0, we considered the five fingertips and the five metacarpal heads with a unique dynamic range 0-50 N (in case of single metacarpal sensor 0-150 N); and the thenar eminence with a dynamic range 0-150 N.

Area	*Mean [N]*	*Peak [N]*	*Size [mmxmm]*
Fingertip 1	0.2/0.2/0.4	0.7/2.2/1.3	16x16
Fingertip 2	6.1/2.4/6.6	10.3/5.8/14.0	16x16
Fingertip 3	1.7/0.4/1.4	3.2/3.1/2.8	16x16
Fingertip 4	0.1/0.1/0.1	0.4/2.7/1.1	16x16
Fingertip 5	0.2/0.8/1.1	0.6/3.0/3.2	16x16
Metacarpal head 2	0.8/1.0/0.7	1.8/2.5/3.5	16x16
Metacarpal head 3	0.2/0.2/0.1	0.7/1.8/2.7	16x16
Metacarpal head 4	8.5/3.8/3.9	10.7/10.3/11.8	16x16
Metacarpal head 5	10.0/14.8/21.7	12.1/23.1/30.6	16x16
Thenar Eminence	33.2/14.4/30.7	51.6/29.8/49.4	32x24

Table 2: Mean and peak values of force collected during the trial (in order respectively tarmac, gravel and cobblestones) in the defined ten areas of pressure with related size.

For level 1, we defined a more customized solution: the five fingertip sensors with a dynamic range of 0-30 N; the five metacarpal head ones with a dynamic range of 0-50 N and the thenar eminence one with a dynamic range 0-150 N.

3.1.2.3 Sensors size (S_S) – Level 0

The level 0 of this design parameter is chosen with the sensors realized in the square or rectangular shape according to the size related to each area reported in Table 2.

3.2 Selection of the Design Parameters Levels for the Optimal Concept

The survey used for the users' needs analysis is divided into two parts. The first one is composed of eleven questions to collect users' demographic information and how the cyclist interacts with the product. The survey was administered to 30 cyclists, 93% of whom were male. In addition, 70% of the sample was between the ages of 26 and 50. The respondents were 90% amateur cyclists, while the remaining 10% were athletes. In addition, 83% of the interviewees practiced cycling at most 15 hours per week. About the mileage for year 30% of the respondents cycling 1000-3000 km, 20% cycling 3000-5000 km and 23% cycling 5000-10000 km. More than 80% of those interviewed considered the use of a smart glove useful, both to prevent injuries and to improve their training, as well as to help in the choice of bike components such as front axle and forks.

3.2.1 Kano analysis

The second part is composed of nine pairs of questions (i.e., functional and dysfunctional questions) to select the most important users' needs (applying the Kano analysis).

Users' Need	*A*	*M*	*O*	*I*	*R*	*Q*	*US*	*UD*
Ergonomic	1	9	18*	2	0	0	0.34	-0.90
Wearable	6	11*	7	5	1	0	0.59	-0.62
Minimal	4	8	11*	5	1	1	0.43	-0.68
Light	7	9*	8	6	0	0	0.54	-0.57
Eco-friendly	14*	5	4	7	0	0	0.64	-0.30
Waterproof	11*	9	4	6	0	0	0.67	-0.44
Easy to use	4	10	11*	5	0	0	0.47	-0.70
Real Time	11*	4	2	12	1	0	0.52	-0.20
Safe	1	8	21*	0	0	0	0.30	-0.97

Table 3: Emotional response types collected based on Kano analysis (i.e., A=Attractive; M=Must be; O=One dimensional; R=Reverse; Q=Questionable; I=Indifferent) for each users' need. The * indicates the higher values collected between the different emotional response types for each users' need. The last two columns report User Satisfaction (US) and User Dissatisfaction (UD) coefficients.

In Table 3 the classification of users' needs based on the Kano analysis, US and UD coefficients achieved by all users' needs are reported. Considering the users' needs reporting a classification of M or O, six users' needs are selected (i.e., ergonomic, wearable, minimal, light, easy to use and safe).

3.2.2 QFD – House of Quality

In Figure 5, the House of Quality matrix reports the relationship between the six selected users' needs and the five defined design parameters in section 2.1. The users' needs in the House of Quality are weighted in the "user importance". It is obtained dividing the UD coefficients range of the selected users' needs (from -0.57 to -0.97) into five equal intervals (0.08 for each interval), obtaining a score from 1 to 5. According to the outputs reported in Figure 5, we divide the design parameters into two groups (Technical Importance Rating under 10 in the group 1, over 10 in the group 2). So, the design parameter S_{req} is assigned to the group 1 while S_S, n_s, G_{pb} and G_m are assigned to group 2.

Relationships (R): • Strong= 3; ⊙ Fair= 2; ○ Weak= 1

Users' Needs	User Importance (UI)	Pressure Sensor Requirements (S_{req})	Pressure Sensors Size (S_s)	Number of the Pressure Sensors (n_s)	Glove Pattern Block (G_{pb})	Glove Material (G_m)
Ergonomic	5		○	⊙	•	○
Wearable	1		○	⊙	•	○
Minimal	2	○	⊙	⊙		
Light	1	○	⊙	⊙		⊙
Easy to use	2	○	○	○		
Safe	5		⊙	⊙		○
Technical Importance Rating Σ(UI X R)	-	5	<u>24</u>	<u>30</u>	<u>18</u>	<u>13</u>

Figure 5: House of Quality matrix. The design parameters classified in group 2 are underlined.

Finally, according to the design parameters levels selected, the optimal concept is obtained, as shown in Figure 6.

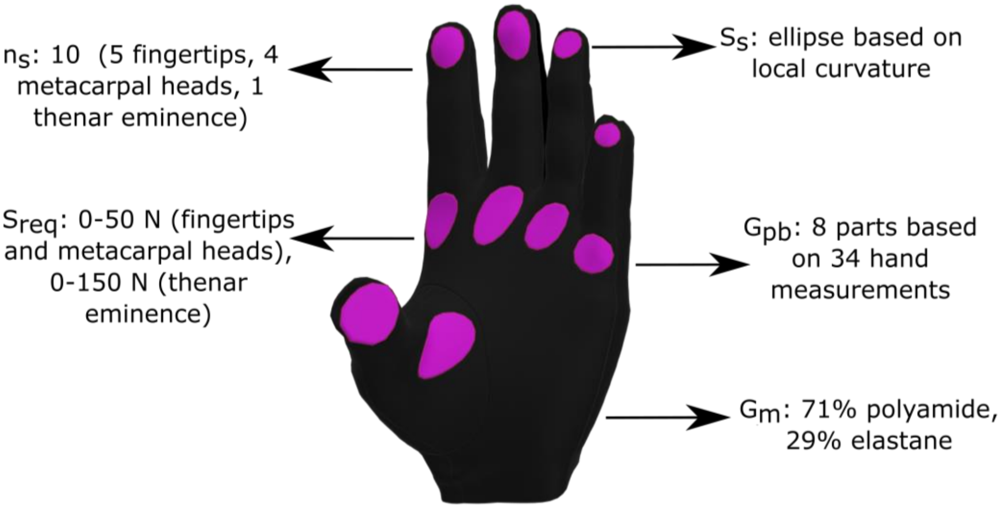

Figure 6: Optimal concept with related selected design parameters levels.

4 PRELIMINARY PROTOTYPING

In this section we present the first steps for the realization of optimal concept prototype.

4.1 Design for Fabrication: Glove Pattern Block with Sensors

In order to realize the optimal concept, the design for fabrication started with definition of the glove pattern block with the integration of the sensors (as shown in Figure 7). According to the optimal concept, the glove pattern block is composed by 8 parts: one for palm and back, one for thumb (with 2 identical subparts) and 6 fourchettes for fingers (with 2 identical parts for fingers 3 and 4). The sensors' location on the fingertips (2,3,4 and 5) is centred on the longitudinal axis of each finger with the upper extreme point of the sensor located at base of the fillet. The metacarpal sensors are centred on the axis of each finger with the upper extreme point of the sensor located 5 mm under the line at the base of fingers on the palm. The thumb sensor is centred on the axis of the upper area of the thumb, with the lowest point on the bottom border of this area. Finally, the thenar eminence sensor location is on the axis of the thumb sensor with the lowest point 5 mm over the bottom border of the part.

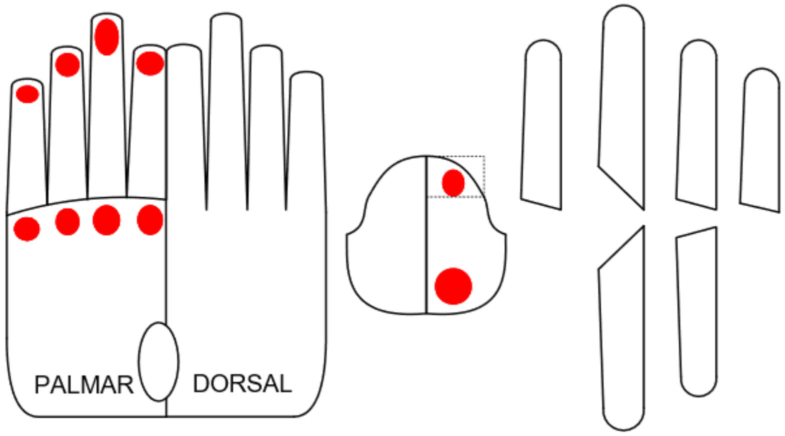

Figure 7: Glove pattern block design from the left to right the following parts: palmar and dorsal, thumb (dorsal part left and palmar one right) finger 2, finger 3 (2 parts), finger 4 (2 parts) and finger 5. The rectangular dotted line represents the upper area of the thumb. The red ellipses represent the areas where have to be printed the sensors.

4.2 Sensors' Prototyping Design and Fabrication

4.2.1 Sensor design

The sensor proposed is a capacitive custom-made force sensor in which the overall capacitance varies according to the force applied on its surface. The force causes a reduction in the plates distance, thanks to a compressible dielectric layer, increasing the initial capacitance value. The sensor is obtained overlapping different materials. In Figure 8 the schematic cross-section is represented. The stack can be divided into two main parts, the two lower layers constitute the sensor substrate: the first one is a technical stretchable fabric made of 71% polyamide and 29% elastane (404-Revolutio-NAL® by Carvico) while the second one is a polyurethane layer functional for next layer deposition. The second group composes the sensor sensitive element: plate #1 is realized with a silver nanoparticles conductive ink (Genesink Smart Aero S-CS61308), the dielectric layer is obtained with a bi-component silicone with a Shore hardness of 16 (Elite Double 16 Fast by Zhermac Dental), and the last layer, plate #2, is realized cutting a polyamide cooper-laminated sheet.

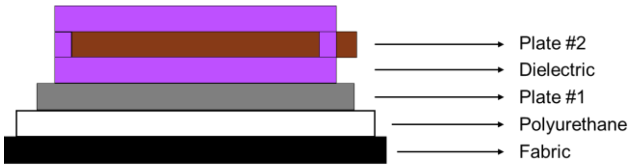

Figure 8: Schematic cross-section of the capacitive sensor.

4.2.2 Sensor realization

The sensor is realized overlapping the described layer. Starting from the technical fabric, a sheet of polyurethane is applied on it with a heat press obtaining a common substrate (19x27 cm) for different smaller sensors which will then be cropped. Plate #1 is realized with a maskless 3D-printing techniques called Aerosol Jet Printing (AJP) that permits to deposit liquid inks transported by an airflow carrier on the chosen substrate creating features ranging from 10 µm to 3 mm. The features desired can be drawn with CAD software. In the following, we show the realization of the sensor for the fingertip 4, according to Figure 3. In Figure 9 the CAD model of Plate #1 is reported and the deposited conductive inks on the polyurethane layer is shown.

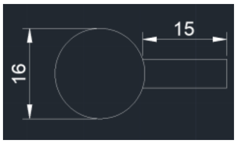

Figure 9: Left: dimensioned CAD drawing of Plate #1. Right: Plate #1 deposited with AJP on the polyurethane substrate.

Plate #2 is realized cropping the desired shape from the copper sheet using a 3D-printed mask and a cutter. In Figure 10 is shown the designed mask model and the cutting operation output. The circular part has a diameter of 14 mm with an overhang of 19 mm.

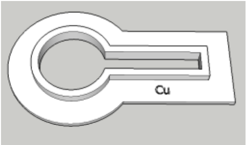

Figure 10: Left: designed 3D-model of the cropping mask. Right: plate #2 cropped from the copper sheet.

The compressible layer is realized casting the liquid silicon in a custom designed mold with plate #2 placed in it. As shown in Figure 11 on the left, the casting mold has four round pillars that support the copper disk 2 mm over the bottom part defining the maximum distance between the two plates. After the silicon polymerization, the copper disk results incapsulated in the silicon substrate (Figure 11, middle). Finally, the two resulting parts are joined together (Figure 11, right) with a glue specific for plastic material (LOCTITE 406).

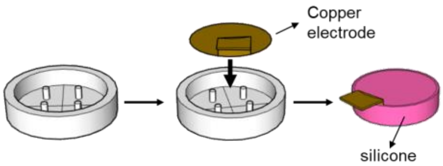


Figure 11: Left: casting mold model and copper electrode placement. Middle: copper electrode (Plate #2) incapsulated in the silicon substrate. Right: realized capacitive force sensor.

4.2.3 Sensor preliminary experimental tests

Preliminary experimental tests have been carried out to determine the capacitance dependence on the force applied in the required range 0-50 N. In the preliminary analysis one sensor is considered and it has been loaded with calibrated weight from 0.02 Kg to 5 kg in step of 0.5 Kg. The starting point is imposed by the mechanical structure weight, used to distribute the force on the sensor surface. The protocol test defined provides four increasing and four decreasing weight paths. The electrical parameters have been measured with an impedance analyzer (HP 4194A). In Figure 12 the results are expressed in terms of mean values and standard deviation. The initial capacitance values C_0 is 28.55 pF, an increasing capacitance trend can be observed as the weight increases, with a mean sensitivity of 0.15 pF/kg in the range 1-5 kg. The sensor shows an increasing precision in the upper range part. Further tests will be performed to better characterize the lower part of the range.

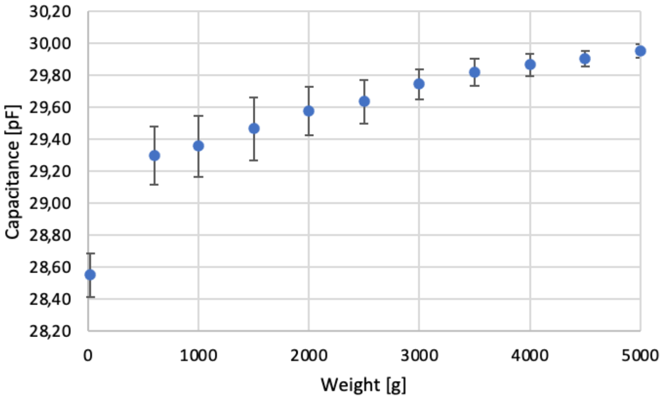

Figure 12: Capacitance mean values with bars of standard deviation measured during the experimental tests.

5 CONCLUDING REMARKS AND FUTURE DEVELOPMENTS

In this work we have presented a methodology for the design of a smart glove for cycling that allows the force analysis at the handlebar. The proposed approach allows the concept generation involving the cyclist for the sport gesture analysis and 3D hand digital scanning. For the optimal concept selection, we involved a significative group of end users using Kano analysis and the House of Quality. The preliminary prototype of the optimal concept in terms of glove pattern block, capacitive sensors design, and fabrication was presented. In particular, we have realized a custom-made capacitive pressure sensor through a fabrication process involving Aerosol Jet Printing and silicon molding. Future developments will be focused on the realization of the prototype of the smart glove with the experimental validation in field conditions.

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