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Innovation, Science and Economic Development Canada
Canadian Intellectual Property Office

CA 3083837 A1 2020/12/12

(21) 3 083 837

(12) DEMANDE DE BREVET CANADIEN
CANADIAN PATENT APPLICATION

(13) A1

(22) Date de dépôt/Filing Date: 2020/06/11
(41) Mise à la disp. pub./Open to Public Insp.: 2020/12/12
(30) Priorité/Priority: 2019/06/12 (US62/860,286)

(51) Cl.Int./Int.Cl. *A42B 3/04* (2006.01), *G01L 1/14* (2006.01), *G01L 25/00* (2006.01), *G01L 5/00* (2006.01), *B32B 7/025* (2019.01)

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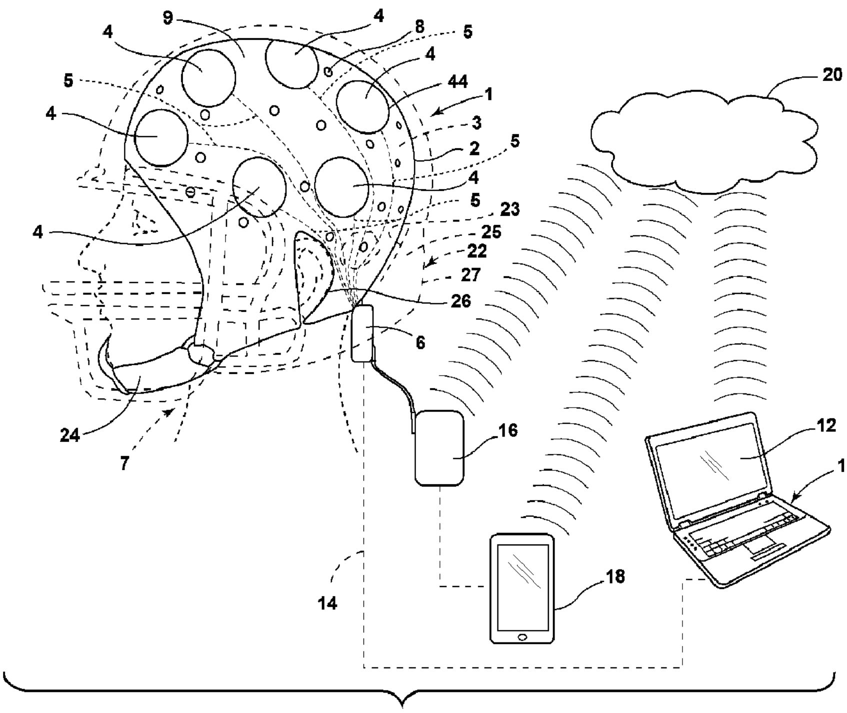
(54) Titre : SYSTEME DE SURVEILLANCE DE LA PRESSION POUR CASQUES
(54) Title: PRESSURE MONITORING SYSTEM FOR HELMETS



(57) Abrégé/Abstract:
A pressure sensing system for measuring pressure acting between a user's head and a protective helmet includes a flexible article that is configured to fit between a wearable protective article and a body part of a user. The system further includes a pressure

(57) Abrégé(suite)/Abstract(continued):
sensor array comprising a plurality of pressure sensors secured to the flexible article. The system may include a data acquisition module configured to provide data from the pressure sensor array to a computer having a display that provides pressure data to a user.

ABSTRACT OF THE DISCLOSURE

A pressure sensing system for measuring pressure acting between a user's head and a protective helmet includes a flexible article that is configured to fit between a wearable protective article and a body part of a user. The system further includes a pressure sensor array comprising a plurality of pressure sensors secured to the flexible article. The system may include a data acquisition module configured to provide data from the pressure sensor array to a computer having a display that provides pressure data to a user.

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PRESSURE MONITORING SYSTEM FOR HELMETS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority to U.S. Provisional Patent Application No. 62/860,286, filed June 12, 2019, entitled "PRESSURE MONITORING SYSTEM FOR HELMETS."

BACKGROUND OF THE INVENTION

[0002] Various types of protective articles such as helmets and pads have been developed. For example, protective helmets and pads worn on the body may be used by participants in athletic events such as football, hockey, etc. Protective helmets and other protective equipment may also be worn by individuals participating in other sports, such as downhill skiing, snowboarding, ice-hockey, wrestling, martial arts, and the like. Furthermore, motor vehicle operators (e.g. motorcycle and ATV operators) may also wear protective helmets and/or other protective items. Protective equipment can also include knee pads, shin guards, shoulder pads and the like.

[0003] Protective helmets may include a relatively hard, rigid outer shell, and resilient material (e.g. padding) on at least a portion of an inside of the helmet. The padding is configured to support the helmet on a user's head and to absorb impact.

BRIEF SUMMARY OF THE INVENTION

[0004] One aspect of the present disclosure is a pressure sensing system for measuring pressure between a user's body and a protective article worn by the user. The pressure sensing system may, optionally, be configured for use with a protective helmet, and may include a flexible sensing assembly (e.g. a cap or other wearable article) that is configured to fit between an inside surface of a protective article (e.g. a helmet or other protective item) and a user's body (e.g. a user's head, chest, shoulders, elbows, hips, knees, shins, etc.). The flexible sensing assembly/cap may comprise a thin fabric that may be flexible and stretchable. The flexible sensing assembly/cap includes a pressure sensor array comprising a plurality of pressure sensors. Each sensor may include a dielectric layer that is deformable in a thickness, a first electrode on a first side of the dielectric layer, and

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a second electrode on a second side of the dielectric layer. The second electrode is movable toward and away from the first electrode by deformation of the dielectric layer. The dielectric layer is configured to maintain a capacitance between the first electrode and the second electrode, and the capacitance changes with the movement of the second electrode toward or away from the first electrode. The system further includes a data acquisition module connected to the flexible sensing assembly (e.g. fabric cap), and a plurality of conductive lines operably interconnecting the pressure sensors to the data acquisition module. The data acquisition module may be configured to provide data from the pressure sensor array to a user interface device such as a computing device having a display and/or other capabilities for providing information to a user.

[0005] The pressure sensors may comprise a dielectric layer sandwiched between conductive layers. One or both conductive layers may be bonded to a fabric layer. One or both conductive layers may be bonded to a plurality of electrical conductors to provide an electrical connection therewith.

[0006] The dielectric layer of each pressure sensor may optionally be flexible between a planar condition and a non-planar condition. The system may optionally include a readout circuit that is electronically coupled with the first and second electrodes of the pressure sensors to measure a change in capacitance and to output a corresponding voltage. At least one of the first and second electrodes optionally comprises conductive ink that is disposed on a flexible base film. The flexible base film optionally comprises a polymer layer and a melt adhesive layer. Fabric may optionally be heat-bonded to the polymer layer by the melt adhesive layer.

[0007] The dielectric layer of each pressure sensor may comprise a porous (soft) polymer material such as a porous polydimethylsiloxane (PDMS). The porous PDMS may be fabricated using nitric acid (HNO_3) in a mixture of PDMS and sodium hydrogen bicarbonate ($NaHCO_3$) for inducing the liberation of CO_2 gas. The porous polymer dielectric material may provide increased sensitivity (change in capacitance) at a given pressure applied to the pressure sensor relative to solid (nonporous) polymer dielectric material. Although the dielectric material may comprise porous PDMS, virtually any dielectric material having sufficient flexibility may be utilized. For example, a soft, non-porous

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dielectric material providing sufficient change in thickness (and capacitance) at low applied pressures may be utilized.

[0008] The article may comprise a protective article (e.g. a helmet) or other protective item such as back plates and/or rib protectors and/or girdles and/or shoulder pads and/or hip pads and/or tail pads, or a limb prosthetic, orthopedic brace, etc. The fabric of the sensing assembly may optionally comprise a flexible fabric of a cap or other item that is configured to be positioned between a user's body and a protective or prosthetic article. The polymer layer of the flexible base film may optionally comprise thermoplastic polyurethane, and the dielectric layer may optionally comprise silicone elastomer material. One or more of the pressure sensors may optionally include a curved outer edge, and the curved outer edge may optionally be circular. One or more of the pressure sensors may optionally be about 1.0 inches to about 2.0 inches in diameter. The pressure sensor array may optionally comprise at least five pressure sensors or other suitable number capable of providing sufficient pressure data to determine if a helmet or other protective article fits comfortably according to predefined criteria. The flexible assembly may comprise a cap that may optionally include a chin strap that is configured to retain the cap on a user's head.

[0009] Another aspect of the present disclosure is a method of measuring pressure between a wearable article (e.g. a helmet or other protective article or a prosthetic device) and a user's head or other body part. The method includes positioning a flexible sensor assembly such as a cap having a plurality of capacitive pressure sensors on a user's head or other body part. A helmet or other protective article is positioned over the flexible assembly (e.g. cap) on the user's body part (e.g. head). Changes in the capacitance of the pressure sensors are utilized to determine the pressure between the user's body (e.g. head) and an inside of the protective article (e.g. helmet). The flexible assembly/cap may optionally be positioned on the user's body/head before the protective article/helmet is positioned over the flexible assembly/cap, or the flexible assembly/cap and the protective article/helmet may be positioned on a user's body/head at substantially the same time. The protective article/helmet may optionally be removed from the user's body/head without removing the flexible assembly/cap from the user's body/head, or the protective article/helmet and flexible assembly/cap may be removed at the same time.

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[0010] Another aspect of the present disclosure is a method of fabricating a flexible sensor assembly such as a cap for sensing pressure on a user due to a wearable (e.g. protective) article such as a helmet, prosthetic device, etc. that is configured to be worn by a user. The method includes fabricating a plurality of thin flexible pressure sensors by forming first and second electrodes on opposite sides of a flexible dielectric material. The pressure sensors are secured to a thin flexible material. The thin flexible material may optionally comprise a fabric in the shape of a cap or other article that can be worn by a user. The pressure sensors may be secured to the thin flexible material either before or after the thin flexible material is formed into the shape of a cap or other wearable article.

[0011] These and other features, advantages, and objects of the present disclosure will be further understood and appreciated by those skilled in the art by reference to the following specification, claims, and appended drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] In the drawings:

[0013] FIGURE 1 is a partially schematic view showing a pressure sensing system according to one aspect of the present disclosure;

[0014] FIGURE 2 is a partially schematic exploded perspective view of a pressure sensor according to one aspect of the present disclosure;

[0015] FIGURE 3 is a partially schematic perspective view showing fabrication of a pressure sensor;

[0016] FIGURE 4 is a fragmentary cross-sectional view of a pressure sensor according to one aspect of the present disclosure;

[0017] FIGURE 5 is a partially fragmentary perspective view showing a test setup utilized to test pressure sensors according to one aspect of the present disclosure;

[0018] FIGURE 5A is an enlarged view of a portion of the test setup of FIGURE 5;

[0019] FIGURE 6A is a chart showing test results for a pressure sensor according to one aspect of the present disclosure;

[0020] FIGURE 6B is a chart showing test results for a pressure sensor according to one aspect of the present disclosure;

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[0021] FIGURE 6C is a chart showing test results for a pressure sensor according to one aspect of the present disclosure;

[0022] FIGURE 6D is a chart showing test results for a pressure sensor according to one aspect of the present disclosure;

[0023] FIGURE 7 is a schematic showing a process of fabricating pressure sensors according to another aspect of the present disclosure;

[0024] FIGURE 8 shows a flexible electrode with permanent wiring;

[0025] FIGURE 9 shows electrodes attached to pieces of fabric;

[0026] FIGURE 10 is an isometric view of a cap subassembly;

[0027] FIGURE 11 is an isometric view of a cap subassembly;

[0028] FIGURE 12 is an isometric view of a cap subassembly;

[0029] FIGURE 13A is an isometric rear view of a cap and sensor arrangement;

[0030] FIGURE 13B is an isometric side view of the cap and sensor arrangement of FIGURE 13A;

[0031] FIGURE 13C is an isometric front view of the cap and sensor arrangement of FIGURE 13A;

[0032] FIGURE 14 is an isometric schematic showing fabrication of a porous PDMS dielectric layer;

[0033] FIGURE 15 is a microscopic image of a porous dielectric layer;

[0034] FIGURE 16 comprises charts showing porosity and changes in capacitance for dielectric materials cured at different temperatures;

[0035] FIGURE 17 comprises charts showing porosity and changes in capacitance for dielectric materials cured at varying PDMS viscosities; and

[0036] FIGURE 18 comprises charts showing changes in porosity and capacitance at a fixed 10:1 PDMS ratio.

<u>DETAILED DESCRIPTION</u>

[0037] For purposes of description herein, the terms “upper,” “lower,” “right,” “left,” “rear,” “front,” “vertical,” “horizontal,” and derivatives thereof shall relate to the invention as oriented in FIGURE 1. However, it is to be understood that the system and components thereof may assume various alternative orientations and step sequences,

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except where expressly specified to the contrary. It is also to be understood that the specific devices and processes illustrated in the attached drawings, and described in the following specification are simply exemplary embodiments of the inventive concepts defined in the appended claims. Hence, specific dimensions and other physical characteristics relating to the embodiments disclosed herein are not to be considered as limiting, unless the claims expressly state otherwise.

[0038] This patent application is related to U.S. Patent No. 9,943,128, entitled "HELMET IMPACT MONITORING SYSTEM," issued on April 17, 2018.

[0039] With reference to FIGURE 1, a pressure sensing system 1 according to one aspect of the present disclosure includes a flexible sensing assembly 2 that may be in the form of a cap or other wearable article that may be made from a thin flexible and/or stretchable fabric material 9 to fit closely around a body part such as a head 3 of a user 7 inside a wearable (e.g. protective) article such as a helmet 22 or other protective article. Inner surface 23 of helmet 22 may be formed by padding or other resilient material 25 disposed inside of an outer shell 27 of helmet 22. The flexible assembly/cap 2 may include a sensor array comprising a plurality of thin flexible pressure sensors 4 that are operably connected to a data acquisition module 6 by conductive lines 5. The data acquisition module 6 may be operably connected to a computing device such as a laptop 10 having a display 12 by a conductive line 14, or wirelessly (e.g. via a wireless communication unit 16). In general, the communication unit 16 may utilize wireless signals via a network 20 to communicate with laptop 10, a smartphone 18, and/or other devices (not shown).

[0040] The cap 2 or other wearable article is preferably made from a thin flexible and/or stretchable fabric 9 that fits closely around the head 3 (or other body part) of a user 7. The cap 2 may be made from virtually any suitable material, and the present disclosure is not necessarily limited to fabrics. If the wearable article comprises a cap 2, the cap 2 may include a chin strap 24 that retains the cap 2 on a user's head 3, and the cap 2 may also include ear openings 26. The cap 2 may also include a plurality of openings 8 to provide for ventilation. The cap 2 is preferably thin so that the cap 2 can fit comfortably between an inner surface 23 of a protective helmet 22 and the head 3 of a user, without significantly increasing the pressure at contact points between the user's head 3 and helmet 22. The thickness of the sensors 4 and fabric of cap 2 is preferably no more than

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about 0.100 inches, and more preferably less than about 0.020 inches. However, it will be understood that the present disclosure is not limited to any specific dimension or range of dimensions, and cap 2 and/or sensors 4 may have virtually any thicknesses, and may have non-uniform thickness. Although the left side of cap 2 is shown in FIGURE 1, it will be understood that the cap 2 may be substantially symmetric about a center line, such that the right side of cap 2 (not shown) is substantially a mirror image of the left side shown in FIGURE 1.

[0041] As discussed in more detail below, the sensors 4 comprise capacitive pressure sensors that generate pressure data that is processed by the computing unit 10, and the pressure results are shown on display 12. The cap 2 may be utilized by a person to try on different helmets 22 in an effort to find a helmet 22 that fits properly. In general, pressures in a range of 0 kPa to about 100 kPa may be considered to have a comfort fit. However, it will be understood that wider or smaller ranges may be utilized as criteria with respect to a comfort fit, and the present disclosure is not limited to a specific range. Alternatively, the pressure data from sensors 4 can be utilized to modify a shape/contour of inner surface 23 of helmet 22 to thereby custom fit a helmet 22 to a particular user to thereby ensure that the pressures meet the predefined comfort fit criteria. The pressure data from the sensors 4 can also be utilized to ensure proper fit of the helmet 22 to a particular user.

[0042] The cap 2 can also be utilized during development of prosthetic or protective articles (e.g. helmets 22) to determine an inner surface shape 23 of helmet 22 providing a best fit for a high percentage of users. For example, cap 2 may be utilized to measure the pressures resulting from a given helmet 22 when used for a plurality of different users, and the surface 23 may be adjusted to a contour that minimizes the average pressure for a maximum number of users.

[0043] Also, cap 2 may be worn by a user 7 during activities (e.g. sporting activities) to monitor impact forces. When utilized in this way, the data can be measured and processed in a manner substantially similar to the arrangement described in U.S. Patent No. 9,943,128 entitled “HELMET IMPACT MONITORING SYSTEM.” Impact forces may result in pressures (e.g. 6,000 kPa or greater) that are significantly higher than static pressures. Thus, sensors 4 may be configured to provide a wide range of pressure

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measurement capabilities (e.g. about 0 or 1.0 kPa to above about 6,000 kPa or more). Alternatively, cap 2 may include both lower pressure sensors 4 as described herein (e.g. about 0 or 1.0 kPa to about 100 kPa), and higher pressure impact sensors (e.g. at least about 100 kPa to about 6,000 kPa or more). Above-referenced U.S. Patent No. 9,943,128 discloses pressure sensors suitable for measuring higher pressures resulting from impacts.

[0044] With reference to FIGURE 2, each sensor 4 may comprise a dielectric layer 34 that is disposed between first and second electrodes 30 and 32. It will be understood that the thicknesses of the various components (layers) shown in FIGURE 2 are exaggerated, and the actual thicknesses of the components may be thinner relative to the overall size of the components. As discussed in more detail below in connection with FIGURE 3, electrodes 30 and 32 may comprise Ag (silver) ink 53 that is printed on a thermoplastic polyurethane (TPU) 36 of a flexible base film 42 (FIGURE 3) or directly onto fabric 58. The flexible base film comprises a TPU layer 36 which may have a thickness of about 50-100 μm, a melt adhesive layer 38 (preferably 20-50 μm), and a temperature stable carrier film 40 (FIGURE 3). Flexible base film 42 may comprise a commercially available INTEXAR® TE-11C available from DuPont Corporation of Wilmington, Delaware, or other suitable material. The dielectric layer 34 may comprise a SYLGUARD® 184 silicone elastomer available from Dow Corning of Midland, Michigan or other suitable dielectric material. The dielectric layer 34 may be formed by mixing liquid PDMS pre-polymer with a curing agent at a ratio of 10 to 1, and the liquid PDMS may then be poured into a mold to form layers by thermally curing the PDMS at a required time and temperature (e.g. 130° C for 15 minutes). It will be understood that this is merely an example of a suitable material and process, and dielectric layer 34 may be formed utilizing virtually any suitable material utilizing any suitable process. As discussed in more detail below, the PDMS dielectric material of layer 34 may be porous (soft) to provide greater changes in capacitance at a given applied pressure to thereby permit accurate measurement of low applied pressures. The dielectric layer 34 may have a thickness “T1” of about 1 mm (i.e. 0.0394 inches). However, the thickness T1 may be greater or smaller than 1 mm, and the present disclosure is not limited to any specific dimension. For example, the thickness T1 may be about 0.5 mm – about 1.5 mm (about 0.0197 inches – about 0.0591 inches), about 0.5 mm

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– about 5.0 mm (about 0.0197 inches – about 0.1969 inches), about 0.1 mm – about 10.0 mm (about 0.00394 inches – about 0.3937 inches), or any other suitable thickness.

[0045] In the illustrated example, the sensor 4 has a diameter "D" of about 37 mm (i.e. about 1.5 inches). However, the diameter D may be significantly larger or smaller as required for a particular application. For example, the diameter D may vary from about 25 mm to about 51 mm (about 1 inches to about 2 inches). Although all sensors 4 may have the same size and shape, the sensors utilized for a cap 2 may, alternatively, have different sizes and shapes. Also, the edges 44 (FIGURE 3) of the sensors 4 may be curved (e.g. circular) as shown, or the sensors 4 may have virtually any other shape. The sensors 4 may be evenly, or approximately evenly, spaced from each other, or the sensors may be spaced in an uneven pattern. Also, although the layers 36, 38, 40 and electrodes 30 and 32 are shown as having different diameters in FIGURE 2, it will be understood that all of the layers (including dielectric layer 34) of sensor 4 may have substantially the same diameter "D." Cap 2 may include any number of sensors 4 in any pattern or configuration. Typically, 10, 12, 14, or 16 (or more) sensors may be utilized. However, fewer sensors 4 may also be utilized. For example, cap 2 could have a single sensor 4 that may be utilized if pressure at a single point or region is to be measured. Typically, cap 2 may include at least five sensors 4.

[0046] FIGURE 3 is a schematic showing fabrication of sensors 4 according to one aspect of the present disclosure. It will be understood that FIGURES 3 and 4 are representative examples, and the present disclosure is not limited to these examples. For example, the present disclosure is not limited to the specific materials and sequences of steps described herein. During a first step 50 (FIGURE 3), the flexible base film 42 (including TPU layer 36, melt adhesive 38, and carrier 40) is preheated as required to provide heat stabilization. Although the time and temperature may vary as required, the flexible base film 42 may be heated at 140° C for about 30 minutes.

[0047] During a second step 52, a temporary subassembly 60 is formed by screen printing silver ink 53 on preheated TPU layer. The subassembly 60 is then cured at an elevated temperature (e.g. about 130° C) for a suitable time (e.g. about 15 minutes) in an oven or other suitable manner.

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[0048] During a third step 54, the carrier film 40 is removed from subassembly 60 to expose the adhesive layer 38. During a fourth step 56, the adhesive 38 is secured to fabric 58 by heat pressing the components together for a suitable period of time (e.g. about 15 to about 30 seconds). It will be understood that virtually any suitable adhering material and process may be utilized, and the present disclosure is not limited to the times, materials, and processes described herein.

[0049] In the illustrated example, the subassembly 62 has a substantially rectangular perimeter 64. However, other shapes and configurations may also be utilized. The subassembly 62 may be cut to form a curved (e.g. circular) perimeter 44 utilizing a suitable cutting process. For example, the subassembly 62 may be cut to form perimeter 44 utilizing a laser cutting system. Perimeter 44 may have virtually any shape (including non-circular shapes) and size as required for a particular application. The subassemblies 62 may then be adhesively bonded to opposite sides of dielectric layer 34 (FIGURE 2) with the fabric 58 being adhesively bonded to the dielectric material 34 (see also FIGURE 4). Fabric 58 may be adhesively bonded to fabric 9 of cap 2. Alternatively, cap 2 may be fabricated from fabric 58, and sensors 4 may be integrally formed with cap 2 by heat bonding TPU 36 directly to cap fabric 9 using adhesive 38 during step 56 (FIGURE 3). Alternatively, cap 2 may comprise two layers of fabric 9 that are bonded to the TPU layers 36 using adhesive 38, with the sensor 4 disposed between the fabric layers 9. Similarly, fabric 58 on opposite sides of sensor 4 may be bonded to layers of fabric 9 using adhesive 38 or other suitable material or technique.

[0050] In general, a comfortable fit may be quantified to be within a pressure range of about 0 kPa (or about 1 kPa) to about 100 kPa. Higher pressures (e.g. about 110 kPa, about 120 kPa, etc.) may also be utilized to define the upper limit of the comfort fit range. Similarly, lower pressures (e.g. about 60 kPa, about 70 kPa, about 80 kPa, about 90 kPa, etc.) may also be utilized to define the upper bound of the comfort fit range. Also, the lower bound of the comfort fit range may comprise pressures above zero (e.g. about 5 kPa, about 10 kPa, about 15 kPa, about 20 kPa, etc.). Thus, the present disclosure is not limited to a specific comfort fit range, and virtually any suitable predefined comfort fit criteria may be utilized. During testing, test sensors 4 were therefore characterized in two pressure ranges: 1) a lower pressure range (about 0 kPa to about 10 kPa); and 2) a higher pressure

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range (about 25 kPa to about 100 kPa). An experimental test setup is shown in FIGURES 5 and 5A. The test sensors 4 were fabricated according to the process described above in connection with FIGURE 4. With reference to FIGURE 5, the test setup 70 included a motorized test stand with force gauge 72 and a precision LCR meter 74. In the illustrated example, the force gauge comprised a Mark-10 model M5-200, the movable platform comprised a Mark-10 ESM 301 motorized test stand, and the LCR 74 comprised an Agilent E4980A. The capacitive response of test sensor 4 was then tested by applying varying compressive forces perpendicular to each test sensor 4. Each test sensor 4 was initially tested from 0 kPa to 10 kPa, and then from 25 kPa to 175 kPa (i.e. greater than 100 kPa) to verify the sensitivities in lower and higher comfort fit pressure ranges (and above the maximum value of the comfort range). The change in capacitance was measured using a custom built LabVIEW™ program on a PC (e.g. laptop 10) connected to the LCR meter 74 via a USB cable or using any wireless methods of data transmission such as Bluetooth, ZigBee, Wi-Fi, and the like. The present disclosure is not limited to the specific sensors 4 and cap 2 as described herein, and any suitable sensors, wearable article, and method may be utilized.

[0051] In general, the capacitance of a fully printed test sensor 4, which is similar to a parallel plate capacitor, is inversely proportional to the thickness T1 (FIGURE 2) of the dielectric layer 34. FIGURE 6A shows the dynamic capacitive response of a test pressure sensor 4 at compressive forces varying from 0 kPa to 10 kPa, which is the lower comfort fit pressure range. Initially, the capacitance of the test pressure sensor 4 was recorded for 30 seconds with no force applied. The test sensor 4 was then subjected to a minimum detectable pressure of 0.2 kPa for 30 seconds, after which the compressive force was released. The response of the test sensor 4 was again recorded for another 30 seconds. This cycle was continued for increasing compressive forces up to 10.5 kPa.

[0052] With reference to FIGURE 6C, the dynamic capacitive response of the test pressure sensor 4 at compressive forces varying from 25 kPa to 175 kPa (> 100 kPa), which is a higher comfort fit pressure range was also tested. During testing, it was observed that the test sensor 4 was reversible, after each compressive force was released, due to the fact that the capacitance always attained its base capacitance value. In the illustrated example, the base capacitance value was 21±0.01 pF.

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[0053] FIGURES 6B and 6C show the change in capacitance at different compressive forces varying from 0 kPa to 10.5 kPa and from 25 kPa to 175 kPa, respectively. A 0.50%, 1.60%, 2.34%, 2.78%, 3.60%, 4.09% and 6.01% change in capacitance was observed as the pressure increased from 0.5 kPa to 1.5 kPa to 2.5 kPa to 3.0 kPa to 6.5 kPa to 10.5 kPa, respectively. In addition, a 8.61%, 10.46%, 11.36%, 11.91%, 12.72% and 13.48% change in capacitance was observed as the pressure increased from 25 kPa to 50 kPa to 75 kPa to 100 kPa to 125 kPa to 175 kPa, respectively. These responses can be attributed to the shortening of the distance between the electrodes due to the application of the varying compressive forces. The results obtained demonstrated a sensitivity of 0.5%/kPa and 0.03%/kPa for the printed test pressure sensor 4 in the 0 kPa to 10 kPa and 25 kPa to 175 kPa pressure ranges, respectively. The porous dielectric material described in more detail below in connection with FIGURES 7-18 may be utilized. In general, a softer porous dielectric material provides greater changes in capacitance for a given load (e.g. at pressures ranging from about 0 kPa to about 100 kPa.

[0054] The pressure sensing system 1 of the present disclosure provides a way to quickly and accurately measure the pressure resulting from a helmet 22 (FIGURE 1) when the helmet 22 is worn by a user 7. The system 1 may be utilized to determine if a specific helmet 22 fits a user (i.e. meets predefined comfort/pressure criteria). It will be understood that the predefined comfort/pressure criteria described above (0 or 1 kPa – 100 kPa) is merely an example of a predefined comfort/pressure criteria. For example, the predefined comfort fit criteria (range) may include pressures above or below 100 kPa (e.g. 80 kPa, 90 kPa, 110 kPa, 120 kPa, etc.). Also, some sensors 4 of the array could have different construction (e.g. different materials and/or different material thicknesses). This could be done to, for example, provide for measuring pressures in different ranges. The system 1 may also be utilized to determine if the inner surface 23 of a helmet 22 needs to be modified to thereby provide a more comfortable fit. The system 1 may also be utilized to develop production helmets fitting the widest range of users based on pressure measurements taken when a helmet is worn by numerous different users.

[0055] It will be understood that the present disclosure is not limited to a cap 2 and helmet 22 as described herein. Virtually any type of wearable article or equipment may be fabricated to include pressure sensors 4. The wearable article may comprise thin,

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flexible and/or stretchable material (e.g. fabric) with one or more pressure sensors 4 secured thereto, and the wearable article may be utilized to measure pressure between a part of a user's body and a protective article. For example, sensors 4 may be incorporated into flexible footwear (e.g. socks) that sense pressure between a user's foot and a protective article such as a shoe, boot, ice skate, ski boot (cross country or downhill), ankle brace, foot brace, etc. Similarly, sensors 4 may be incorporated into thin flexible wearable articles such as shirts and/or pants to detect pressure between protective leg and/or shoulder "pads" of the type worn during football, hockey, and/or other sports or activities. Still further, sensors 4 may be incorporated into flexible (e.g. fabric) articles configured to be worn on an elbow or knee, and elbow or knee protectors may be worn over the flexible article. Still further, sensors 4 may be utilized in wearable articles that are configured to be utilized in clinical applications to ensure proper fit of limb prosthetics, orthopedic braces and the like. The wearable articles may also be used to measure forces transmitted to a user's body during use of limb prosthetics, orthopedic braces, and other such items. In each case, sensors 4 may be utilized to sense pressure between an article and a user's body to provide a proper fit. Sensors 4 may also be utilized during use to detect changes in pressure resulting from user movement and/or impacts to the wearable (protective or prosthetic) article while it is worn by a user.

[0056] With reference to FIGURE 7, a method of fabricating pressure sensors according to another aspect of the present disclosure includes steps 102A-102G. A substrate 104 is provided at step 102A. Substrate 104 may comprise a sheet of thermoplastic polyurethane (TPU) or other suitable material. Substrate 104 is preferably thin (e.g. 010 inches – 0.050 inches) and sufficiently flexible to readily conform to a curved surface of a human body (e.g. a head, arm, leg, etc.). However, thicker or thinner sheets may be utilized, and substrate 104 could be rigid. At step 102B, a layer of conductive material 105 is formed on the substrate 104. The conductive layer 105 may comprise metal (e.g. silver) or other suitable conductive material. The substrate 104 and conductive layer 105 may be cut at 107 by use of a laser cutter or other suitable technique to provide a plurality of subassemblies 106 as shown at step 102C. The subassemblies 106 may include individual substrates 104A and conductive layers 105A that are circular or other shape as required for a particular application. In general, each individual substrate 104A may

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optionally have the same size and shape as the conductive layers 105A to which it is attached. However, a subassembly 106 may comprise a substrate 104A and a conductive layer 105A having dissimilar sizes and shapes.

[0057] At step 102D, the subassembly 106 is positioned adjacent fabric 108, and the substrate 104A is heat press laminated to fabric 108 utilizing heat and pressure (arrows 109) utilizing heated plates 110 or other suitable laminating tool or process. As discussed in more detail below, the fabric 108 may comprise a small piece of fabric having a size and shape that is similar to (or somewhat larger) than subassembly 106 (e.g. circular), or the fabric 108 may comprise a larger piece of fabric that is utilized to form a flexible cap or other item configured to fit closely against or around a body part of a subject.

[0058] At step 102E, a layer of thermoplastic polymer material 112 (e.g. TPU) is heat-laminated (adhered) to the conductive layer 105 using heated plate 110 to provide heat and pressure (arrows 109) to secure conductive strands 114 of wire 111 to the conductive layer 105 to form an electrode subassembly 116. TPU 112 thereby acts as a hot melt adhesive. Wire 111 preferably includes a plurality of conductive strands 114A and an insulated sheath 113. The individual strands 114A are preferably spaced apart across the surface 105A (see also FIGURE 8) to thereby ensure that the strands 114 of wire 111 are mechanically secured to the conductive layer 105, while also ensuring a strong electrical connection between the strands 114 of wire 111 and the conductive layer 105.

[0059] At step 102F, first and second electrode subassemblies 116A and 116B (produced by steps 102A-102E) are adhesively bonded to opposite sides 115A and 115B of a dielectric material 115 utilizing adhesive PDMS or other suitable adhesive. As discussed in more detail below, the dielectric material 115 may comprise a porous PDMS or other suitable material. Force (arrows 117) may be applied to the electrode subassemblies 116A and 116B to adhesively bond the electrode subassemblies 116A and 116B to the opposite sides 115A, 115B of dielectric material 115 to thereby form a pressure sensor 120 as shown at step 102G.

[0060] With reference to FIGURE 8, one or both of the electrode subassemblies 116A, 116B may include a layer of fabric 108 having a plurality of connectors such as tabs 118 that may be formed by cutting (e.g. laser cutting, knife, etc.) a sheet of fabric. As discussed in more detail below, the tabs 118 may be utilized to secure the pressure sensor

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120 to a larger sheet of fabric (e.g. by sewing or other suitable technique). It will be understood that tabs 118 are optional.

[0061] With reference to FIGURE 9, conductive layers 105A may be heat laminated to larger pieces of fabric 119A-119F utilizing heat lamination (step 102D) as described above in connection with FIGURE 7. Fabric pieces 119A-119F are subsequently connected along seams 124 to form a layer of fabric 119 of a cap subassembly 125A as shown in FIGURE 10. Seams 124 may be sewn or formed by other suitable techniques. Thus, the heat press laminating step 102D (FIGURE 7) may comprise laminating the conductive layers 105A of each bottom electrode 116B to larger pieces of fabric 119A-119F as shown in FIGURE 9. Strands 114 of wires 111 (FIGURE 10) can be heat-laminated to the substrates 105A utilizing step 102E of FIGURE 7 to form bottom electrodes 116B as shown in FIGURE 10. Strands 114 of wires 111 may be bonded to conductive layers 105A prior to interconnecting fabric pieces 119A-119F together along seams 124 (i.e. strands 114 may be bonded to conductive layers 105A and wires 111 may be sewn to fabric pieces 119A-119F when fabric pieces 119A-119F are separate as shown in FIGURE 9). The fabric pieces 119A-119F can then be sewn together along seams 124 to form a subassembly such as cap subassembly 125A (FIGURE 10). Wires 111 can be secured to the fabric pieces 119A-119F by sewing (threads 138) or other suitable attachment technique. It will be understood that virtually any size and shape of fabric pieces may be used, and the present disclosure is not limited to forming a cap. Rather, fabric pieces 119A-119F and cap subassembly 125A are merely examples of one possible configuration. Also, a single piece of fabric may be utilized in some applications rather than individual pieces 119A-119F.

[0062] With reference to FIGURE 11, the dielectric material 115A may be adhesively bonded to the electrode subassemblies 116B, and top electrodes 116A may be adhesively bonded to the dielectric material 115. This may be accomplished utilizing the process described above in connection with step 102F of FIGURE 7. As shown in FIGURE 12, the tabs 118 of upper electrode subassemblies 116A may be sewn or otherwise attached to the fabric layer 119 (pieces 119A-119F) using thread 138 to secure the top electrode subassemblies 116A. However, it will be understood that tabs 118 are optional. One or more straps 126A-126C may be secured to selected ones of the fabric pieces 119A-119F (e.g. by sewing with threads 138) to form a second cap subassembly 125B.

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[0063] With further reference to FIGURE 13A-13C, additional pieces of fabric 121A-121F may be sewn to the fabric layer 119 (fabric pieces 119A-119F) to form an outer layer of fabric 121 that covers sensors 120. Indicia 127 may be printed or otherwise marked on the fabric pieces 121A-121F to signify the location and number of each sensor 120. The wires 111 may be operably connected to a connector 128 to thereby permit the cap 125 to be electrically connected to one or more electronic devices (FIGURE 1) such as a data acquisition module 6, communication signal 16, laptop 10, smartphone 18, and/or other devices (not shown).

[0064] With further reference to FIGURE 14, porous dielectric material may be made using steps 129A and 129B. At step 129A, a mixture 130 of PDMS + Sodium Hydrogen Bicarbonate ($NaHCO_3$) (baking soda) + Nitric Acid (HNO_3) is poured into cavity 131 of a mold 132. The PDMS in mixture 130 may comprise a mixture of hardener and elastomer. As discussed in more detail below, various variables (e.g. curing temperature, HNO_3 content, and viscosity of the PDMS solution) may be controlled to increase or decrease porosity of dielectric material 115 as required for a particular application. In general, a more porous dielectric material 115 will have a lower Young's modulus. Thus, a given pressure acting on a pressure sensor 120 having a more porous dielectric material 115 will result in a larger deformation of the more porous dielectric material 115 (compared to a less porous dielectric material 115), which in turn results in a larger change in capacitance for a given applied pressure. The dielectric material 115 may be fabricated to have relatively high porosity whereby the pressure sensor 120 is capable of measuring relatively low pressures.

[0065] Referring again to FIGURE 14, at a second step 129B, the mixture 130 in mold cavity 131 of mold 132 is annealed, thereby releasing water vapor and carbon dioxide (CO_2). The mold 132 and mixture 130 may be positioned in a container 134 having an opening 136 during the annealing process. As discussed in more detail below, container 134 may comprise a beaker 134A and a glass plate 134B. FIGURE 15 is a microscopic image showing openings or pores 137 in the dielectric material 115.

<u>Fabric Based Porous PDMS Pressure Sensor Fabrication</u>

[0066] For the fabrication of a porous PDMS dielectric layer 115 according to a specific example, PDMS according to a specific example, pre-cursor and curing agent ratio (10:1, w/w) may be mixed with $NaHCO_3$ powder in a 5:1 (w/w) ratio (FIGURE 14). Then,

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HNO_3 may be added to the PDMS-$NaHCO_3$ mixture in 1:5 (w/w) and stirred for about 10 minutes to control the liberation of CO_2 bubbles during the annealing process which in turn controls the pore size and distribution of pores. The mixture 130 (FIGURE 14) was poured into a mold 132 and left for about 15 minutes to obtain proper spreading and release of the entrapped air bubbles. The mold 132 may then be placed inside a beaker 134A. The air flow around the mold 132, which can affect the uniformity of the pore size during the annealing process, may be controlled by closing the beaker 134A with a glass plate 134B. Lid 134B may have a small opening 136 in the center of lid 134B which acts as an exhaust for water vapors 135 produced during the decomposition of the $NaHCO_3$. Finally, the beaker 134A may be thermally annealed in an oven for 30 minutes at 140 °C. During annealing, the $NaHCO_3$ decomposes, thereby liberating CO_2 gases to form a porous PDMS dielectric layer 115. The effect of varying the annealing temperature, the content of HNO_3, and PDMS viscosity (PDMS pre-cursor and curing agent ratio) are discussed below.

The following chemical reaction illustrates the decomposition of $NaHCO_3$ during the annealing process:

$$NaHCO_3 + HNO_3 \xrightarrow{\text{Heating}} NaNO_3 + H_2O + CO_2\uparrow$$

Following this, the porous PDMS 115 may be immersed in a diluted solution of IPA and then sonicated in deionized water for a period of time (e.g. about 30 minutes) to remove the byproduct - sodium nitrate ($NaNO_3$) salt. The porous PDMS layer 115 may then be dried in an oven for a suitable period of time (e.g. about 2 hours) at a suitable temperature (e.g. about 100 °C).

[0067] Initially, a polymer (e.g. TPU) substrate 104 may be heated at 140°C for 30 minutes for pre-print heat stabilization (e.g. step 102A, FIGURE 7). A screen printer (AMI MSP 485) from Affiliated Manufacturers Inc. may be used to deposit conductive Ag ink on the substrate 104 to form conductive layer 105 (e.g. step 102B, FIGURE 7). The screen used in the screen printer may be stainless-steel with mesh count, wire diameter, deflection angle and MS-22 emulsion thickness of 325, 28 µm, 22.5° and 12.7 µm, respectively. The screen printed Ag ink may be thermally cured at 130 °C for 8 minutes. Following this, the

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temperature stable carrier film was peeled off from the TPU substrate and placed on a fabric 108 (step 102C, FIGURE 7). The substrate 104 was permanently attached to the fabric 108 by heat pressing it using a laminator (Geo Knight – DK20SP), for 30 seconds. The fabric-based electrodes and porous PDMS dielectric layer 115 were then patterned into circles with a diameter of 35 mm by using a laser-assisted cutting process. A permanent wiring technique was designed for the electrical connections by placing the ends 114 of stripped wires 111 on the Ag layer 105 of the fabric electrodes and laminating them using a new base film 112 (step 102E, FIGURE 7). Finally, the laser patterned dielectric layer 115 was sandwiched between a top and bottom electrode 116A, 116B (step 102F, FIGURE 7) to form a complete pressure sensor 120 using adhesive PDMS 122 (step 102F, FIGURE 7).

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Porosity Control Analysis

[0068] Sensor-to-sensor uniformity in capacitive pressure sensors with porous dielectric layers may be affected by variations in porosity. A substantially uniform pore size and distribution may be necessary for some applications (e.g. where an array of sensors is required). Higher concentration of pores and larger sizes of the pores typically results in greater deformation for a given load (pressure), which results in greater relative capacitance change for a given load. The liberation of the CO_2 gas (which leaves the pores in the PDMS solution) may be controlled/adjusted by varying the curing temperature, the amount of the HNO_3, and the viscosity of the PDMS solution. The sensor performance and porosity changes due to varying the content of HNO_3 (10%, 15%, and 20%) was investigated in terms of pore size, dielectric layer thickness, dielectric constant, and the relative capacitive change for applied pressures ranging from 0 to 1000 kPa. The thickness of the fabricated sensor for 10%, 20% and 30% HNO_3 in the PDMS solution was measured 1321 µm , 1661 µm , and 1680 µm, respectively. The average pore size was changed from 278 µm, 454 µm, and 496 µm by increasing the content of the nitric acid (Table 1) which justifies the increase in the thickness of the porous layer as well. An increase in the pore size can be attributed to more liberation of CO_2 gas, which resulted in a decreasing dielectric constant of 1.99 to 1.91 to 1.90, for 10%, 15%, and 20% nitric acid, respectively.

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Table 1

Nitric Acid	Porous Pressure Sensor Features				
	Pore Size (µm)	***Thickness(d) (µm)***	***Dielectric Constant(Ɛ)***	***BaseCap.(C) (pF)***	***Cap.Change % (0-1000 kPa)***
10% (S4)	278±63	1321±4	1.99±0.02	11.7±0.3	170
15% (S5)	454±89	1661±4	1.91±0.01	8.3±0.2	282
20% (S6)	496±120	1680±16	1.90±0.01	8.2±0.2	323

[0069] With reference to FIGURE 16, the relative capacitance change was increased from 170% (for 10% nitric acid) to 282% (for 15% nitric acid) to 323% (for 20% nitric acid). This confirms that PDMS materials with larger pore sizes will tend to have more deformation for a given applied load.

[0070] Changing the viscosity of the PDMS before the annealing process and varying the annealing temperature are other factors (process parameters) that were also investigated. During the fabrication of porous PDMS layers, varying the pre-cursor/curing agent ratio changes the viscosity of the PDMS solution and thus affects the amount of the liberated CO_2 gas as well as the porosity of the fabricated porous PDMS layer 115.

[0071] To investigate the effect of viscosity on the pores size and distribution, three samples with different PDMS pre-cursor/curing agent ratios of 5:1, 10:1, and 15:1 were fabricated, and the porosity, thickness, and dielectric constant were measured for each sample as illustrated in FIGURE 17 as well as Table 2.

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Table 2

PDMS Viscosity	Porous Pressure Sensor Features				
	Pore Size (µm)	***Thickness(d) (µm)***	***Dielectric Constant(Ɛ)***	***BaseCap.(C) (pF)***	***Cap.Change % (0-1000 kPa)***
1:5 (S7)	375±67	1588±10	2.09±0.09	16.7±0.2	94
1:10 (S8)	496±120	1680 ±16	1.90±0.01	8.2±0.2	323
1:15 (S9)	468±120	1911 ±4	1.80±0.01	6.7±0.1	460

[0072] Temperature effect was also studied by changing the annealing temperature from 110 °C to 140 °C to 170 °C. It was observed that by increasing the PDMS pre-cursor/curing agent ratio (decreasing the viscosity of the PDMS solution) at a fixed annealing temperature of 140°C, the pore size tended to increase. On the other hand, increasing the annealing temperature (at a fixed 10:1 PDMS ratio), which accelerates the liberation of the CO_2 gas during the annealing process, resulted in a larger average pores size. The dielectric constant and the thickness of the fabricated porous PDMS layer (as expected) decreased and increased, respectively, for the samples with larger pore size as illustrated in Table 3.

Table 3

Curing Temp.	Porous Pressure Sensor Features				
	Pore Size (µm)	***Thickness(d) (µm)***	***Dielectric Constant(Ɛ)***	***BaseCap.(C) (pF)***	***Cap.Change % (0-1000 kPa)***
110°C (S1)	411±79	997±6	2.44±0.02	18.6±0.6	100
140°C (S2)	496±120	1680±16	1.90±0.01	8.2±0.2	323
170°C (S2)	502±131	2078±6	1.71±0.01	6.2±0.1	485

[0073] The relative capacitance change and pore size distribution are shown in FIGURE 18.

Durability and Repeatability of the Fabricated Pressure Sensor

[0074] In addition to porosity variation, electrode structure and sensor attachment may affect the uniformity of the fabricated sensors 120. One potential cause of hysteresis

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and nonuniformity of prior sensors is weak attachment of the conductive electrode and the dielectric layer, as well as the durability of the wiring and the electrode layer. Also, environmental effects such as temperature and humidity, may cause a change in the base capacitance, slow recovery of the signal, and cause variation of the relative capacitance change over different loading/unloading cycles. In order to overcome the above-mentioned problems, a heat press lamination process (step 102E, FIGURE 7) was performed as a permanent wiring technique. This process may, optionally, be used without hot/cold soldering or crimp connectors. Referring again to FIGURE 7, for the attachment of the porous PDMS dielectric layer 115 to the fabricated flexible fabric electrodes 116A, 116B, a 50 µm thick adhesive PDMS (1:1 w/w) layer was bar coated on top of the fabricated electrodes (step 102F, FIGURE 7) and the dielectric layer 115 was sandwiched between the electrodes 116A, 116B. The fabricated sensor 120 was then placed in an oven at a temperature of 80°C for 1 hour to cure the adhesive layer.

[0075] While the present disclosure describes various embodiments for illustrative purposes, such description is not intended to be limited to such embodiments. On the contrary, the applicant's teachings described and illustrated herein encompass various alternatives, modifications, and equivalents, without departing from the embodiments, the general scope of which is defined in the appended claims. Except to the extent necessary or inherent in the processes themselves, no particular order to steps or stages of methods or processes described in this disclosure is intended or implied. In many cases the order of process steps may be varied without changing the purpose, effect, or import of the methods described.

[0076] Information as herein shown and described in detail is fully capable of attaining the above-described object of the present disclosure, the presently preferred embodiment of the present disclosure, and is, thus, representative of the subject matter which is broadly contemplated by the present disclosure. The scope of the present disclosure fully encompasses other embodiments which may become apparent to those skilled in the art, and is to be limited, accordingly, by nothing other than the appended claims, wherein any reference to an element being made in the singular is not intended to mean "one and only one" unless explicitly so stated, but rather "one or more." All structural and functional equivalents to the elements of the above-described preferred embodiment

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and additional embodiments as regarded by those of ordinary skill in the art are hereby expressly incorporated by reference and are intended to be encompassed by the present claims. Moreover, no requirement exists for a system or method to address each and every problem sought to be resolved by the present disclosure, for such to be encompassed by the present claims. Furthermore, no element, component, or method step in the present disclosure is intended to be dedicated to the public regardless of whether the element, component, or method step is explicitly recited in the claims. However, that various changes and modifications in form, material, work-piece, and fabrication material detail may be made, without departing from the spirit and scope of the present disclosure, as set forth in the appended claims, as may be apparent to those of ordinary skill in the art, are also encompassed by the disclosure.

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CLAIMS

The invention claimed is:

1. A pressure sensing system for measuring at least one pressure acting between a user's head and a protective helmet, the pressure sensing system comprising:

a flexible cap configured to fit between an inside surface of a helmet and a user's head;

a pressure sensor array comprising a plurality of pressure sensors secured to the cap, each sensor including:

a dielectric layer that is deformable in a thickness;

a first electrode on a first side of the dielectric layer;

a second electrode on a second side of the dielectric layer overlying and moveable toward and away from the first electrode by deformation of the dielectric layer, the dielectric layer maintaining a capacitance between the first electrode and the second electrode, the capacitance changing with a movement of the second electrode toward or away from the first electrode;

a data acquisition module connected to the flexible cap; and

a plurality of conductive lines operably interconnecting the pressure sensors to the data acquisition module whereby the data acquisition module is capable of providing data from the pressure sensor array to a user interface device.

2. The pressure sensing system of claim 1, wherein:

the dielectric layer of each pressure sensor is flexible between a planar condition and a non-planar condition.

3. The pressure sensing system of either one of claim 1 or claim 2, including

a readout circuit electronically coupled with the first and second electrodes of the pressure sensors to measure a change in the capacitance and output a corresponding voltage.

4. The pressure sensing system of any one of claims 1 to 3, wherein:

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at least one of the first and second electrodes comprises conductive ink disposed on a flexible base material, wherein the base material is selected from the group consisting of films and fabrics.

5. The pressure sensing system of claim 4, wherein:

the flexible base material comprises a polymer film layer and a fabric layer heat-bonded to the polymer film layer.

6. The pressure sensing system of any one of claims 1 to 5, wherein:

the dielectric layer comprises a material selected from the group consisting of silicone elastomers and porous PDMS.

7. The pressure sensing system of claim 6, wherein:

The first and second electrodes comprise first and second conductive layers that are heat press laminated to first and second fabric layers, respectively, by a layer of thermoplastic polymer material.

8. The pressure sensing system of claim 7, wherein:

the conductive lines comprise multi-strand wires having spaced-apart strands that are heat press laminated to the conductive layers by a layer of thermoplastic polymer material.

9. A method of measuring pressure between an article and a user's body, the method comprising:

positioning a flexible sensing assembly having a plurality of capacitive pressure sensors on a user's body;

positioning an article over the flexible sensing assembly on the user's body;

utilizing changes in the capacitance of the pressure sensors to determine the pressure between the user's body and the article.

10. The method of claim 9, wherein:

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the flexible sensing assembly is positioned on the user's body before the article is positioned over the flexible sensing assembly.

11. A method of fabricating a flexible sensing assembly, the method comprising:

forming a porous PDMS dielectric material by mixing a PDMS pre-cursor, PDMS curing agent, $NaHCO_3$, and HNO_3;

fabricating at least one pressure sensor by positioning first and second electrodes on opposite sides of a porous PDMS dielectric material;

securing the at least one pressure sensor to a thin flexible material.

12. The method of claim 11, wherein:

the at least one pressure sensor comprises a plurality of pressure sensors;

the thin flexible material comprises a fabric formed in the shape of a cap; and including:

securing the plurality of pressure sensors to the thin flexible material.

13. The method of claim 12, wherein:

The first and second electrodes are fabricated by printing a layer of conductive material onto a polymer substrate; and including:

bonding an electrical conductor to the layer of conductive material.

14. The method of claim 13, wherein:

the electrical conductor comprises a multi-strand wire; and including:

spreading apart at least some of the strands at an end of the wire;

followed by bonding the spread apart strands to the conductive material.

15. The method of claim 14, including:

positioning the strands between the conductive material and a layer of thermoplastic polymer material;

heat press laminating the thermoplastic polymer material to the conductive material.

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16. The method of claim 15, wherein:

the conductive material is printed on a layer of thermoplastic polymer material; and including:

heat press laminating the conductive material to a layer of fabric material.

17. The method of claim 16, including:

adhesively bonding the first and second electrodes to the porous PDMS dielectric material.

18. A pressure sensing system for measuring at least one pressure acting between a user’s body and an article, the pressure sensing system comprising:

a flexible sensing assembly configured to fit between an article and a user’s body;

the flexible sensing assembly including a pressure sensor array comprising a plurality of pressure sensors secured to a flexible material, each sensor including:

a dielectric layer that is deformable in a thickness;

a first electrode on a first side of the dielectric layer;

a second electrode on a second side of the dielectric layer overlying and movable toward and away from the first electrode by deformation of the dielectric layer, the dielectric layer maintaining a capacitance between the first electrode and the second electrode, the capacitance changing with a movement of the second electrode toward or away from the first electrode; and

a plurality of conductors connected to the pressure sensors.

19. The pressure sensing system of claim 18, wherein:

the dielectric layers of the pressure sensor comprises a porous PDMS material.

20. The pressure sensing system of claim 19, wherein:

the first and second electrodes of the pressure sensors comprise conductive layers bonded to opposite sides of the dielectric layers;

the flexible material comprises fabric;

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at least one conductive layer of each pressure sensor is heat press laminated to the fabric by a layer of thermoplastic polymer material;

the conductors comprise multi-strand wires, each multi-strand wire having an end with spaced-apart strands that are heat press laminated to the conductive layer by a layer of thermoplastic polymer material.

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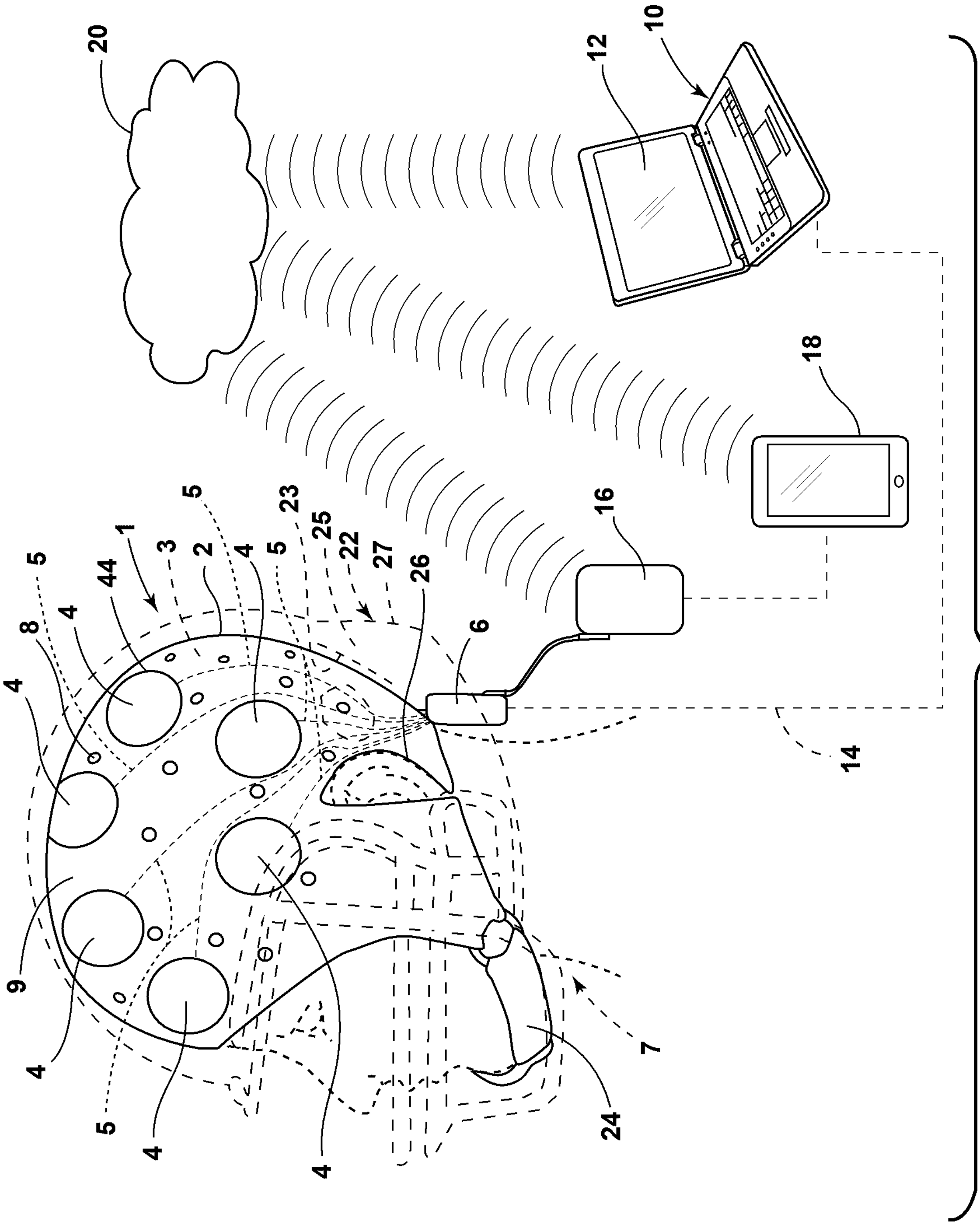

FIG. 1

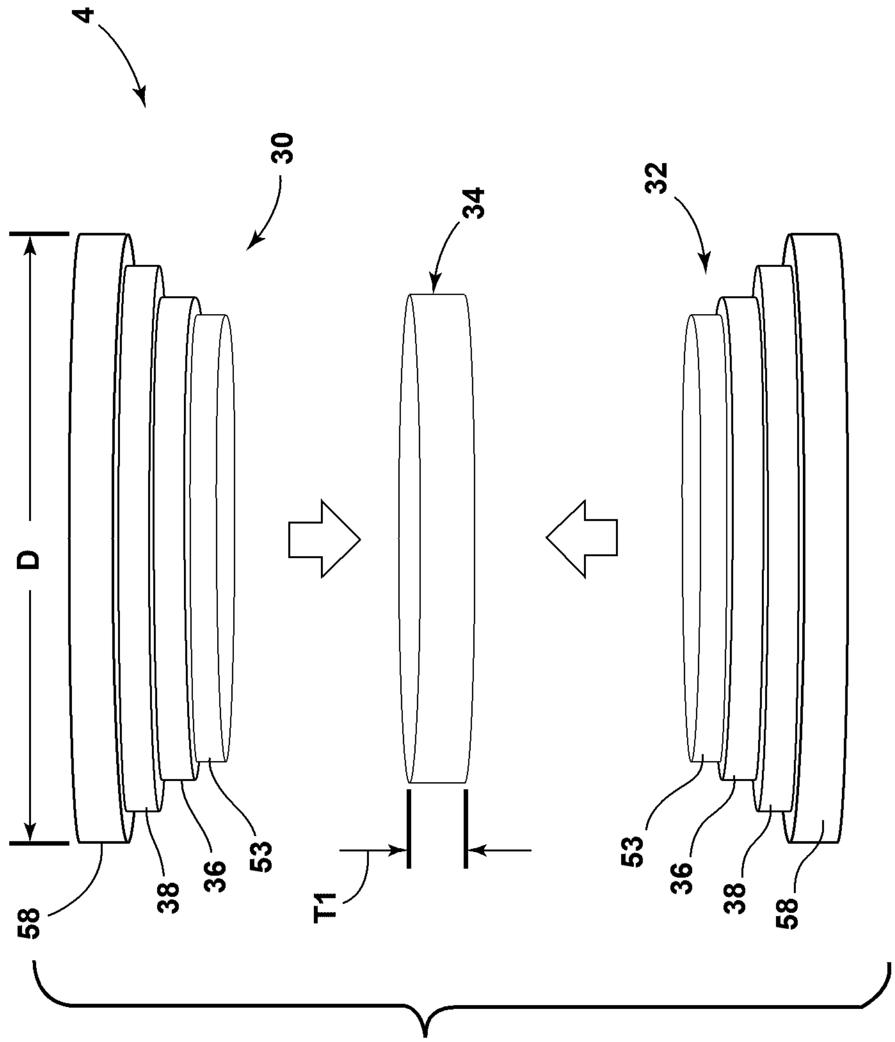

FIG. 2

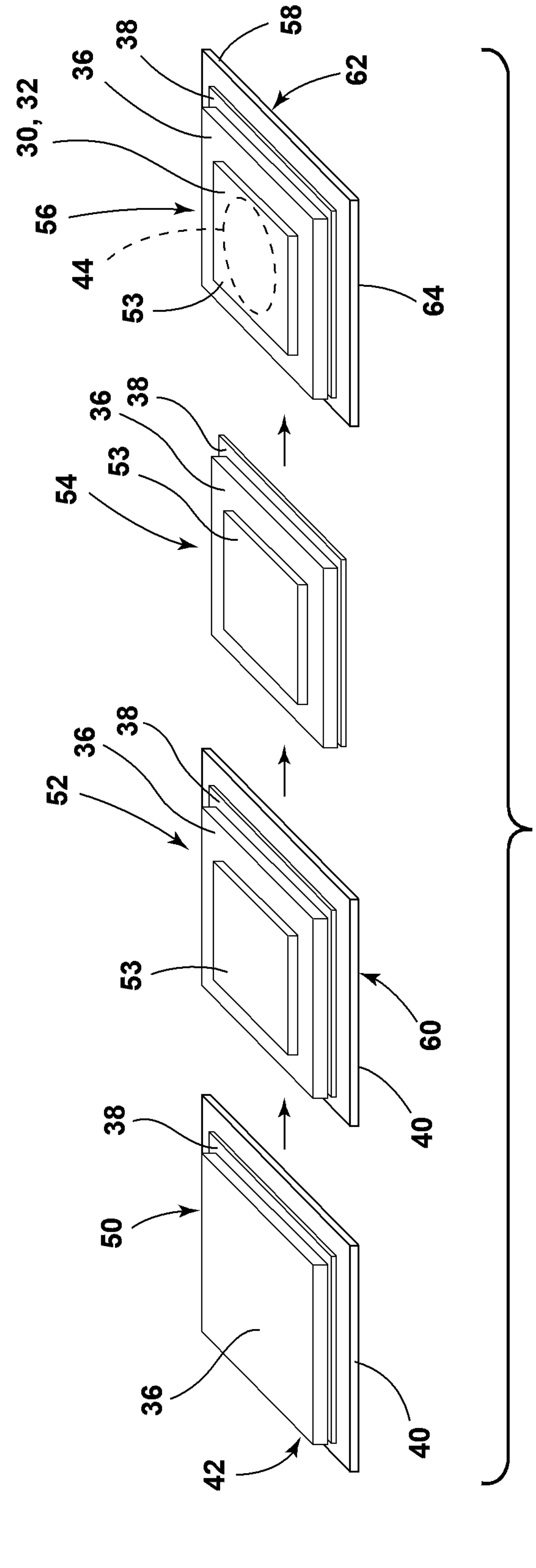
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FIG. 3

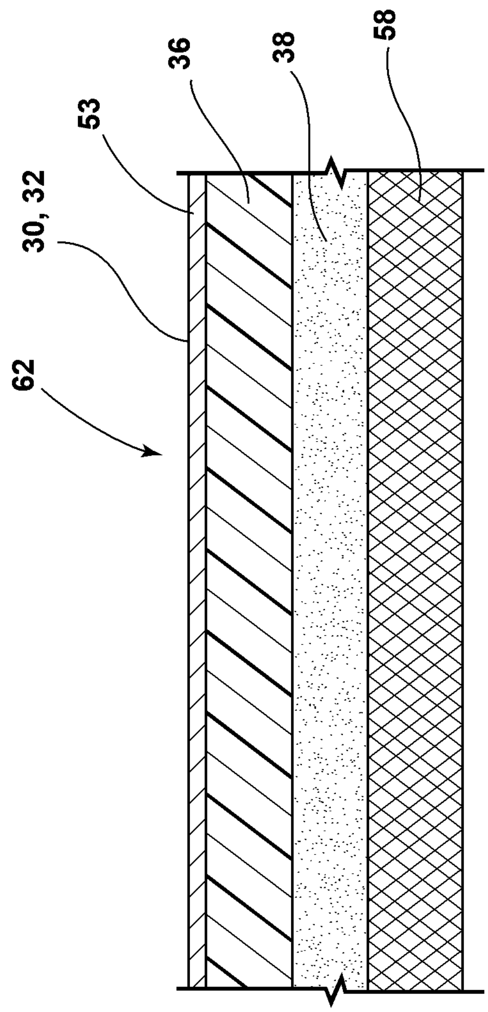

FIG. 4

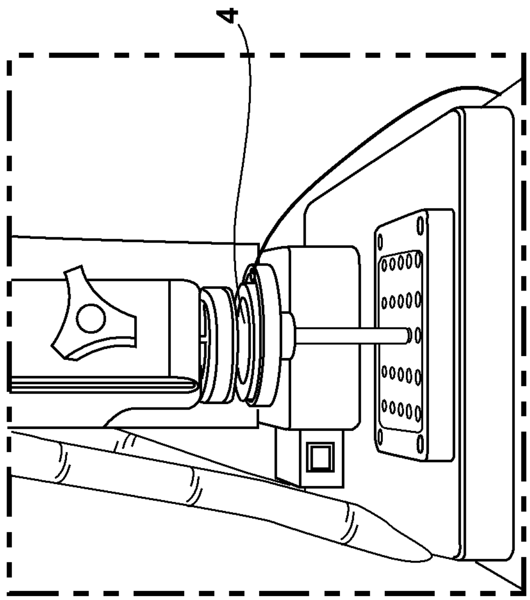

FIG. 5A

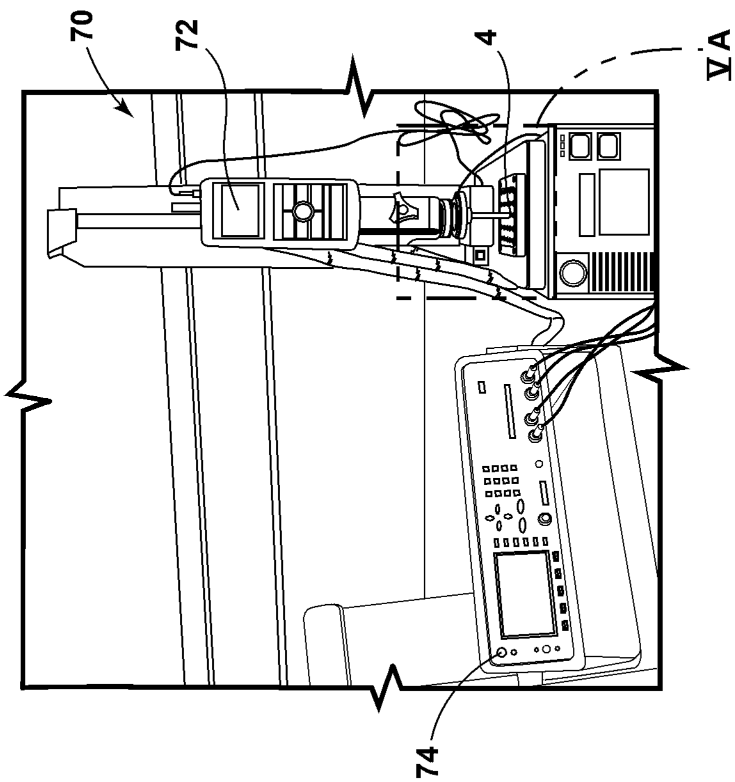

FIG. 5

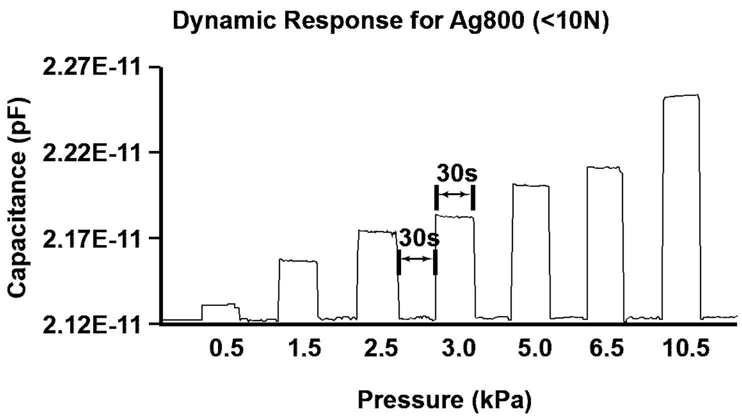

FIG. 6A

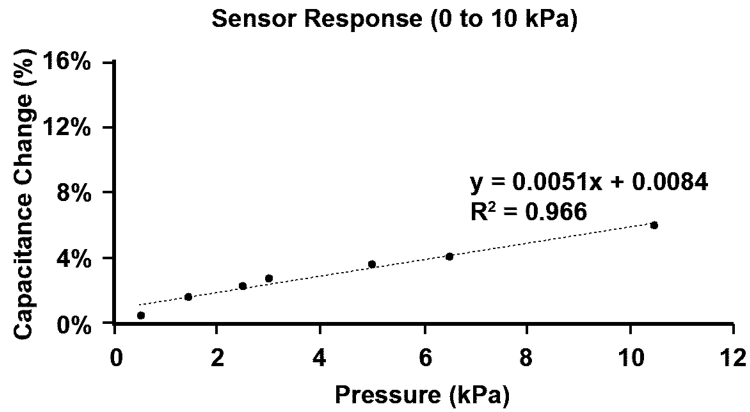

FIG. 6B

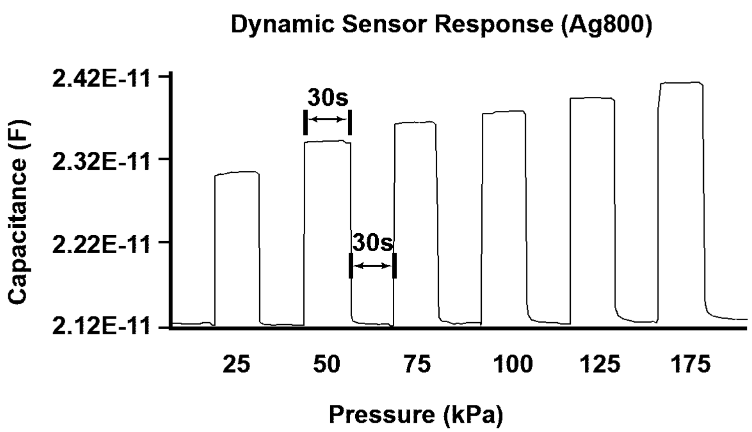

FIG. 6C

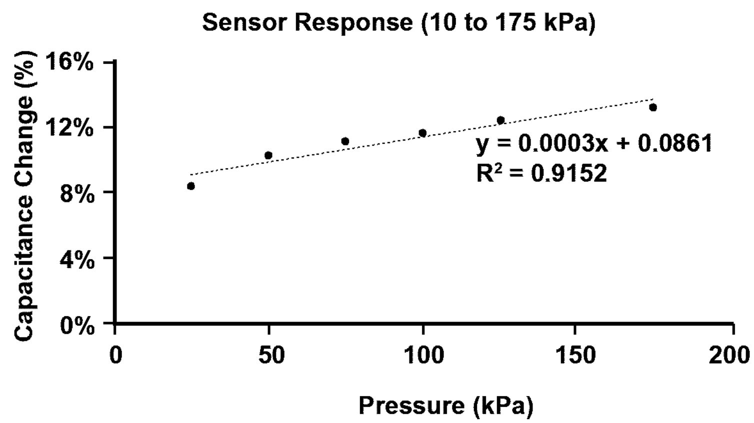

FIG. 6D

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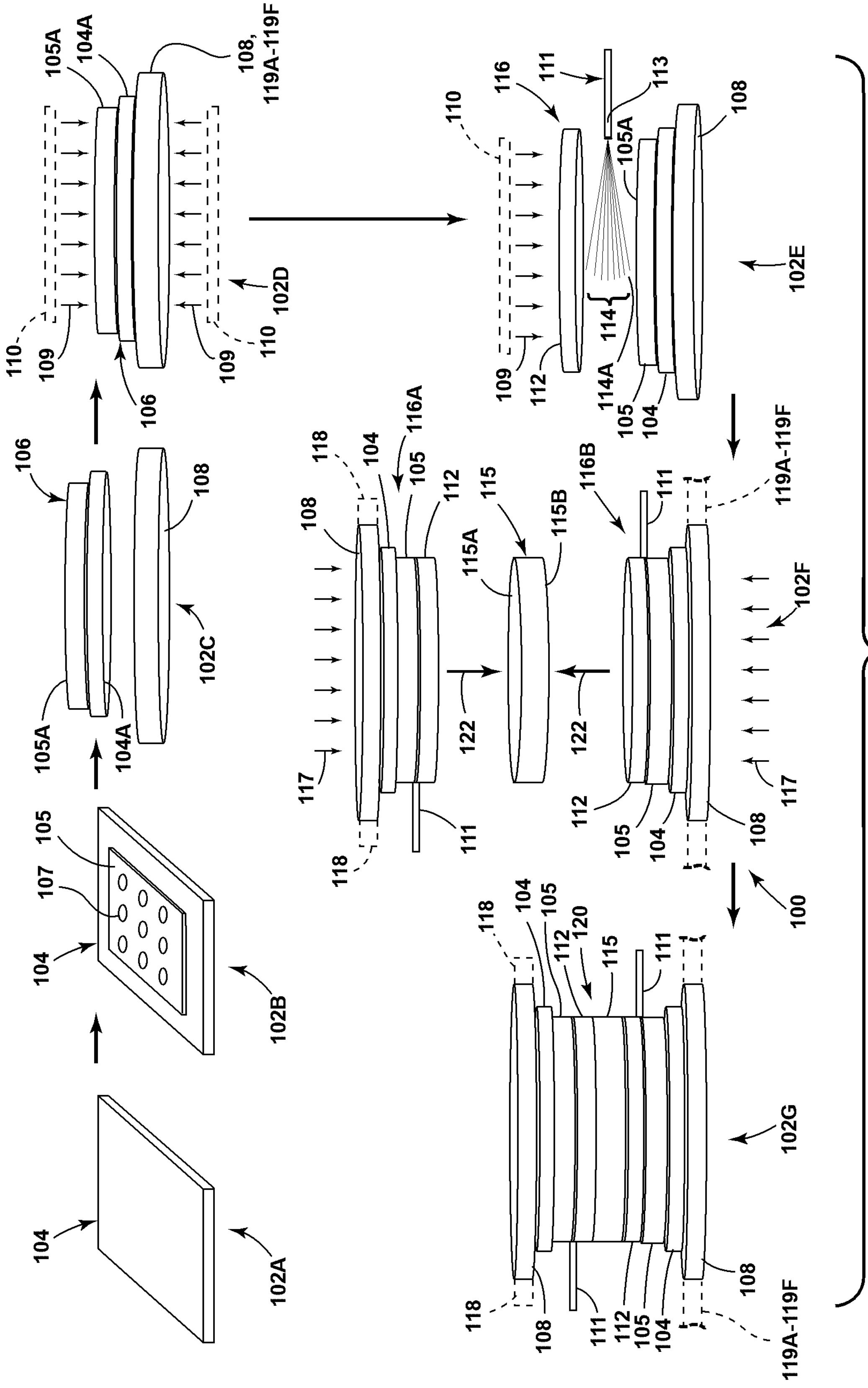
104
102A
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102B
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104A
102C
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108
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109
105A
104A
108,
119A-119F
102D
106
116
111
113
105A
114
114A
112
105
104
102E
118
104
116A
105
112
115
115A
115B
116B
111
117
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119A-119F
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120
102G
118
108
111
112
105
104
119A-119F

FIG. 7

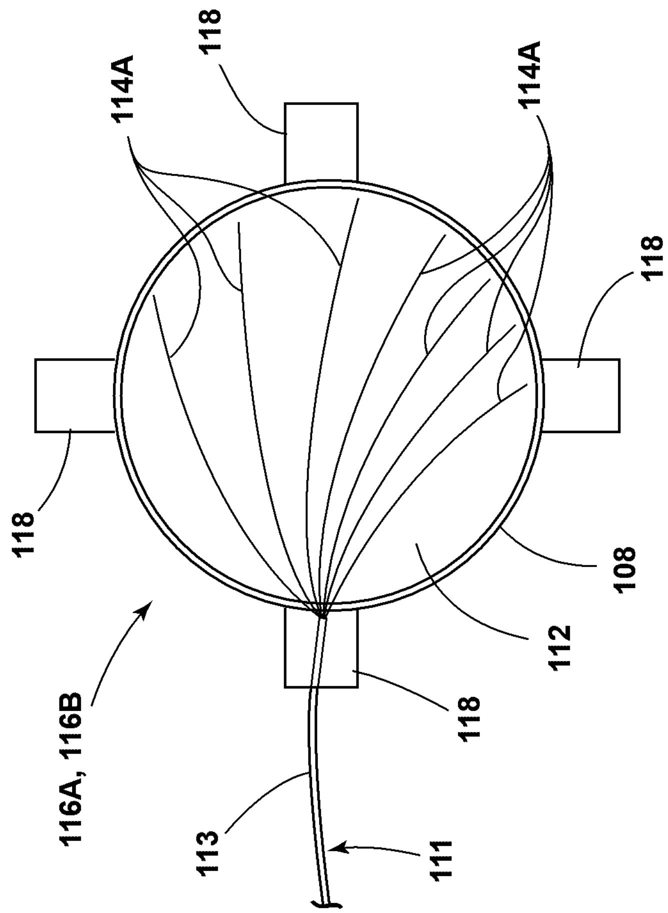

FIG. 8

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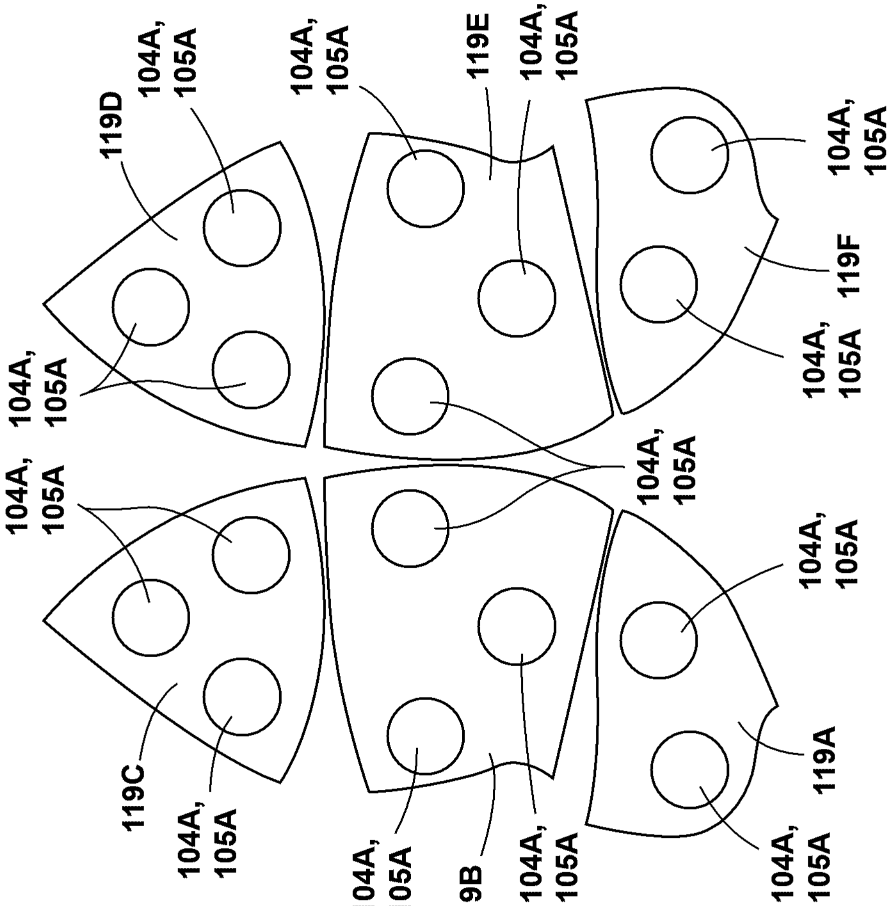

FIG. 9

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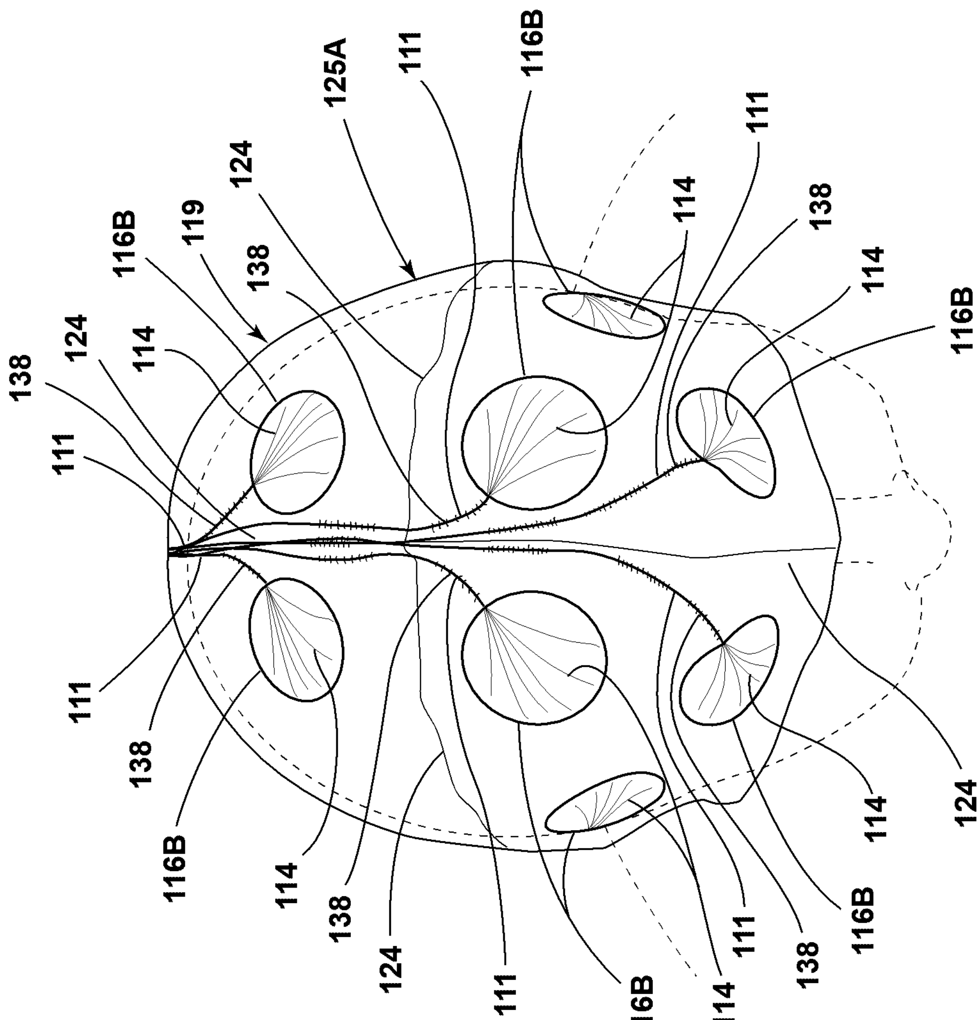

FIG. 10

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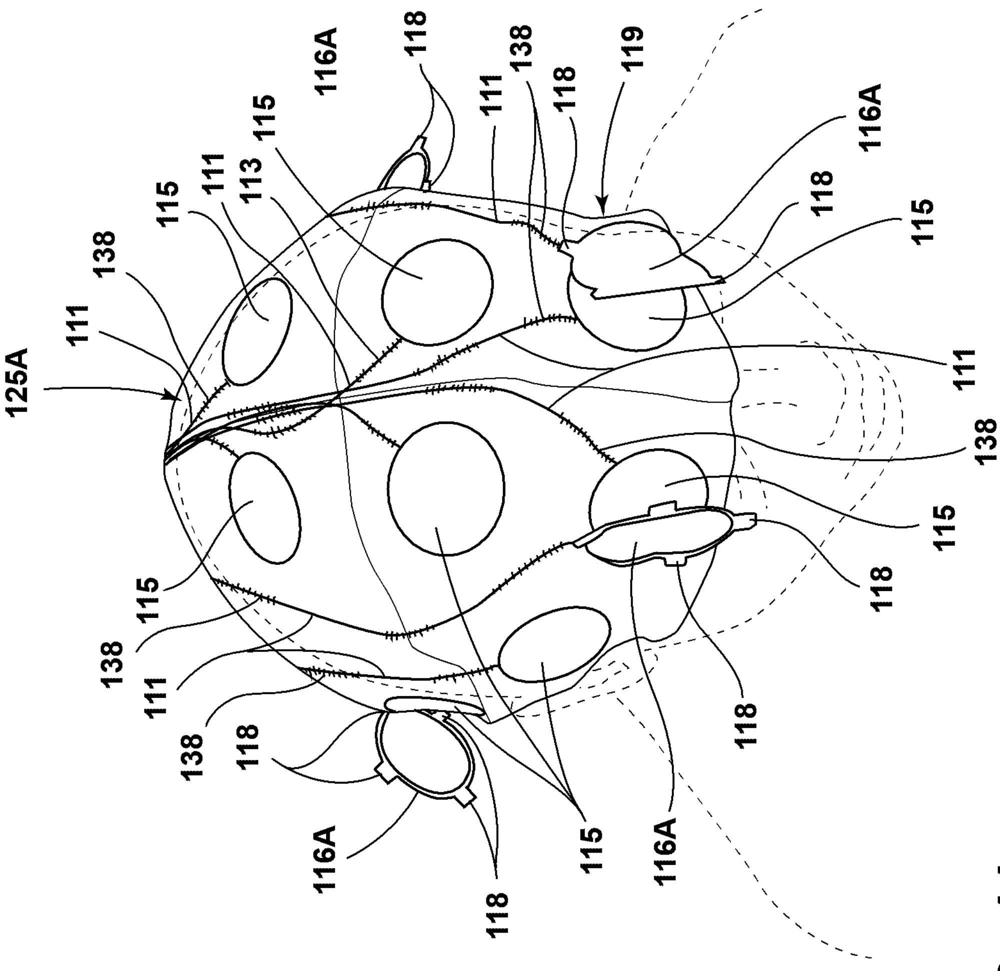
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115
111
113
115
116A
118
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119
116A
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116A
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116A
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FIG. 11

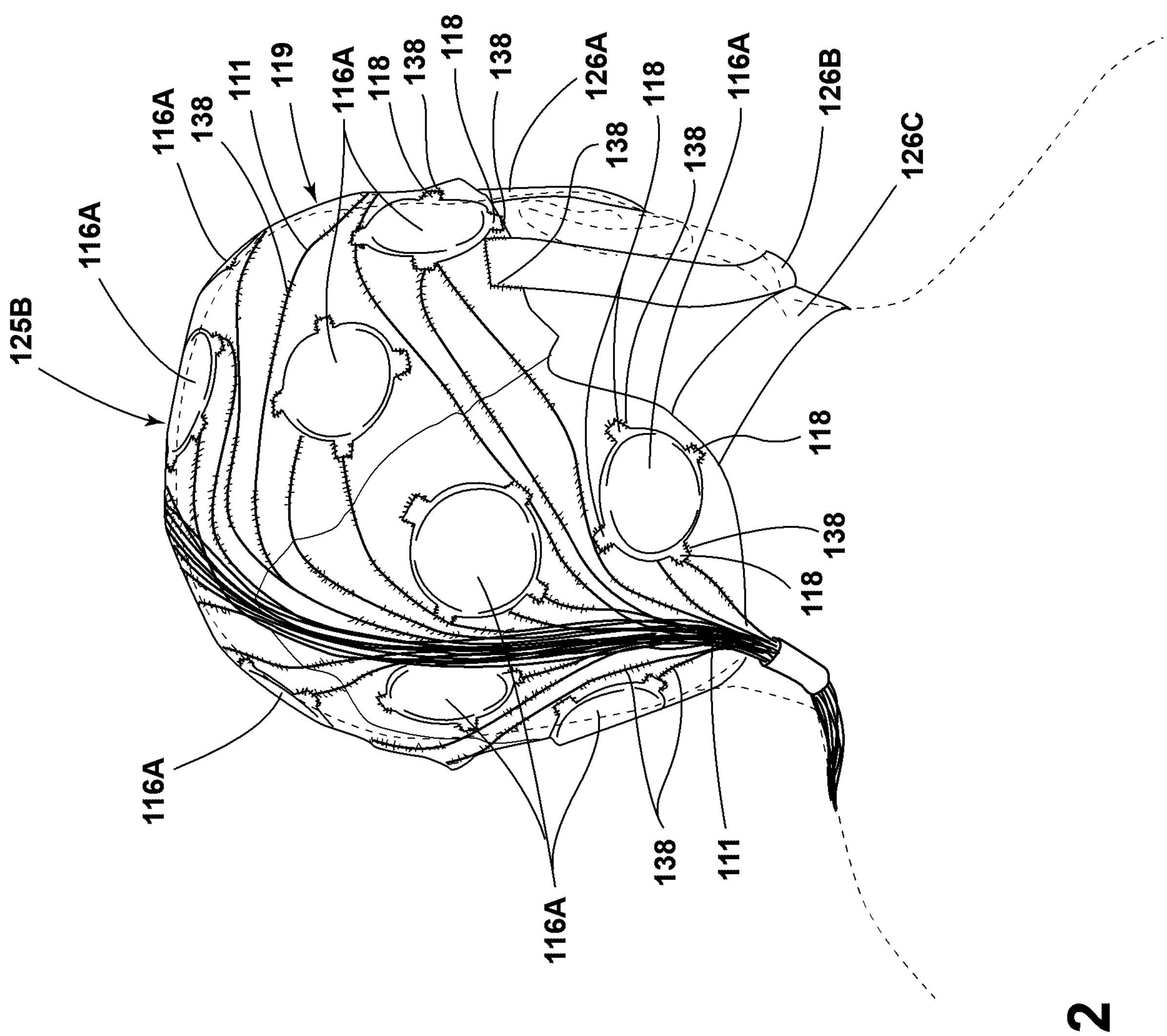


FIG. 12

Date Reçue/Date Received 2020-06-11

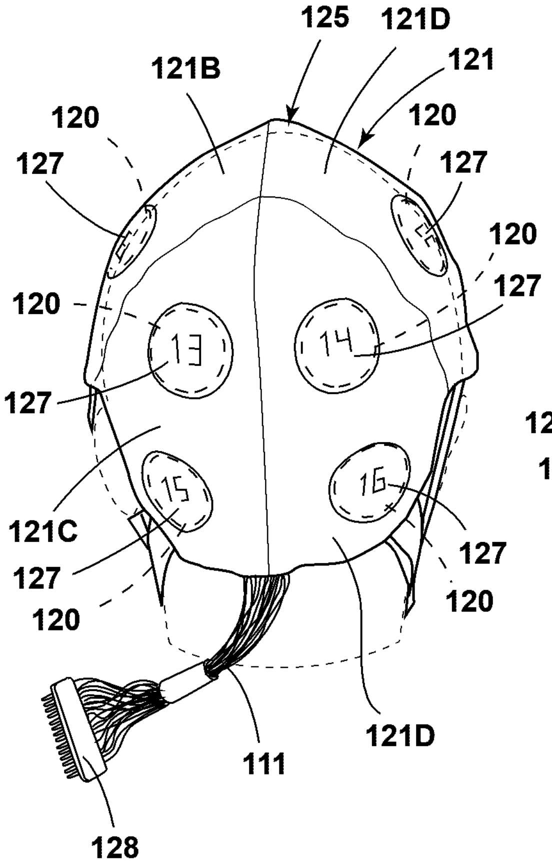


FIG. 13A

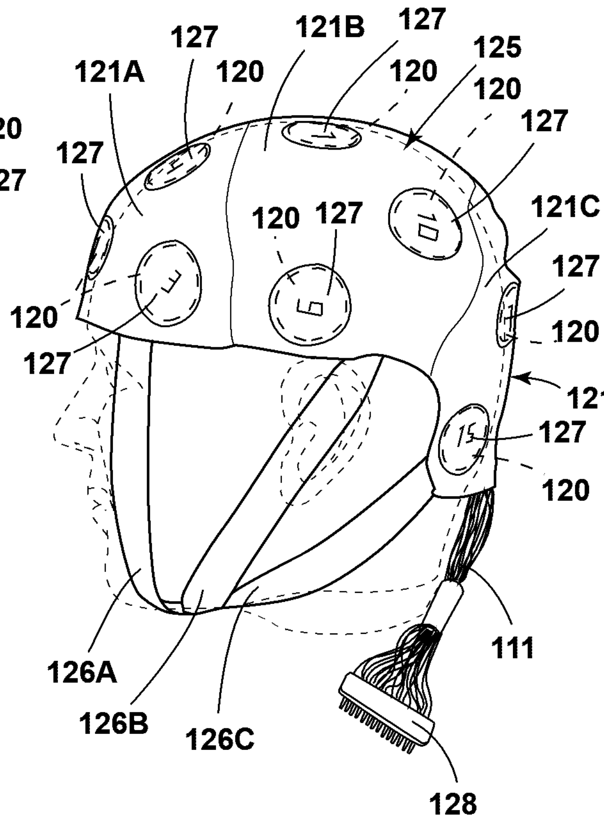


FIG. 13B

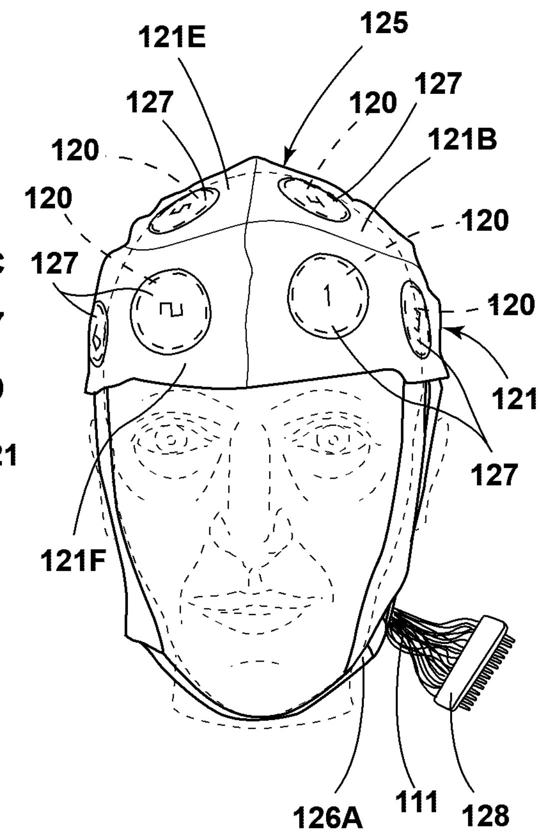


FIG. 13C

Date Reçue/Date Received 2020-06-11

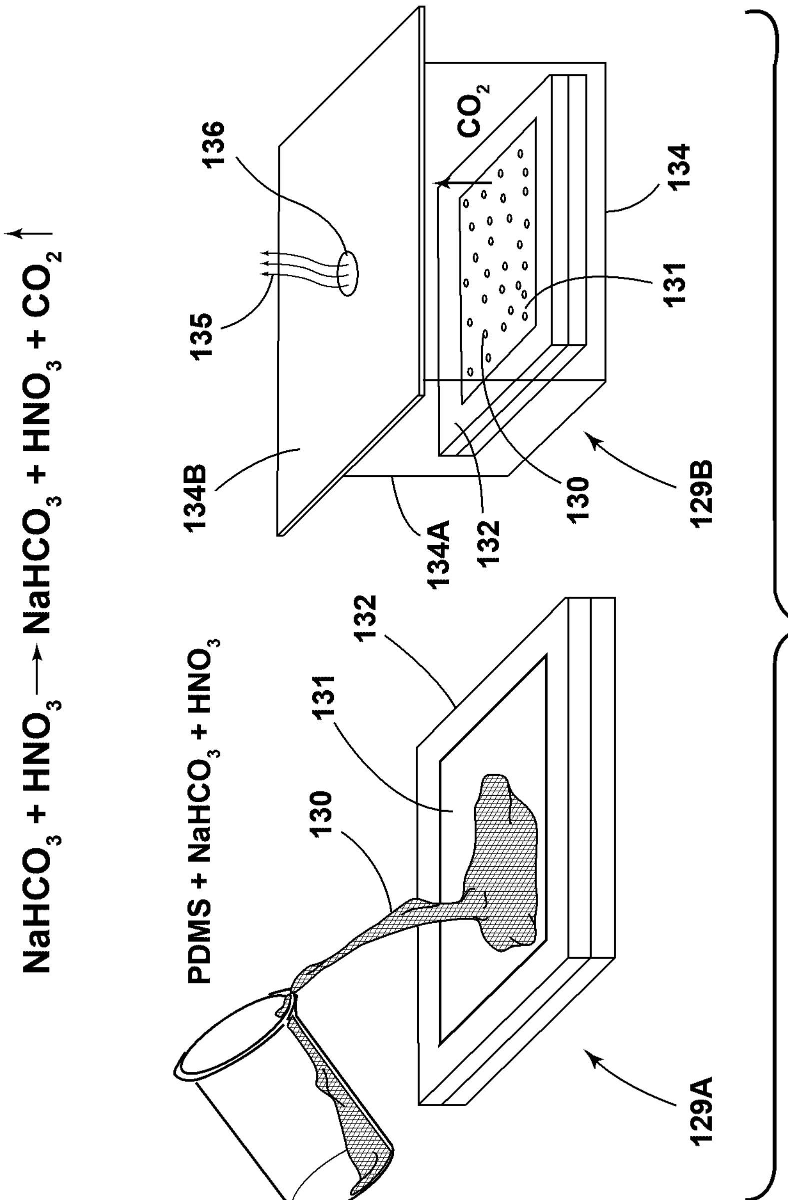

$NaHCO_3 + HNO_3 \rightarrow NaHCO_3 + HNO_3 + CO_2 \uparrow$
$PDMS + NaHCO_3 + HNO_3$
130
131
132
129A
134B
135
136
134A
132
130
129B
131
134
CO_2

FIG. 14

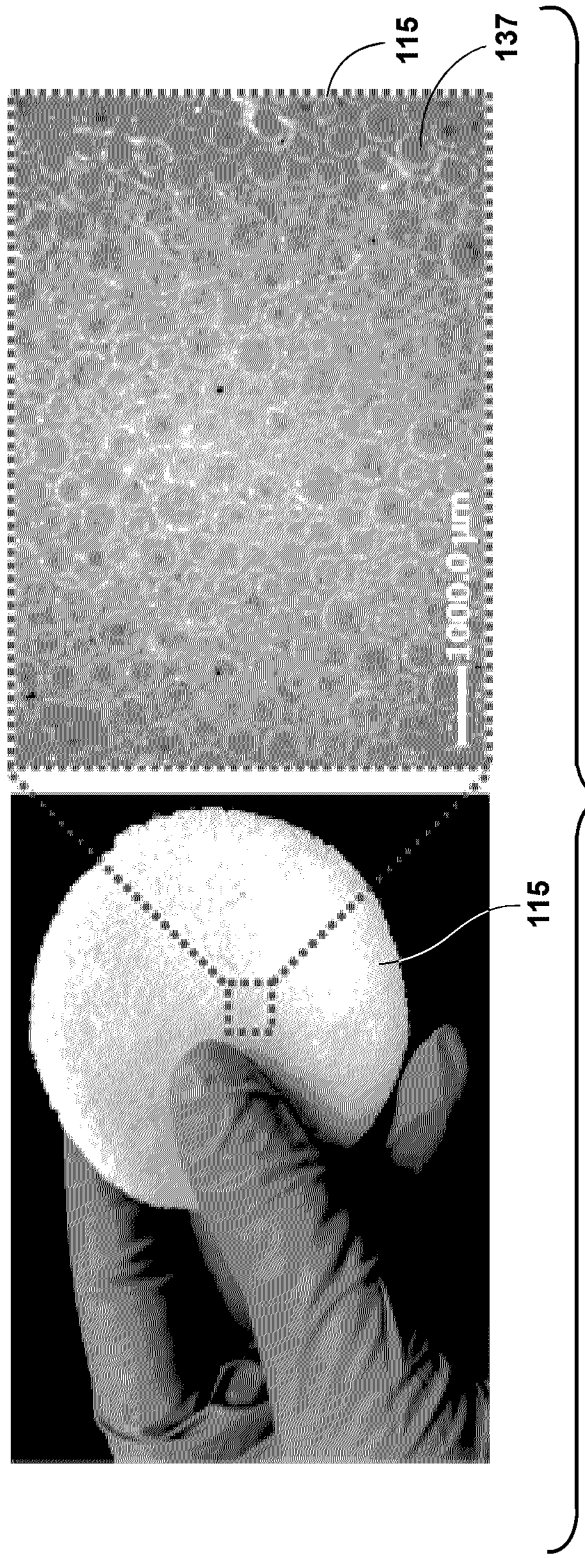


FIG. 15

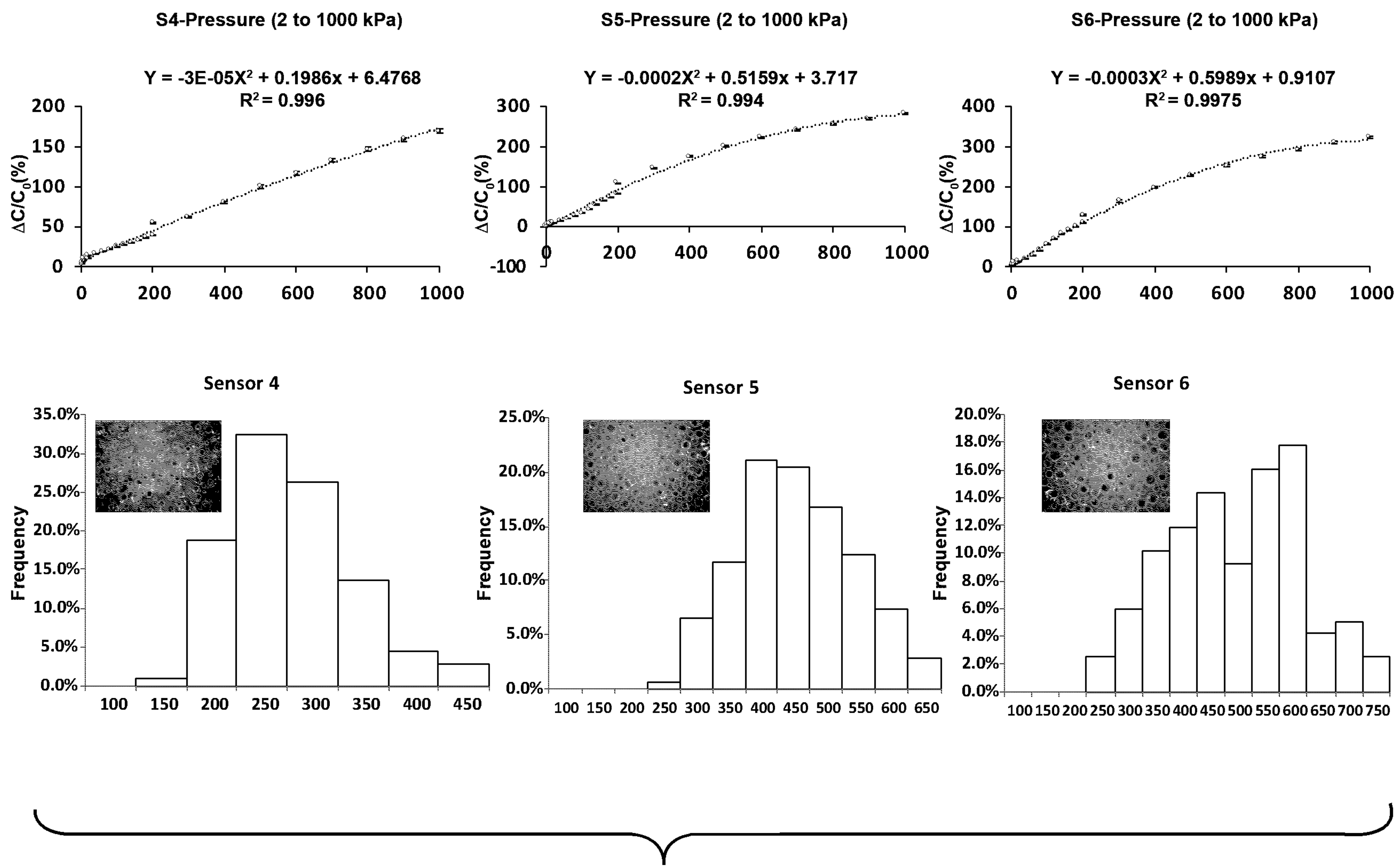


FIG. 16

Date Reçue/Date Received 2020-06-11

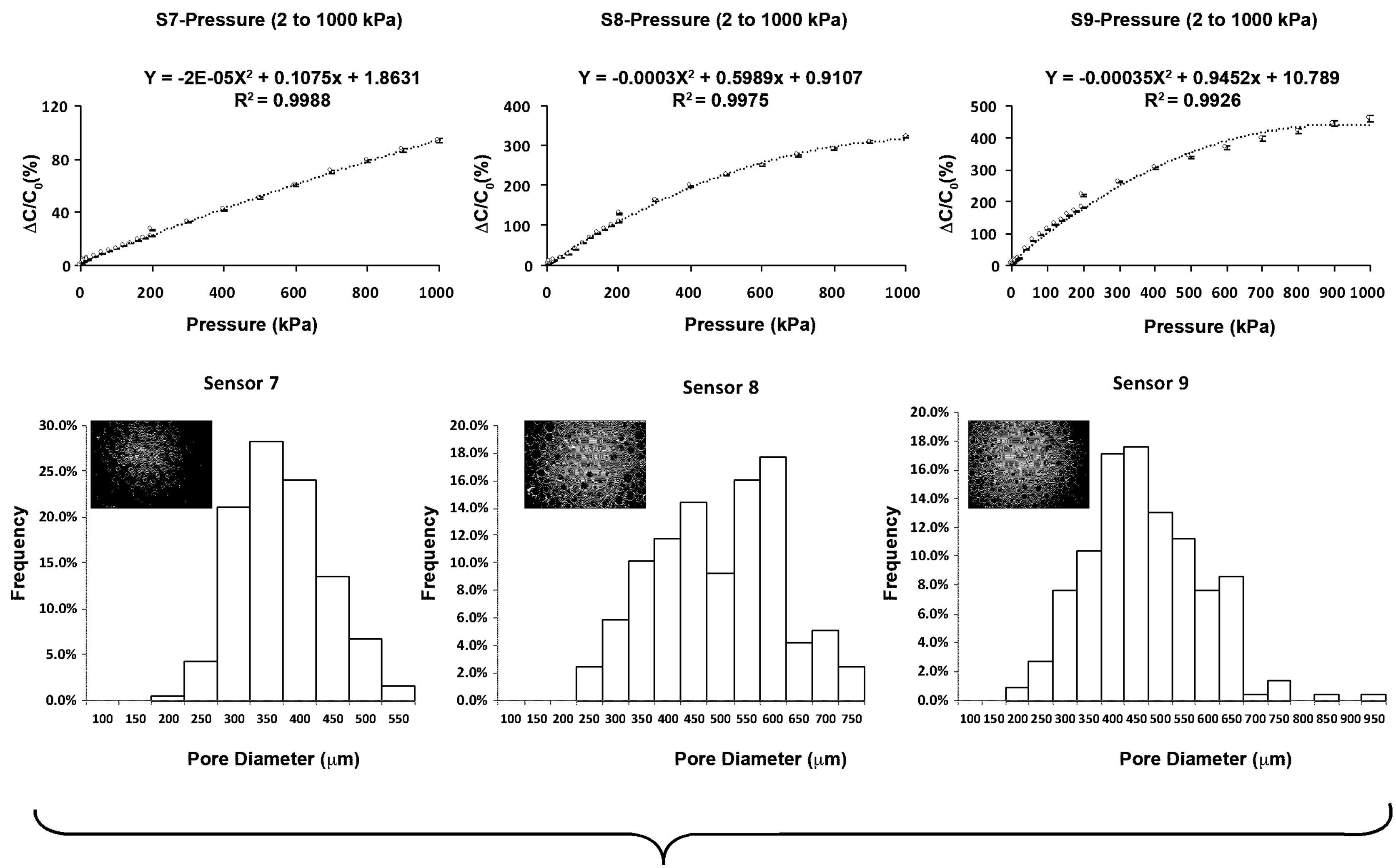


FIG. 17

Date Reçue/Date Received 2020-06-11

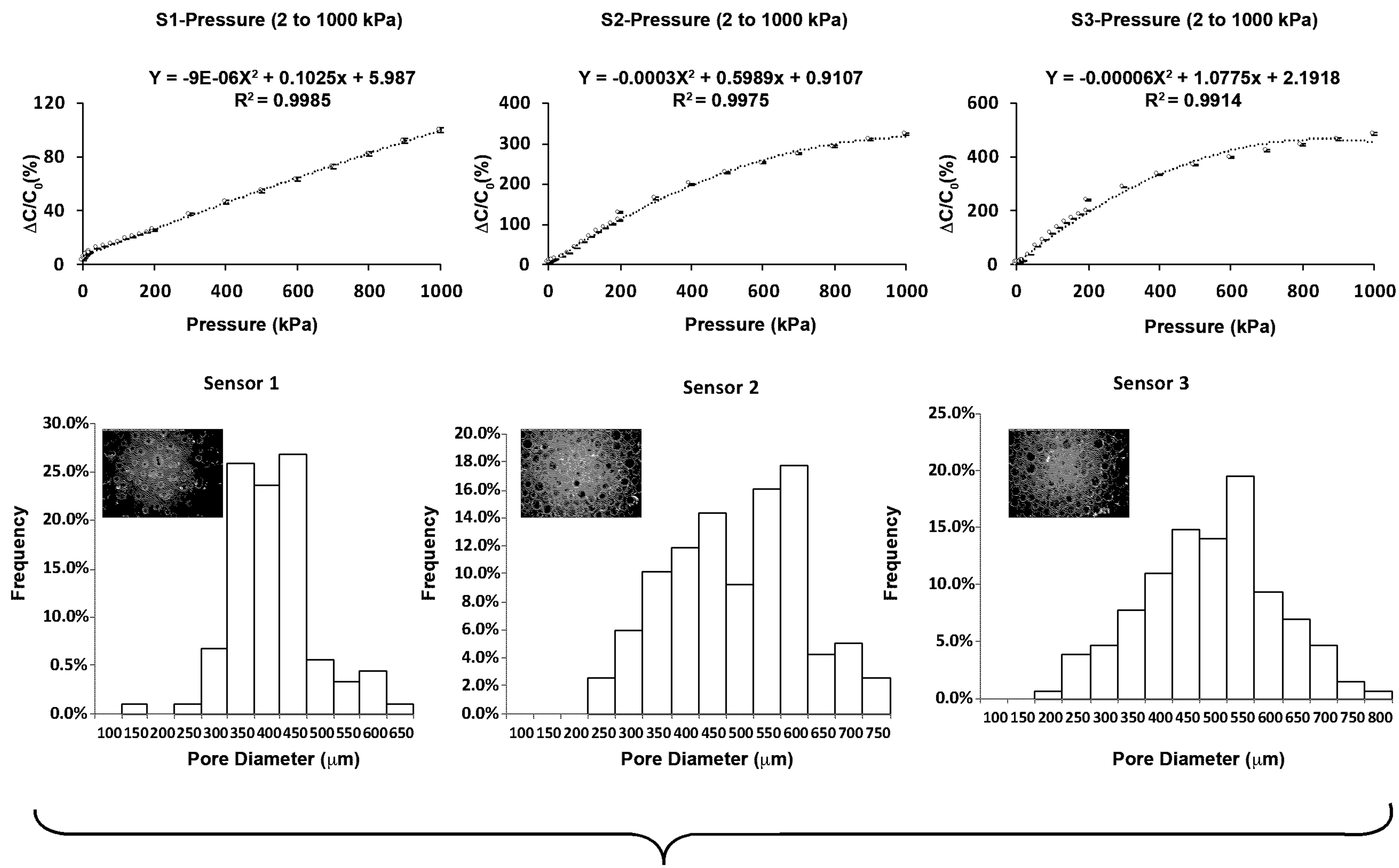
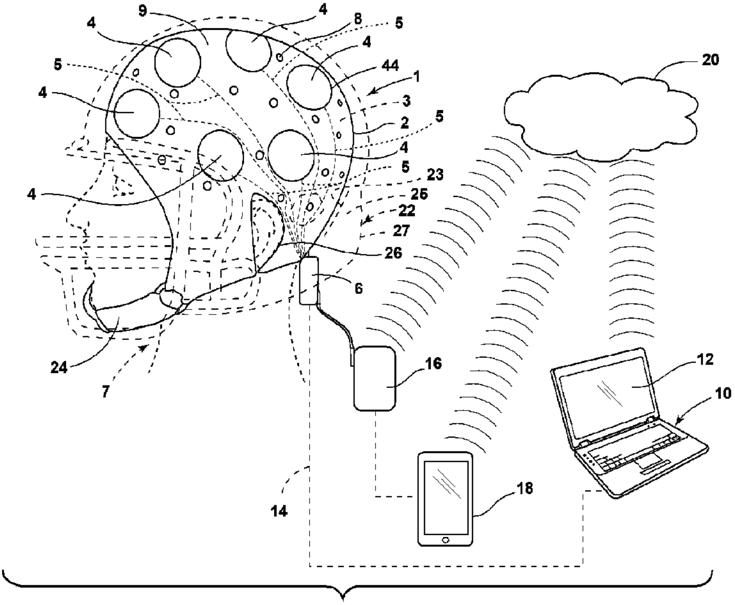


FIG. 18

Date Reçue/Date Received 2020-06-11



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