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(54) **NEURAL SLEEVE FOR NEUROMUSCULAR STIMULATION, SENSING AND RECORDING**

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(73) Assignee: **Battelle Memorial Institute**

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Publication Classification

(51) **Int. Cl.**

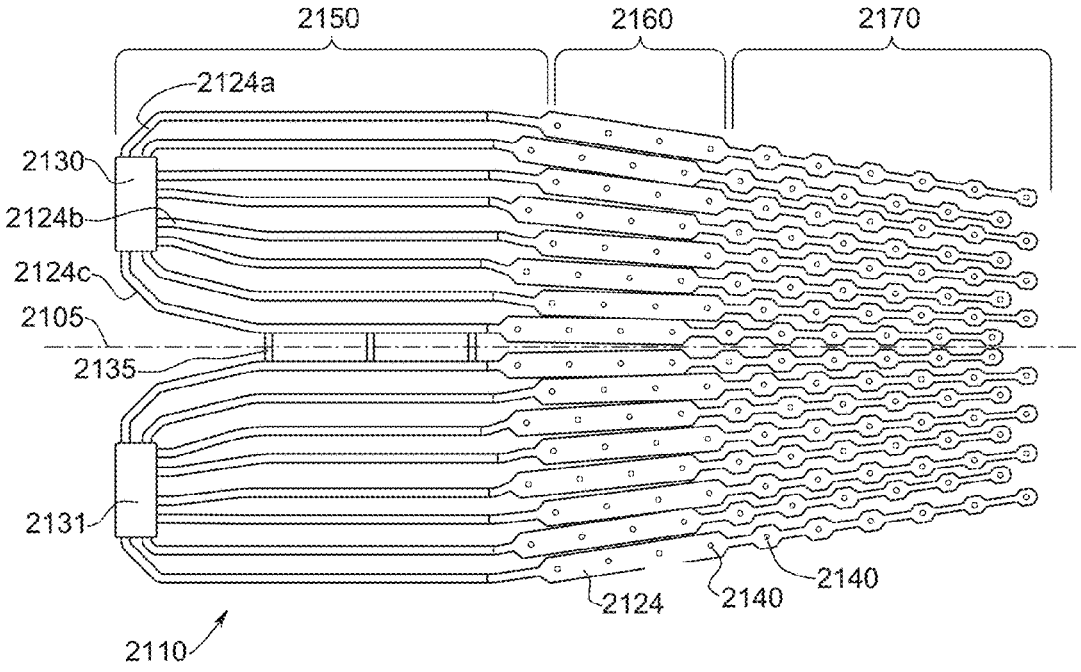
A61N 1/04	(2006.01)
G06F 3/01	(2006.01)
A61N 1/36	(2006.01)

(52) **U.S. Cl.**

CPC ***A61N 1/0484*** (2013.01); ***A61N 1/36003*** (2013.01); ***A61N 1/0456*** (2013.01); ***G06F 3/017*** (2013.01)

(57) **ABSTRACT**

The present disclosure relates to neuromuscular stimulation and sensing cuffs. The neuromuscular stimulation cuff has at least two fingers and a plurality of electrodes disposed on each finger. More generally, the neuromuscular stimulation cuff includes an outer, reusable component and an inner, disposable component. One or more electrodes are housed within the reusable component. The neuromuscular stimulation cuff may be produced by providing an insulating substrate layer, forming a conductive circuit on the substrate layer to form a conductive circuit layer, adhering a cover layer onto the conductive circuit layer to form a flexible circuit, and cutting at least one flexible finger from the flexible circuit. The neuromuscular stimulation cuff employs a flexible multi-electrode design which allows for reanimation of complex muscle movements in a patient, including individual finger movement.



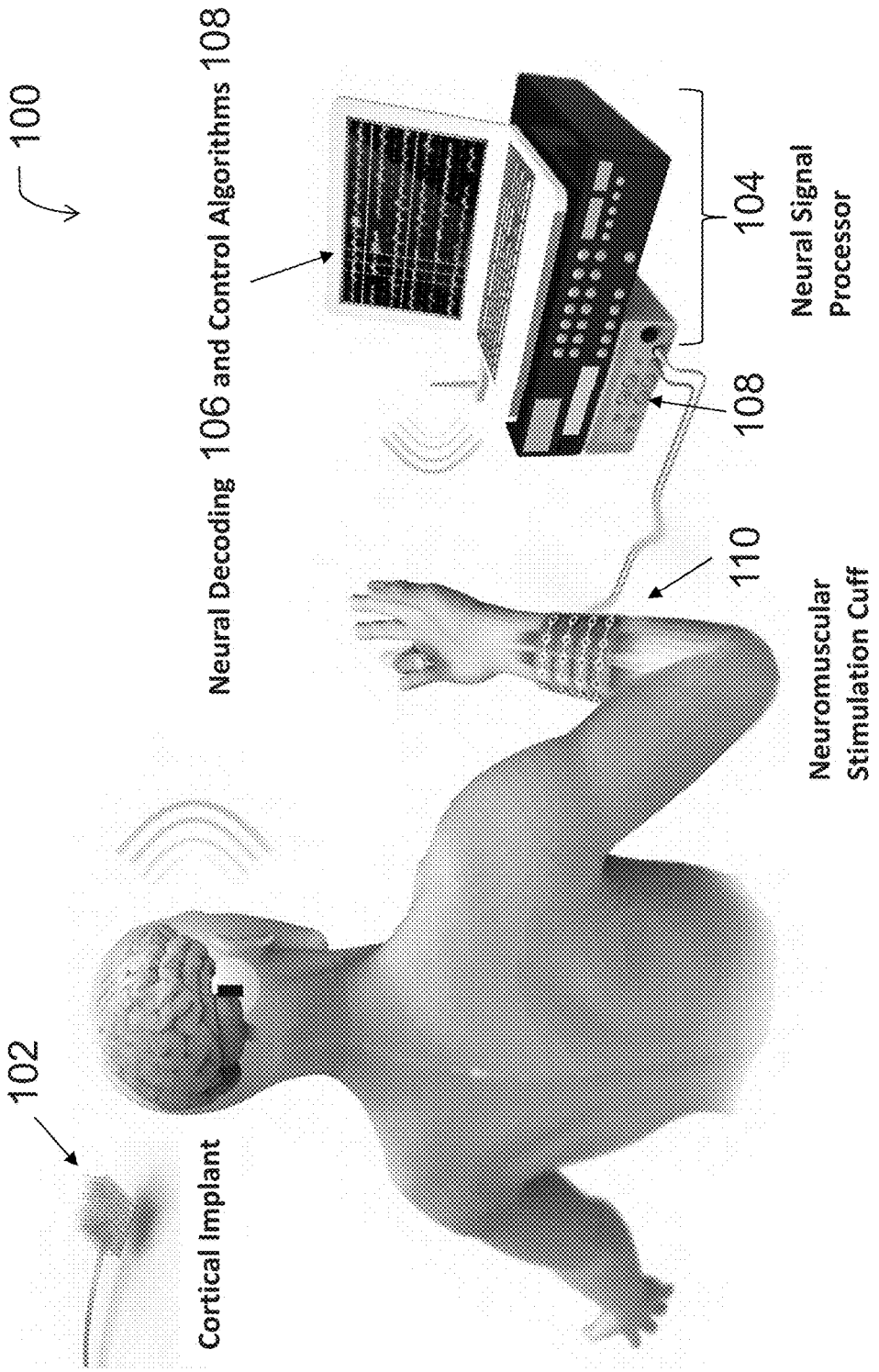

100
102
Cortical Implant
Neural Decoding 106 and Control Algorithms 108
104
Neural Signal Processor
108
110
Neuromuscular Stimulation Cuff

FIG. 1

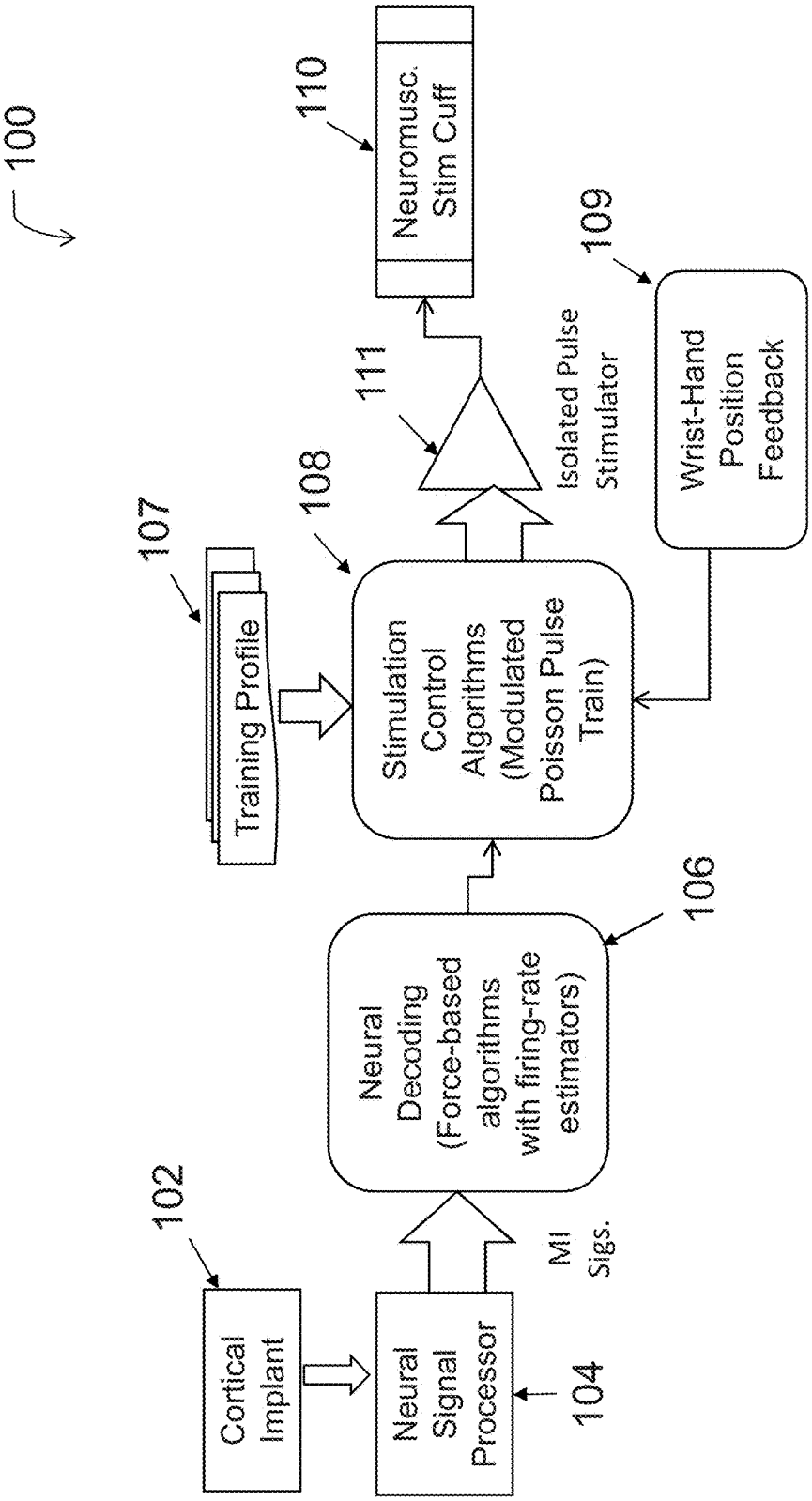

100
110
Neuromusc. Stim Cuff
109
Wrist-Hand Position Feedback
111
Isolated Pulse Stimulator
107
108
Training Profile
Stimulation Control Algorithms (Modulated Poisson Pulse Train)
106
Neural Decoding (Force-based algorithms with firing-rate estimators)
102
Cortical Implant
Neural Signal Processor
104
MI Sigs.

FIG. 2

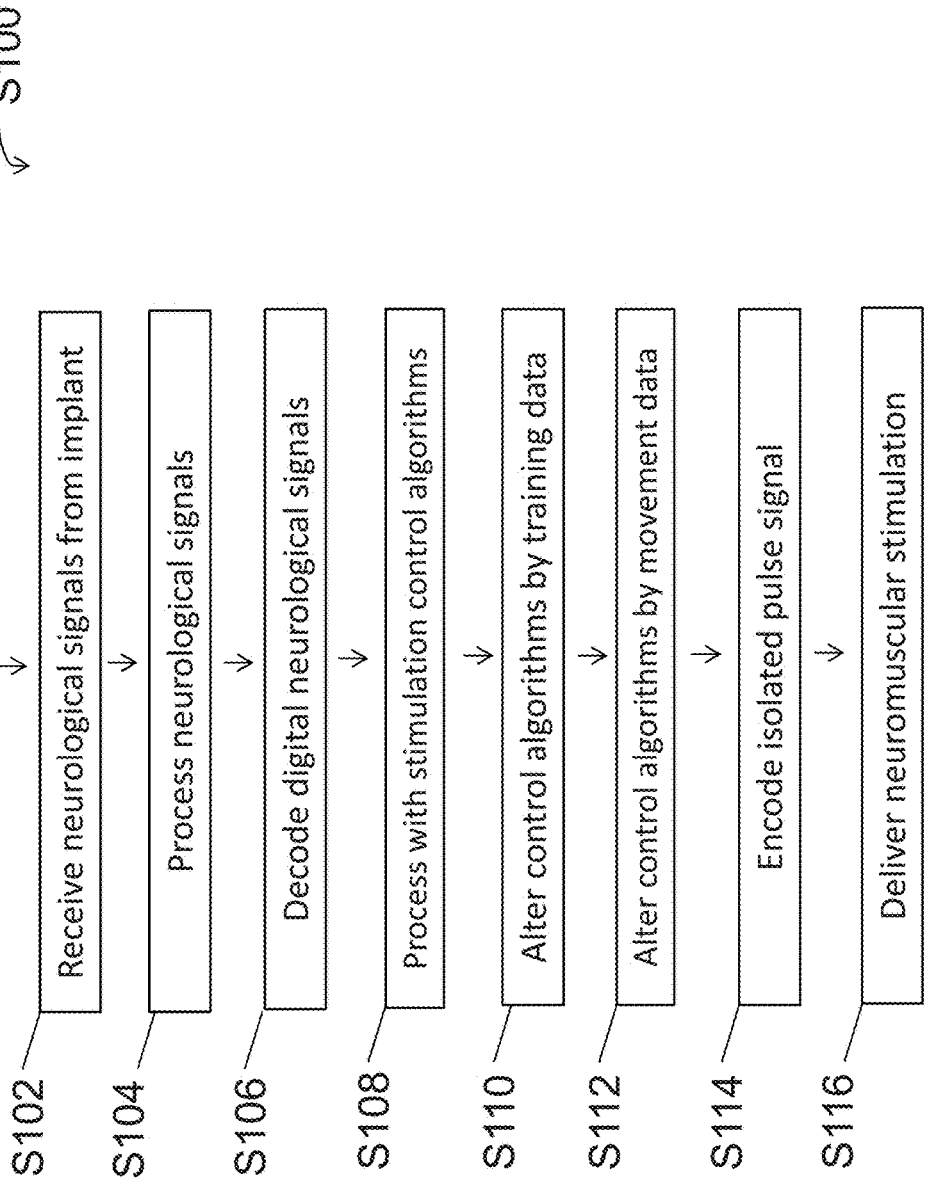

S100
S101
S102
Receive neurological signals from implant
S104
Process neurological signals
S106
Decode digital neurological signals
S108
Process with stimulation control algorithms
S110
Alter control algorithms by training data
S112
Alter control algorithms by movement data
S114
Encode isolated pulse signal
S116
Deliver neuromuscular stimulation

FIG. 3

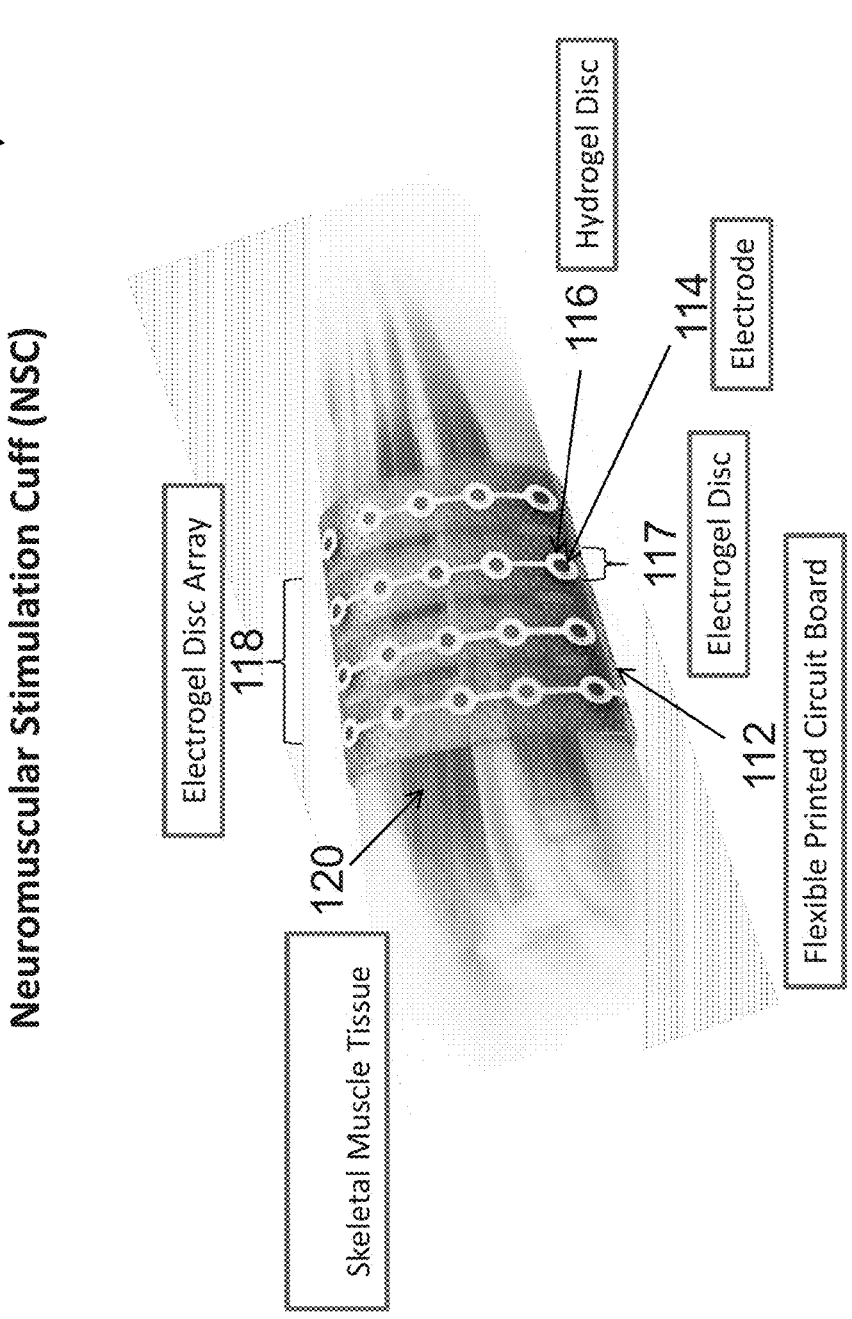

110
Neuromuscular Stimulation Cuff (NSC)
Electrogel Disc Array
118
Hydrogel Disc
116
114
Electrode
117
Electrogel Disc
112
Flexible Printed Circuit Board
120
Skeletal Muscle Tissue

FIG. 4

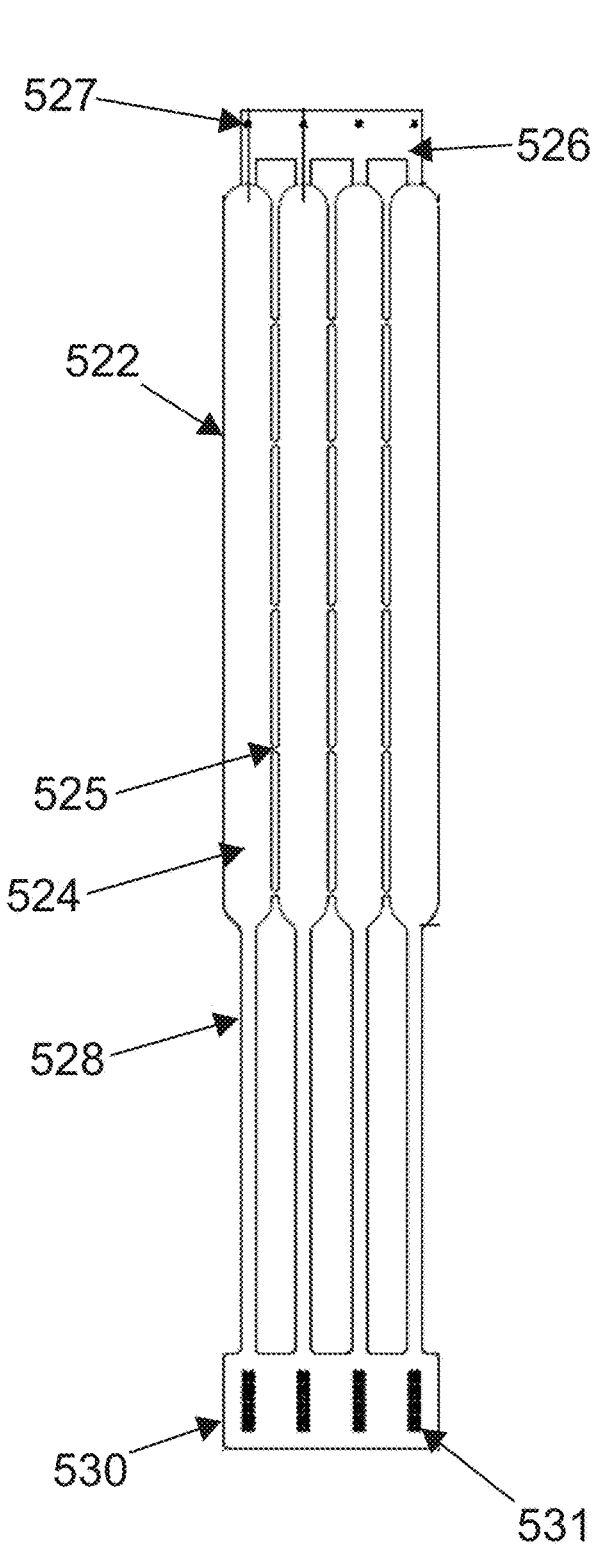


FIG. 5

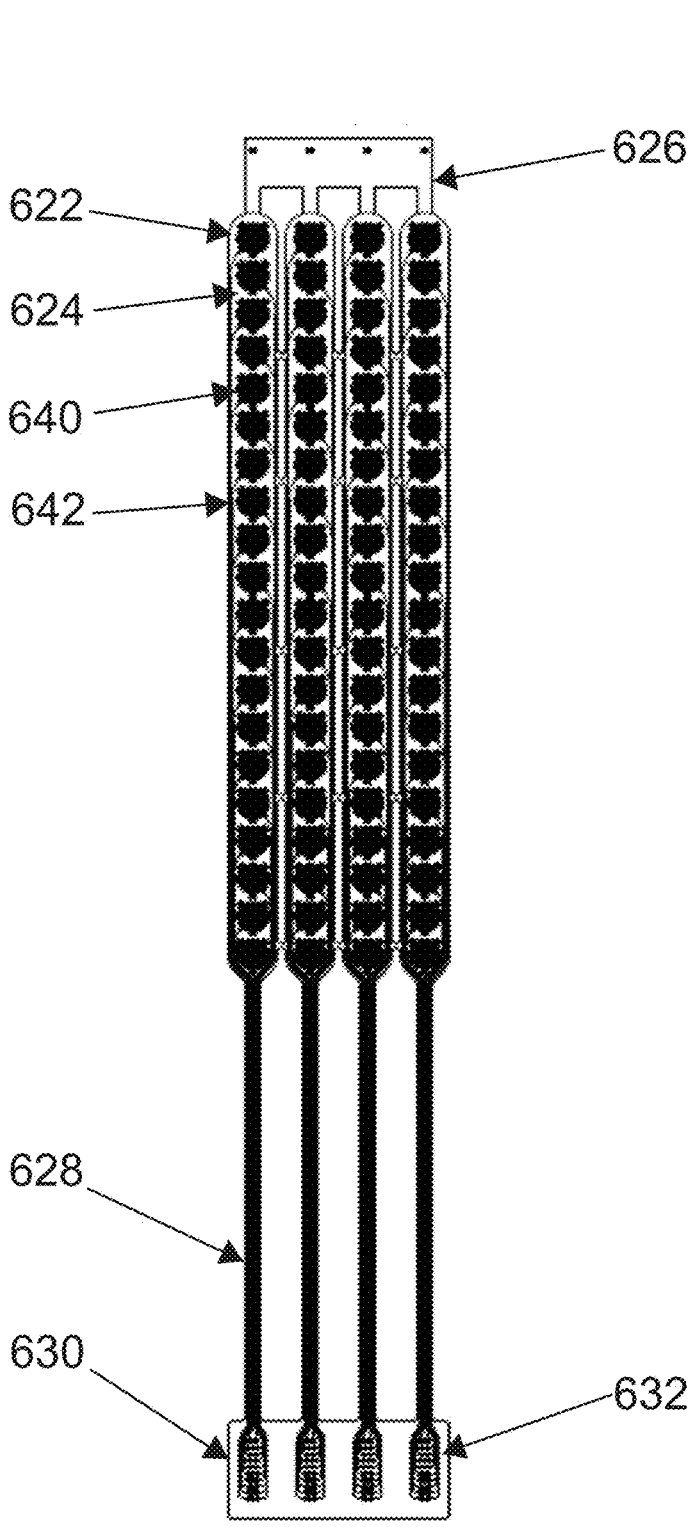


FIG. 6

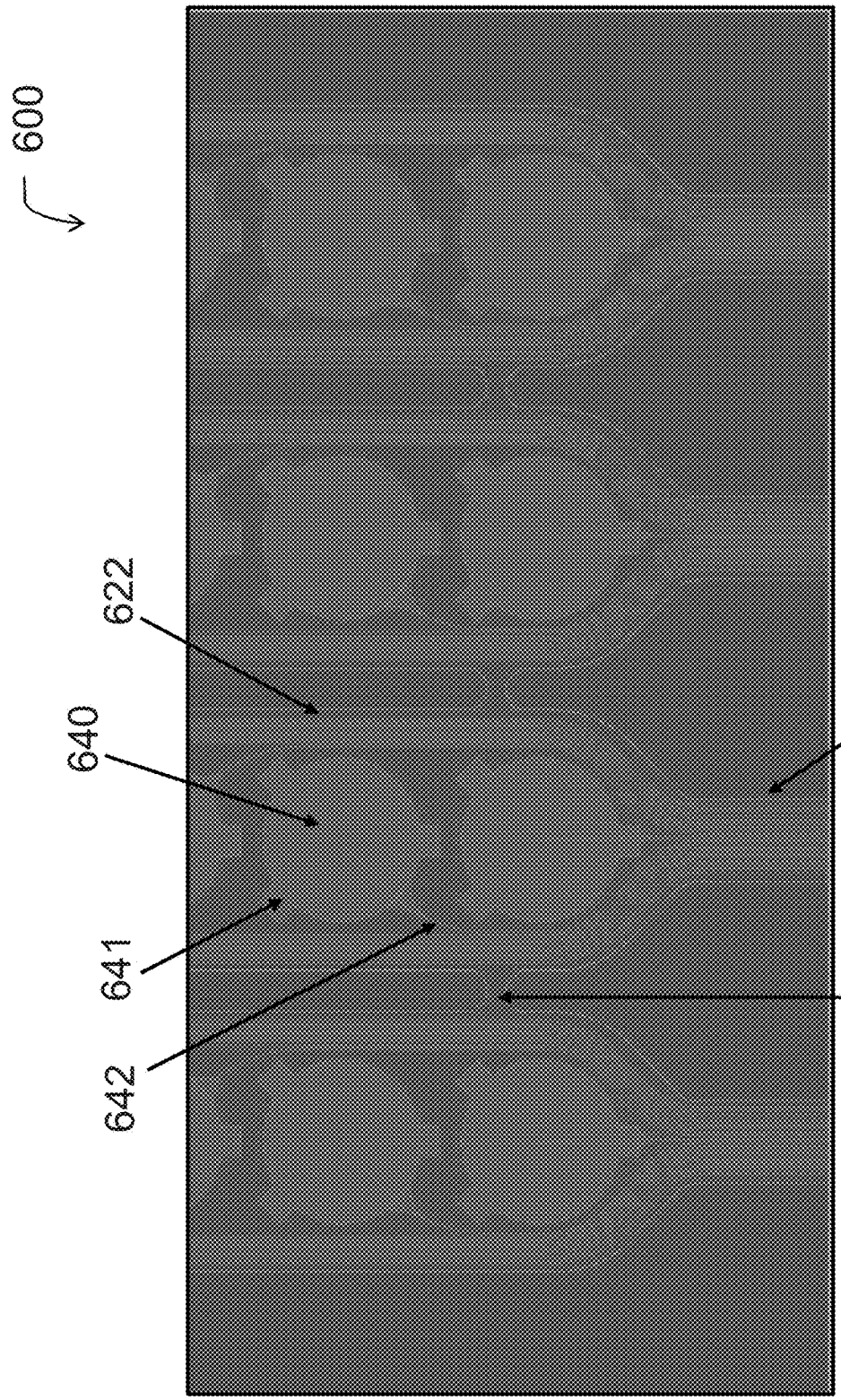


FIG. 7

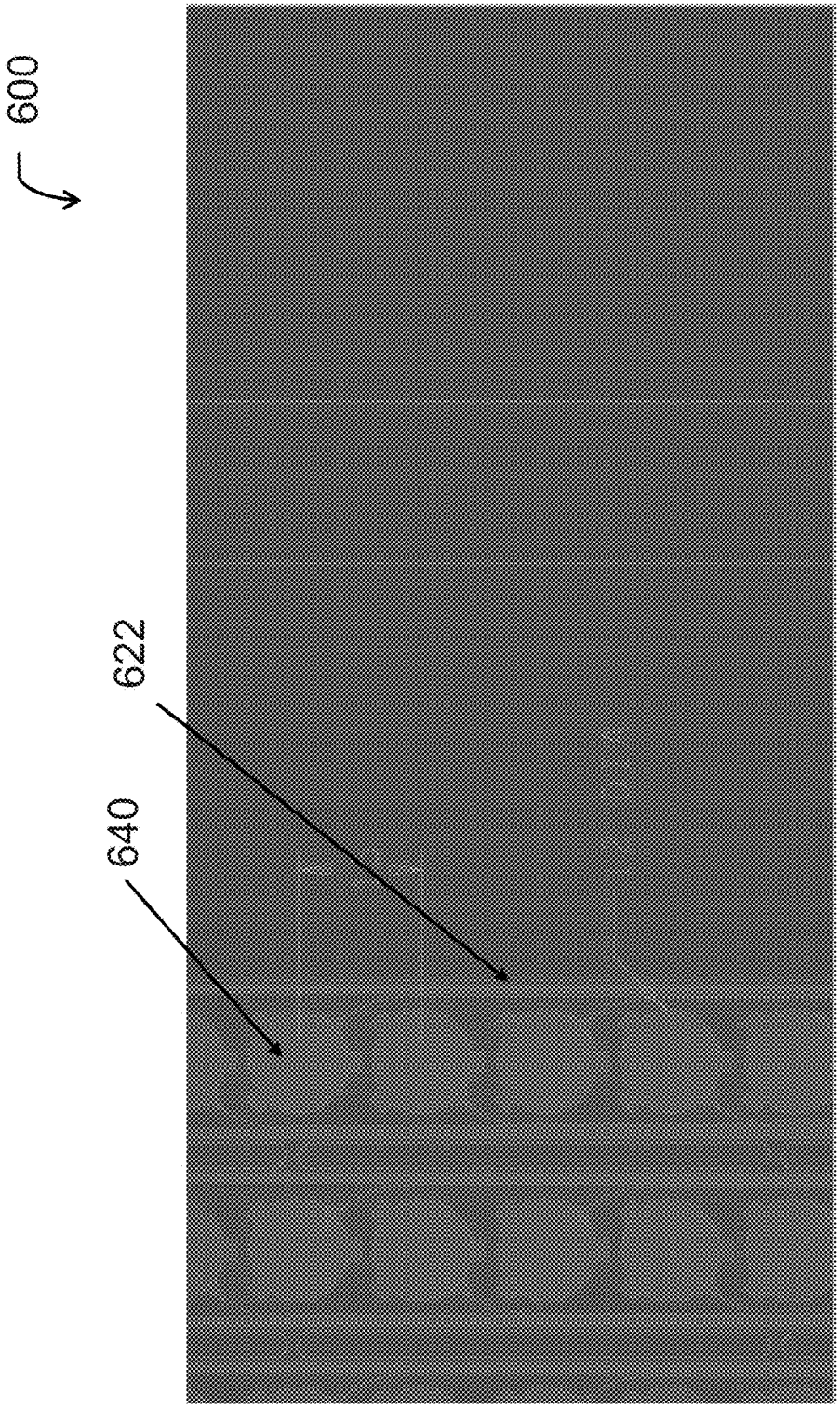


FIG. 8

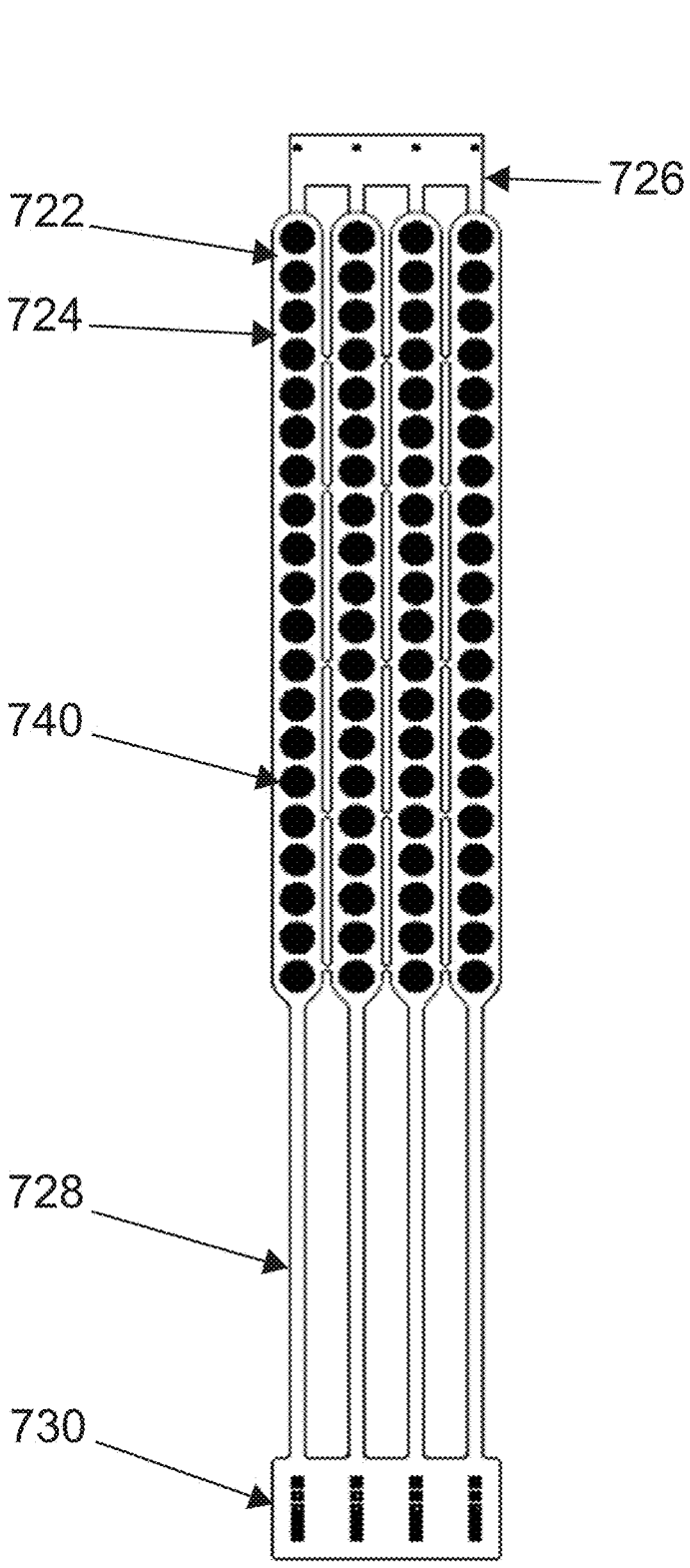


FIG. 9

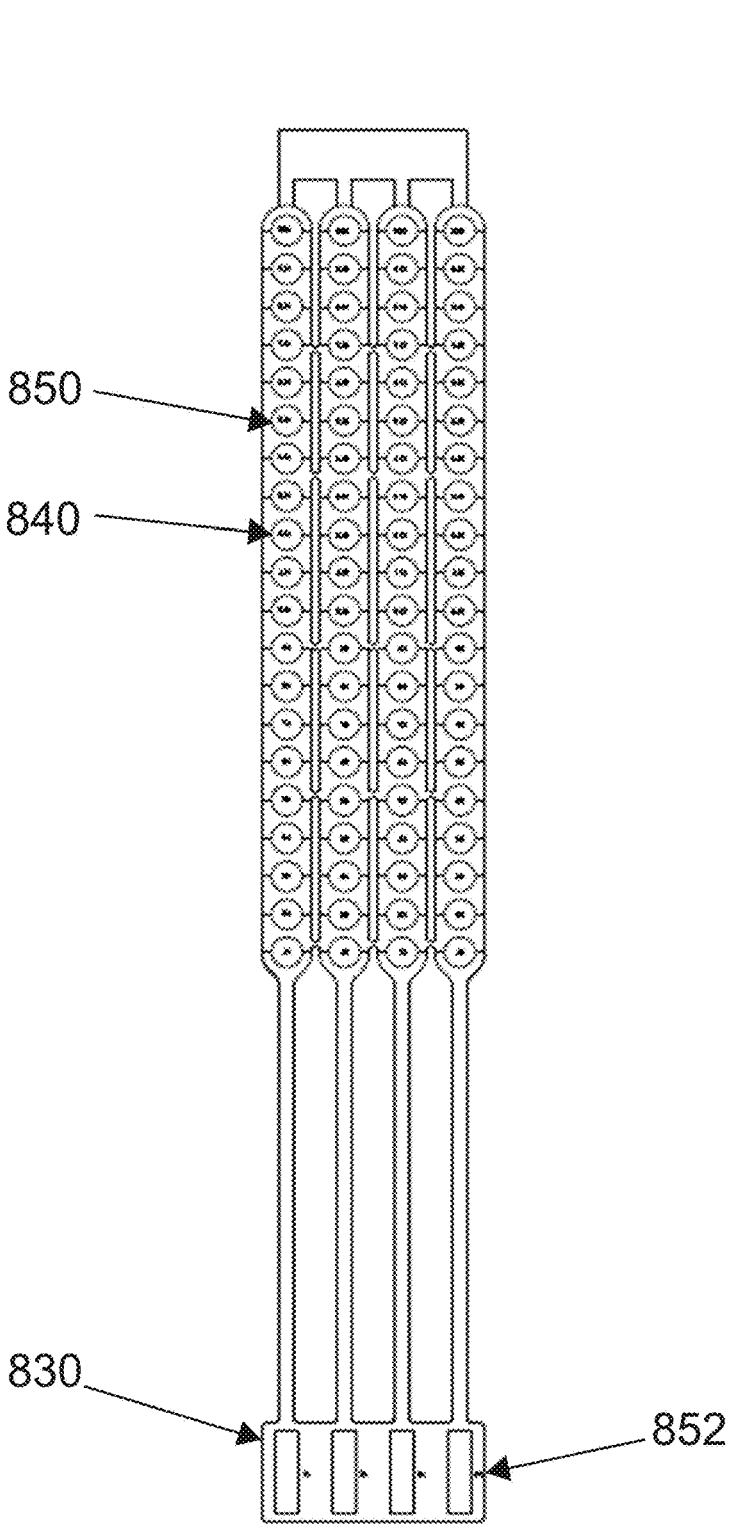


FIG. 10

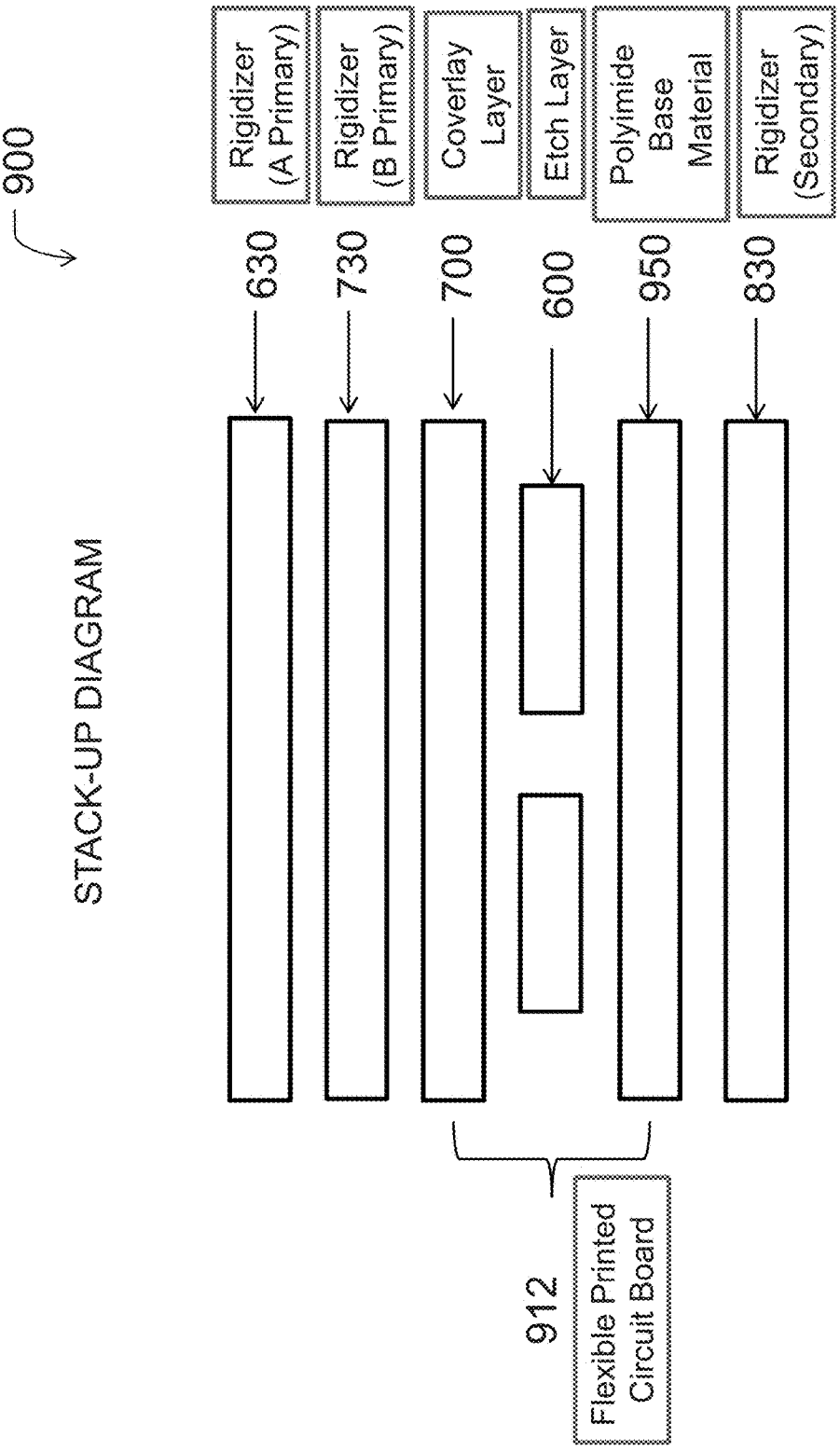

900
STACK-UP DIAGRAM
Rigidizer (A Primary)
Rigidizer (B Primary)
Coverlay Layer
Etch Layer
Polyimide Base Material
Rigidizer (Secondary)
630
730
700
600
950
830
912
Flexible Printed Circuit Board

FIG. 11

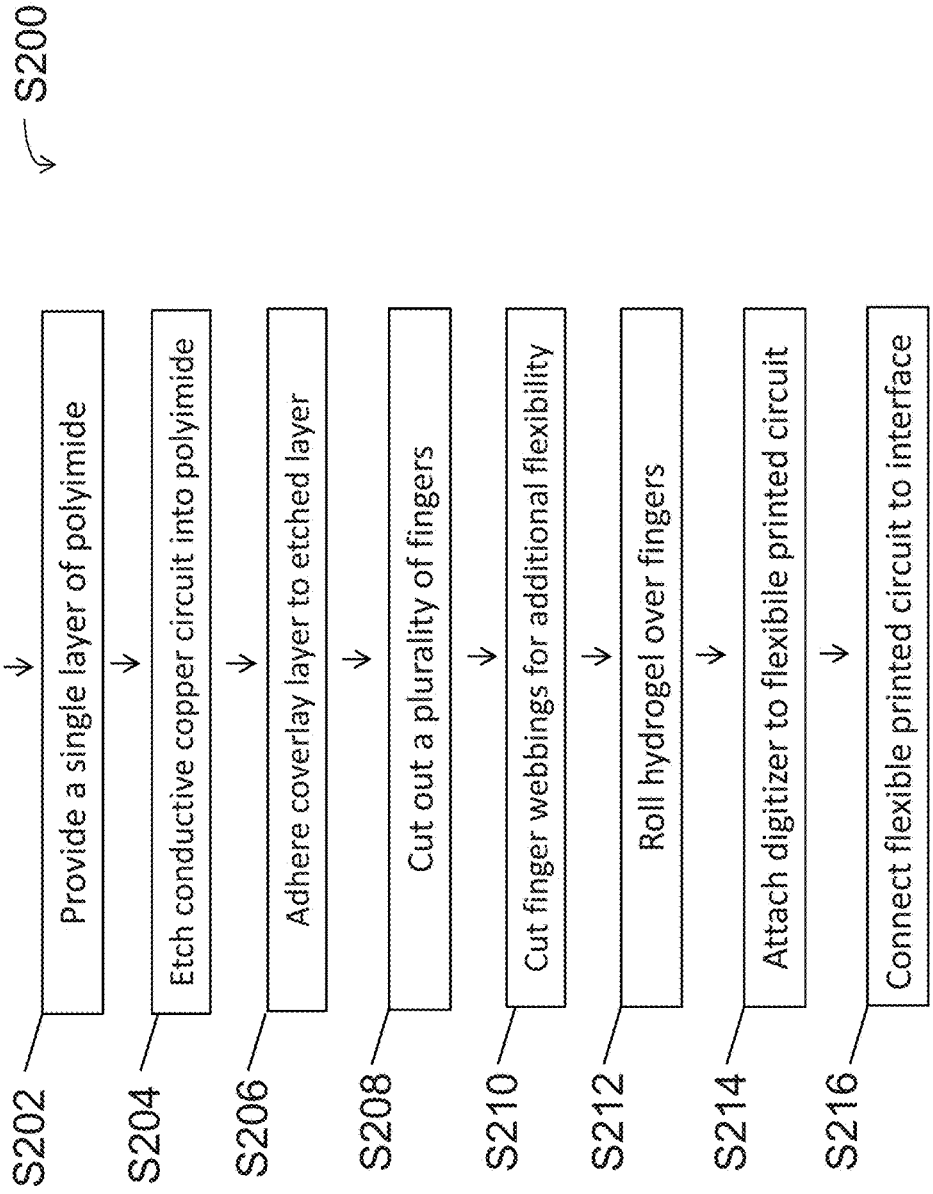

S200
S101
S202
Provide a single layer of polyimide
S204
Etch conductive copper circuit into polyimide
S206
Adhere coverlay layer to etched layer
S208
Cut out a plurality of fingers
S210
Cut finger webbings for additional flexibility
S212
Roll hydrogel over fingers
S214
Attach digitizer to flexibile printed circuit
S216
Connect flexible printed circuit to interface

FIG. 12

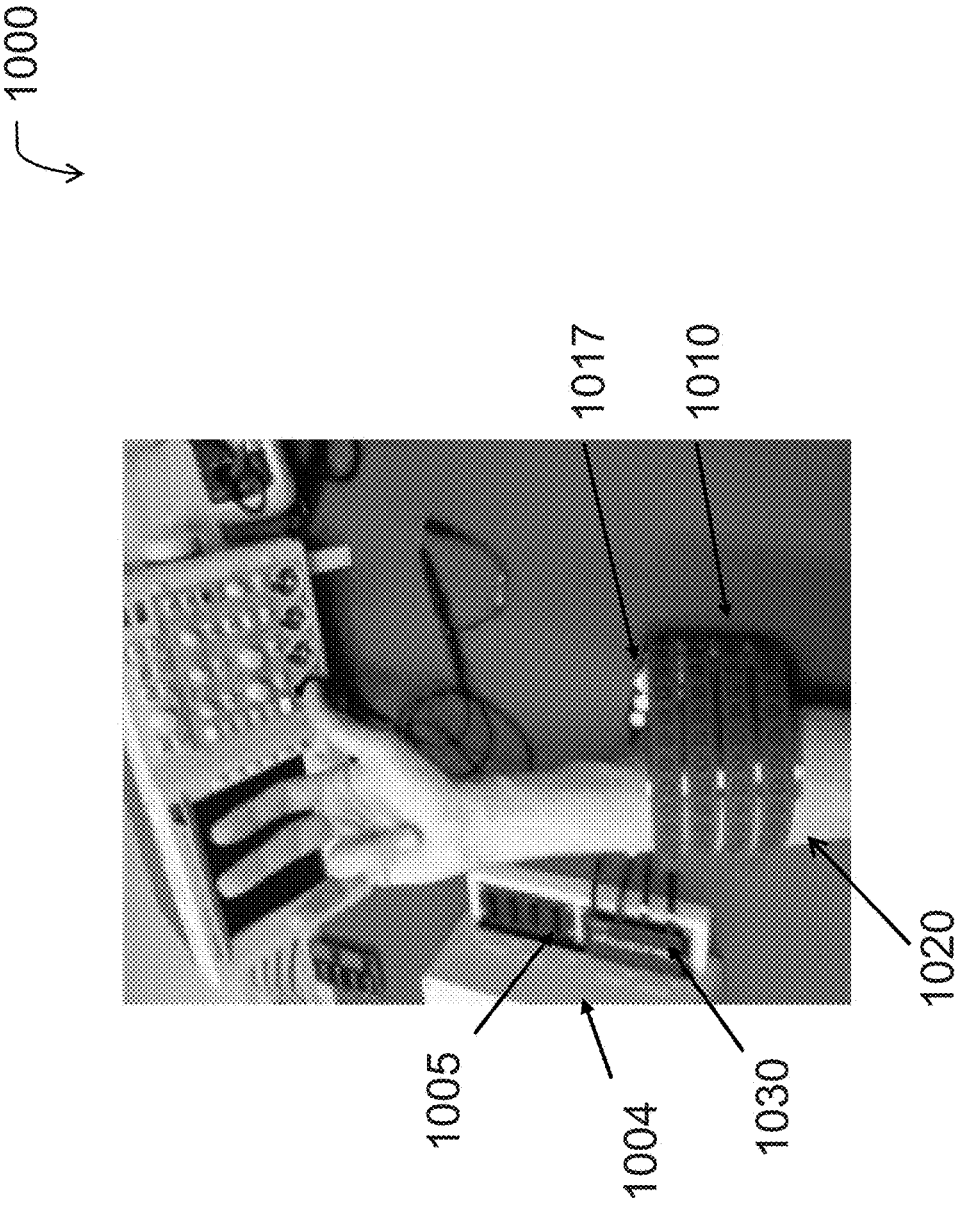


FIG. 13

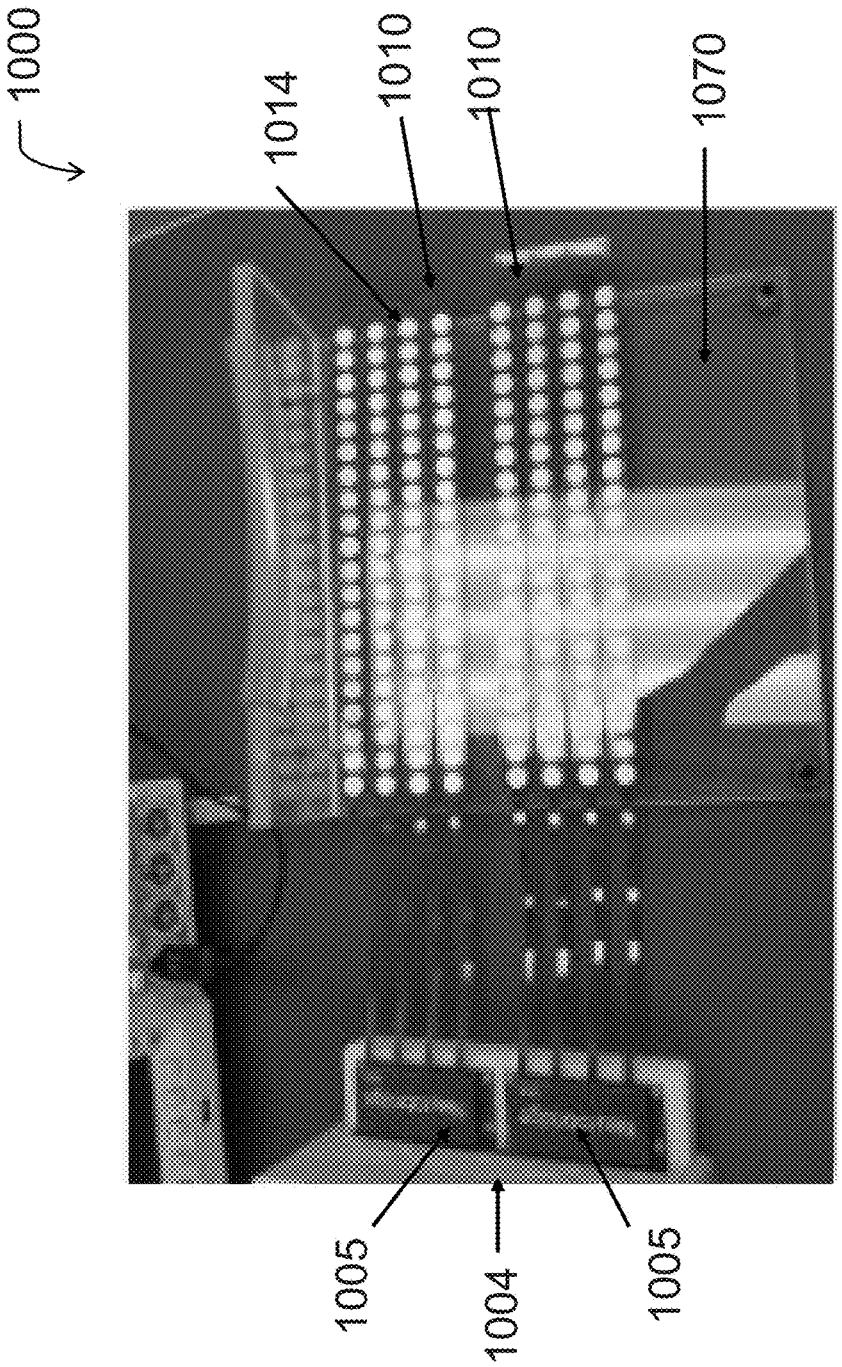


FIG. 14

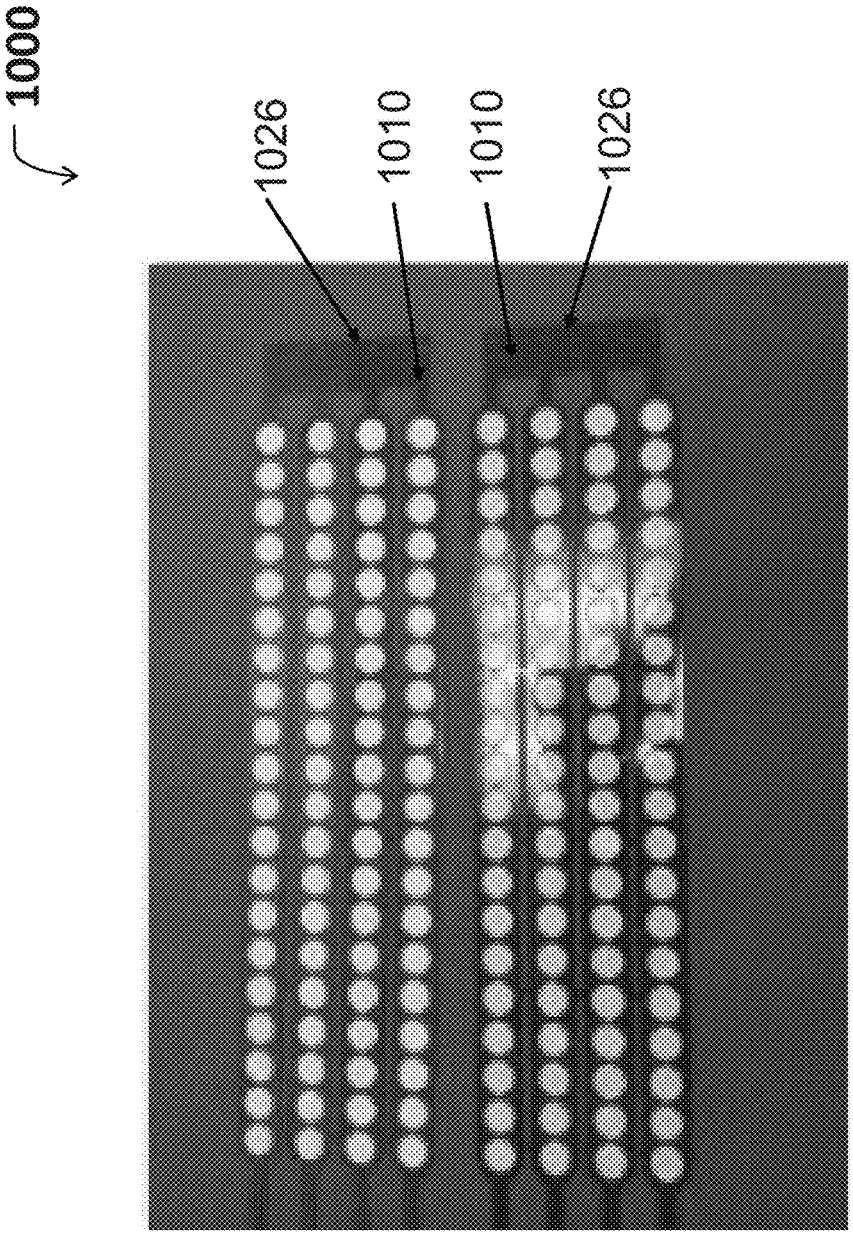


FIG. 15

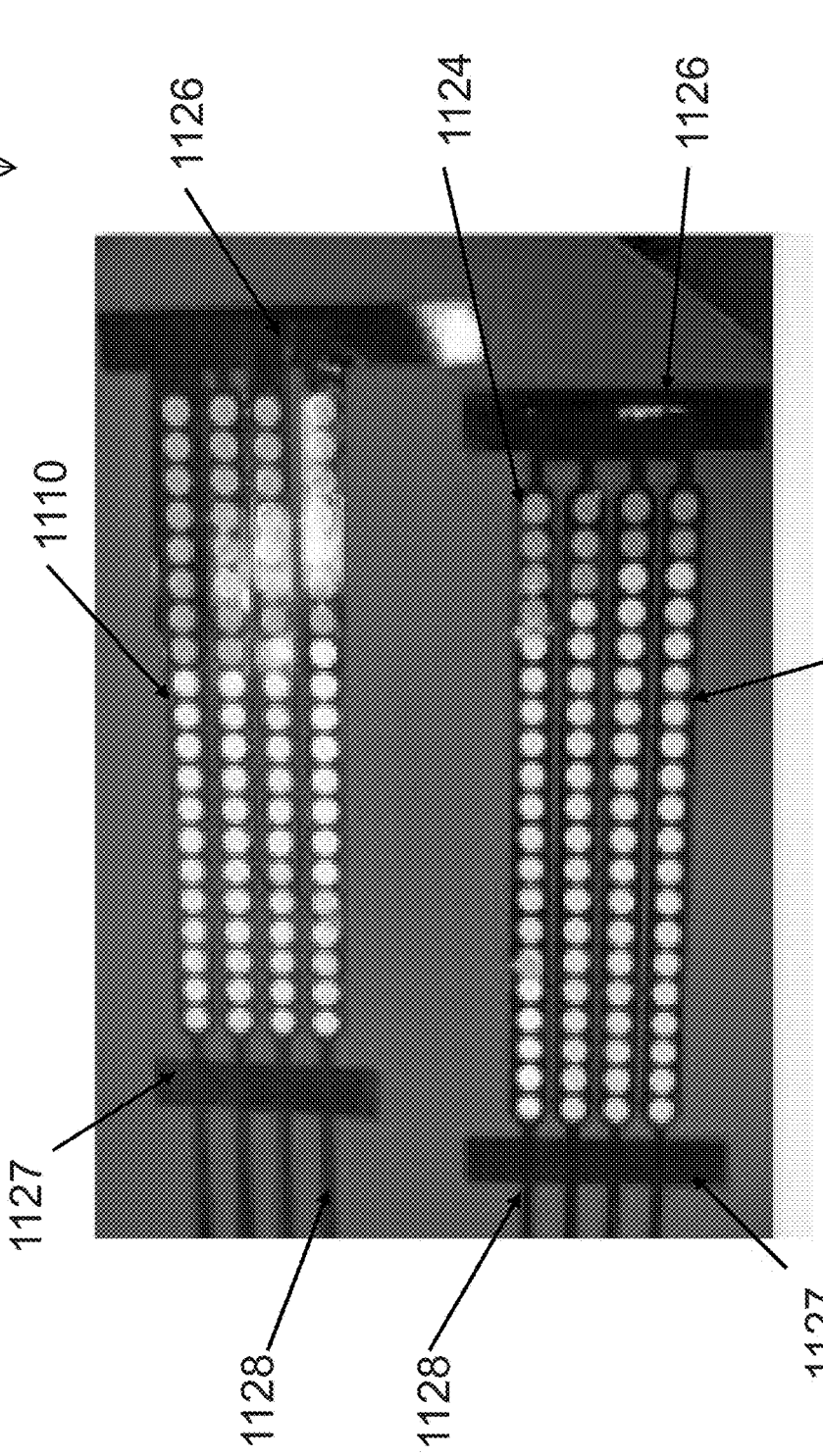


FIG. 16

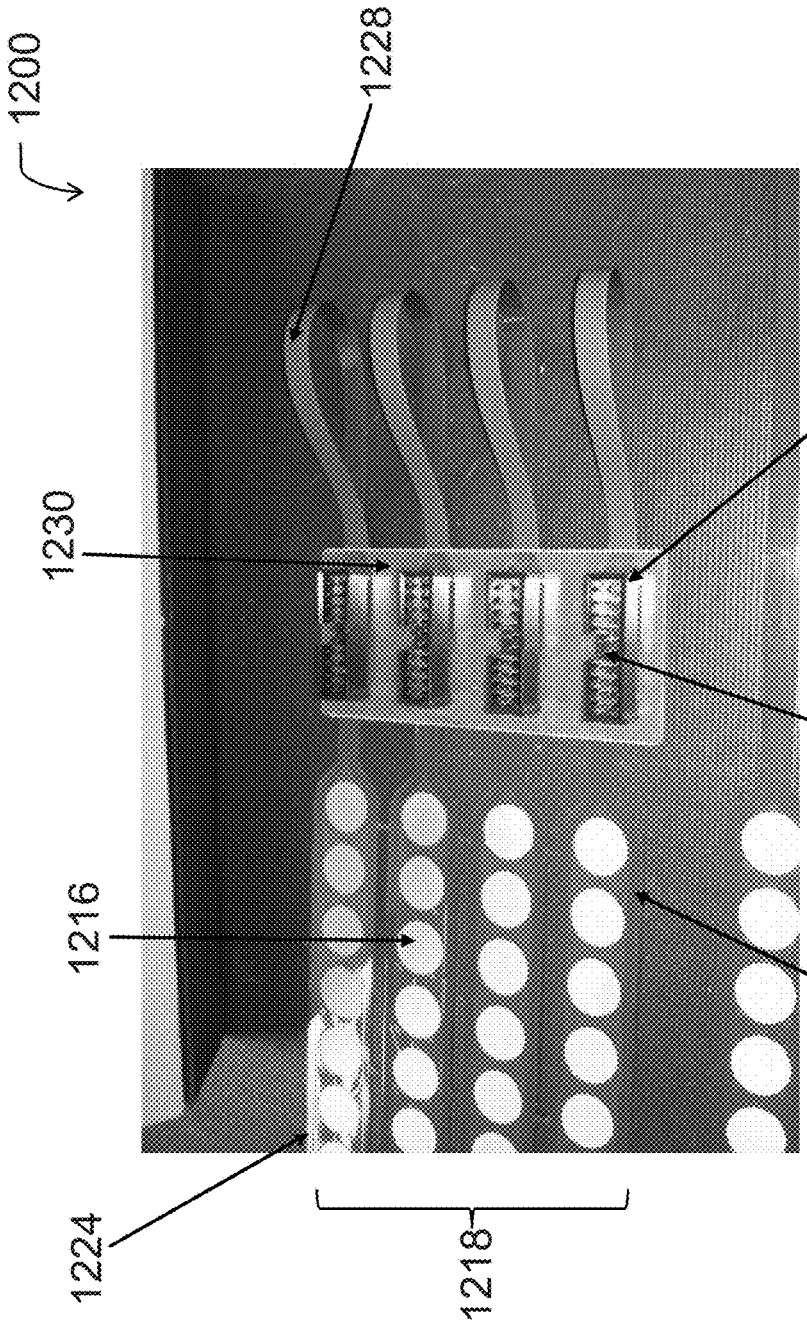


FIG. 17

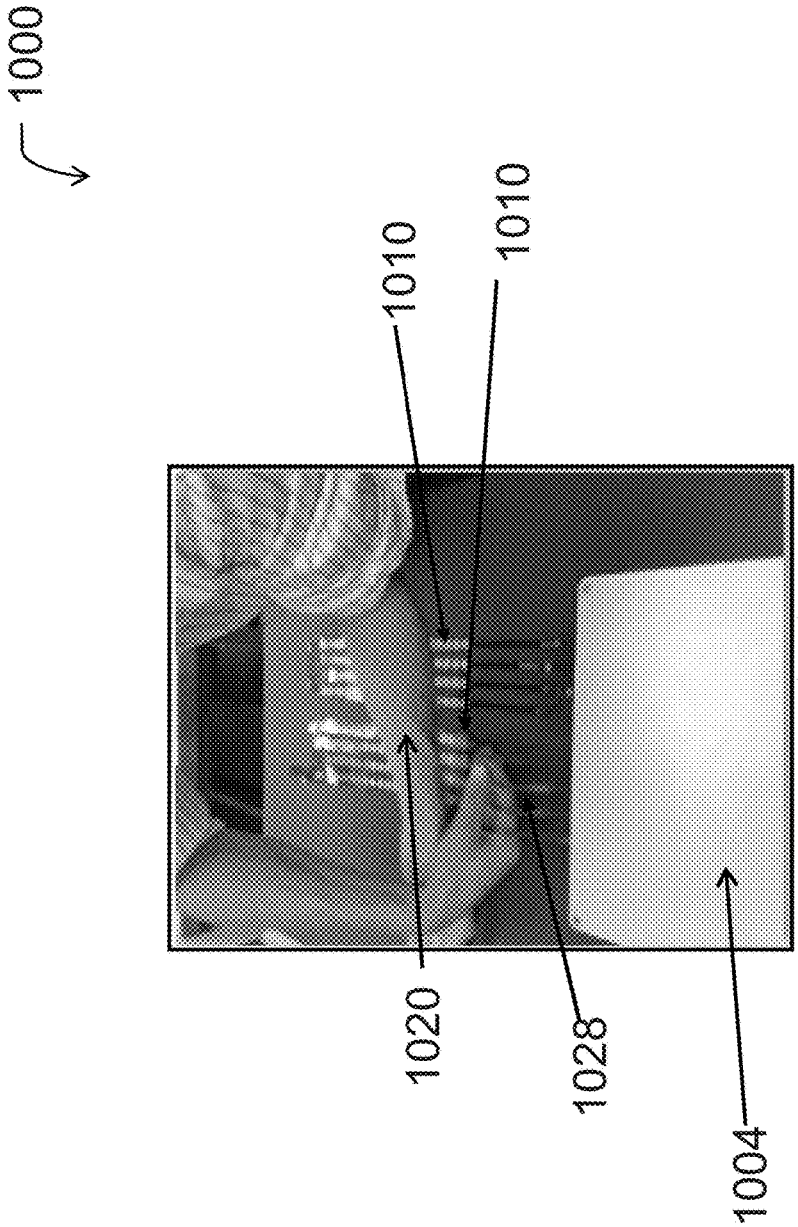


FIG. 18

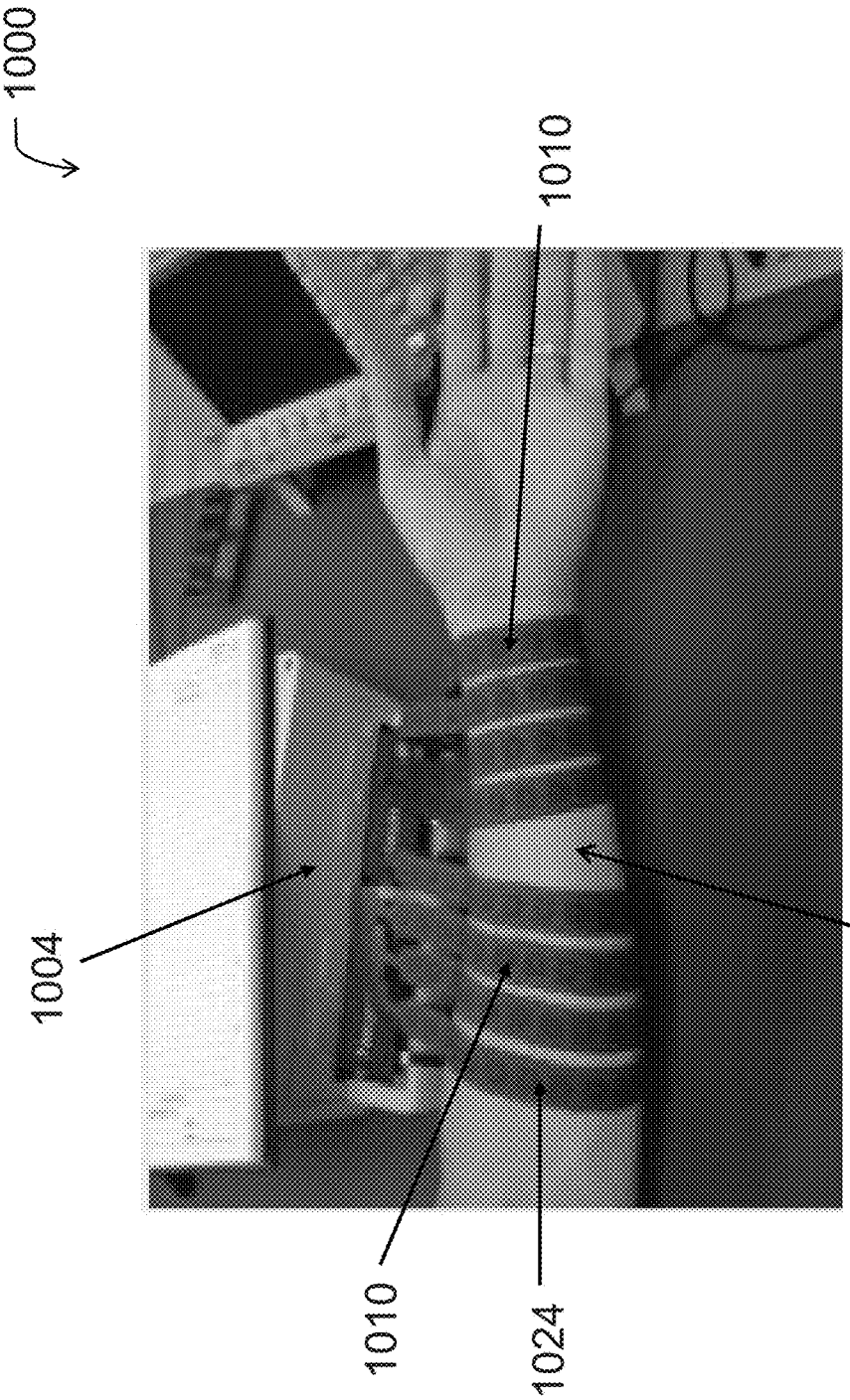


FIG. 19

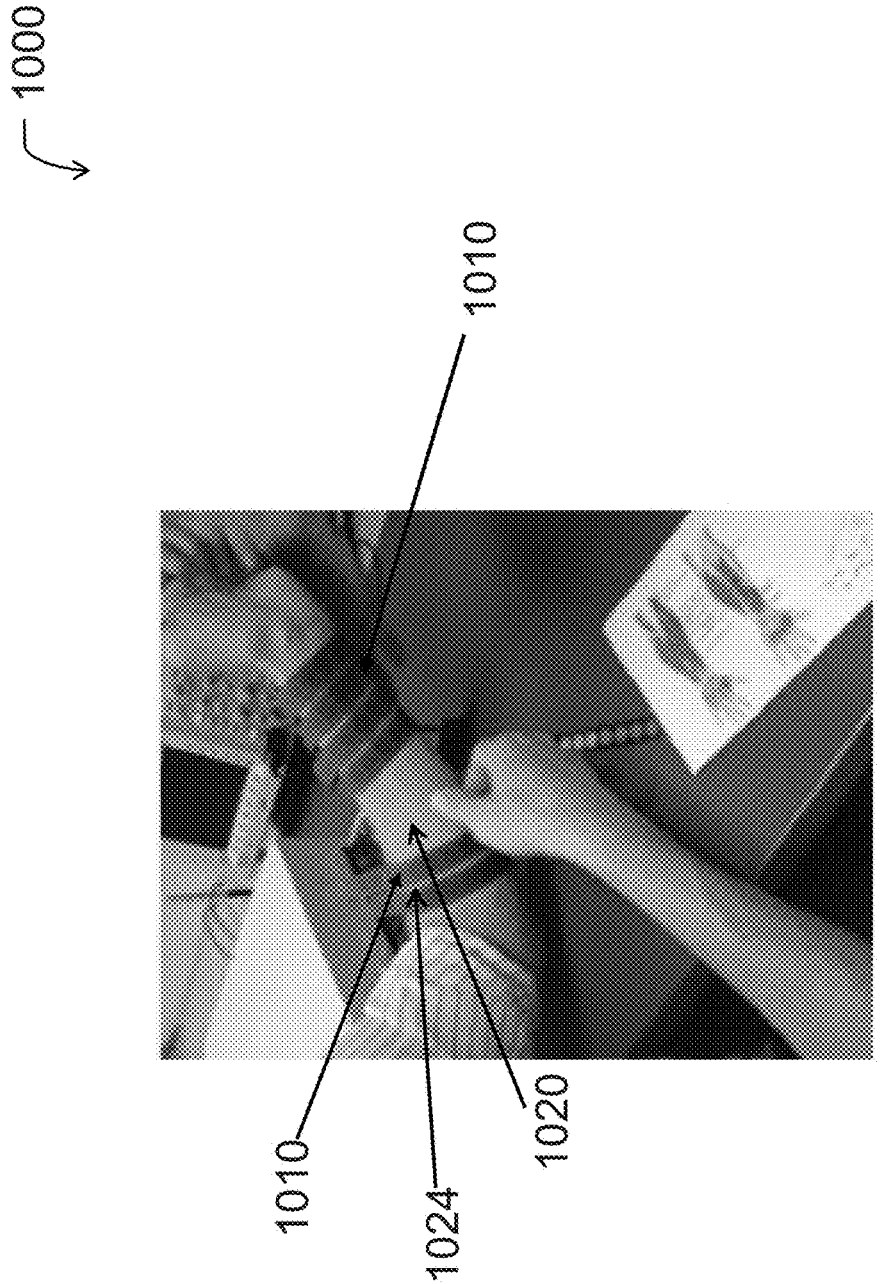


FIG. 20

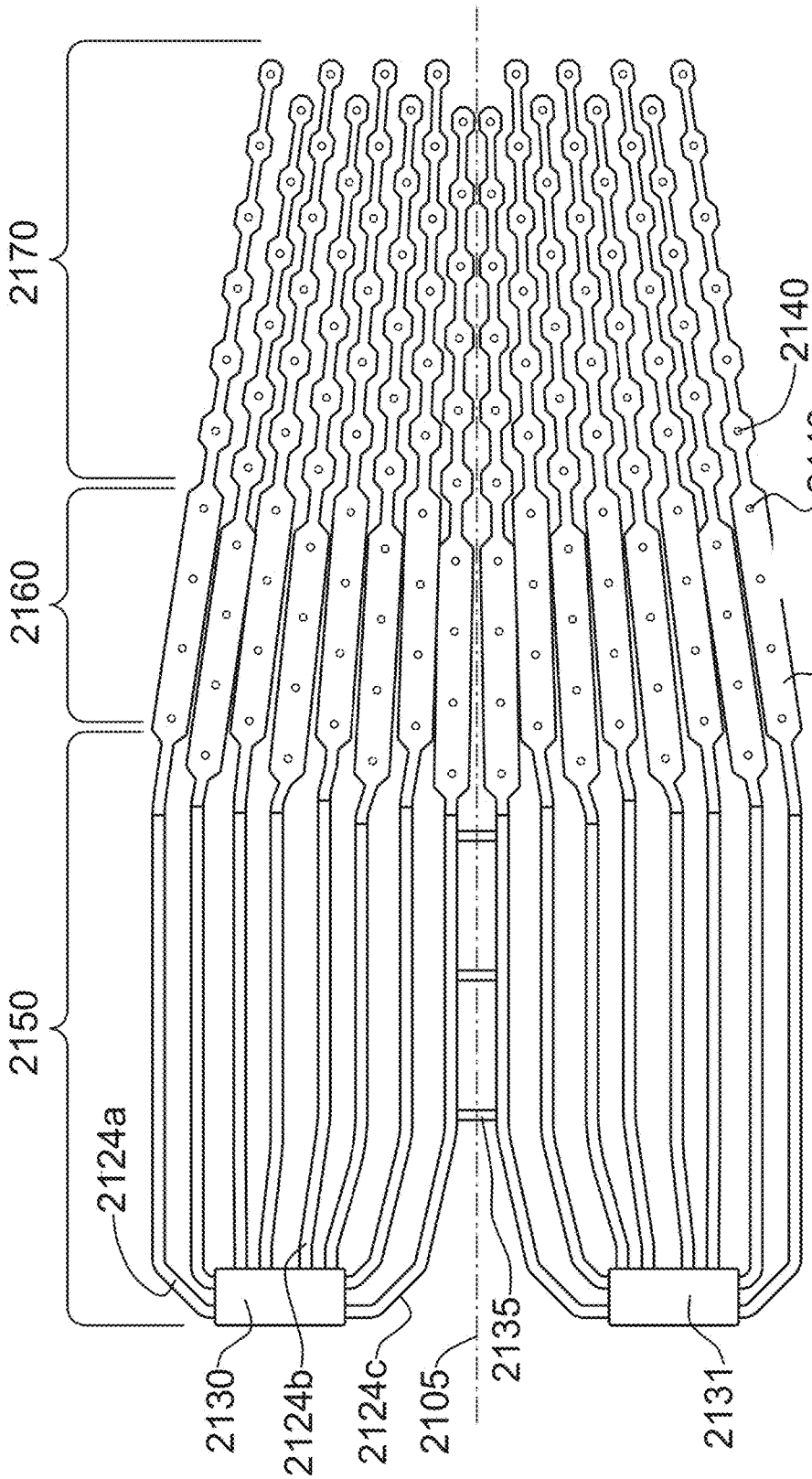

2170
2160
2150
2140
2140
2124
2124a
2130
2124b
2124c
2105
2135
2131
2110

FIG. 21

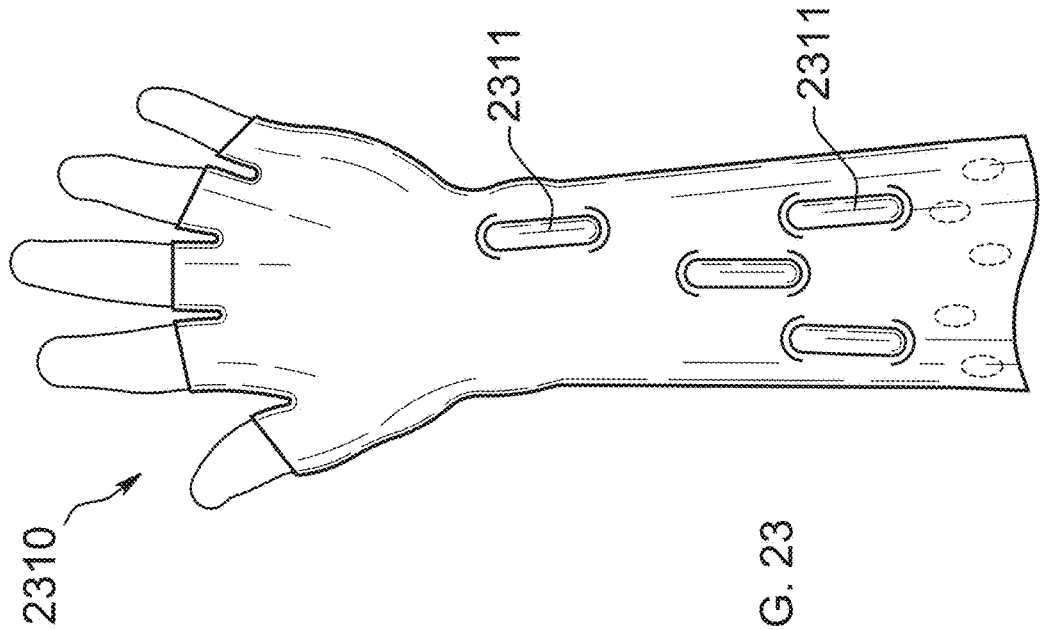


FIG. 23

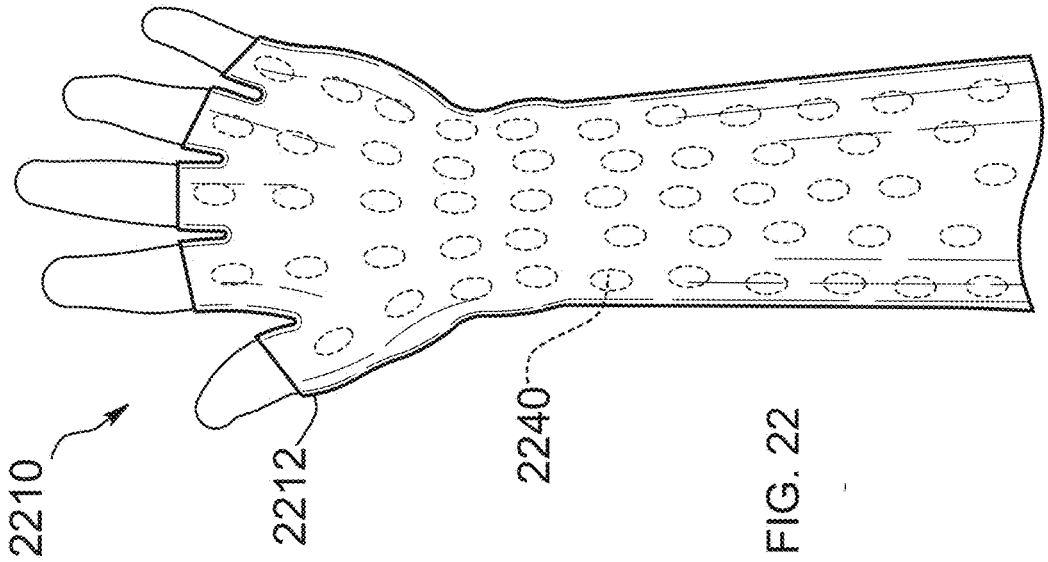


FIG. 22

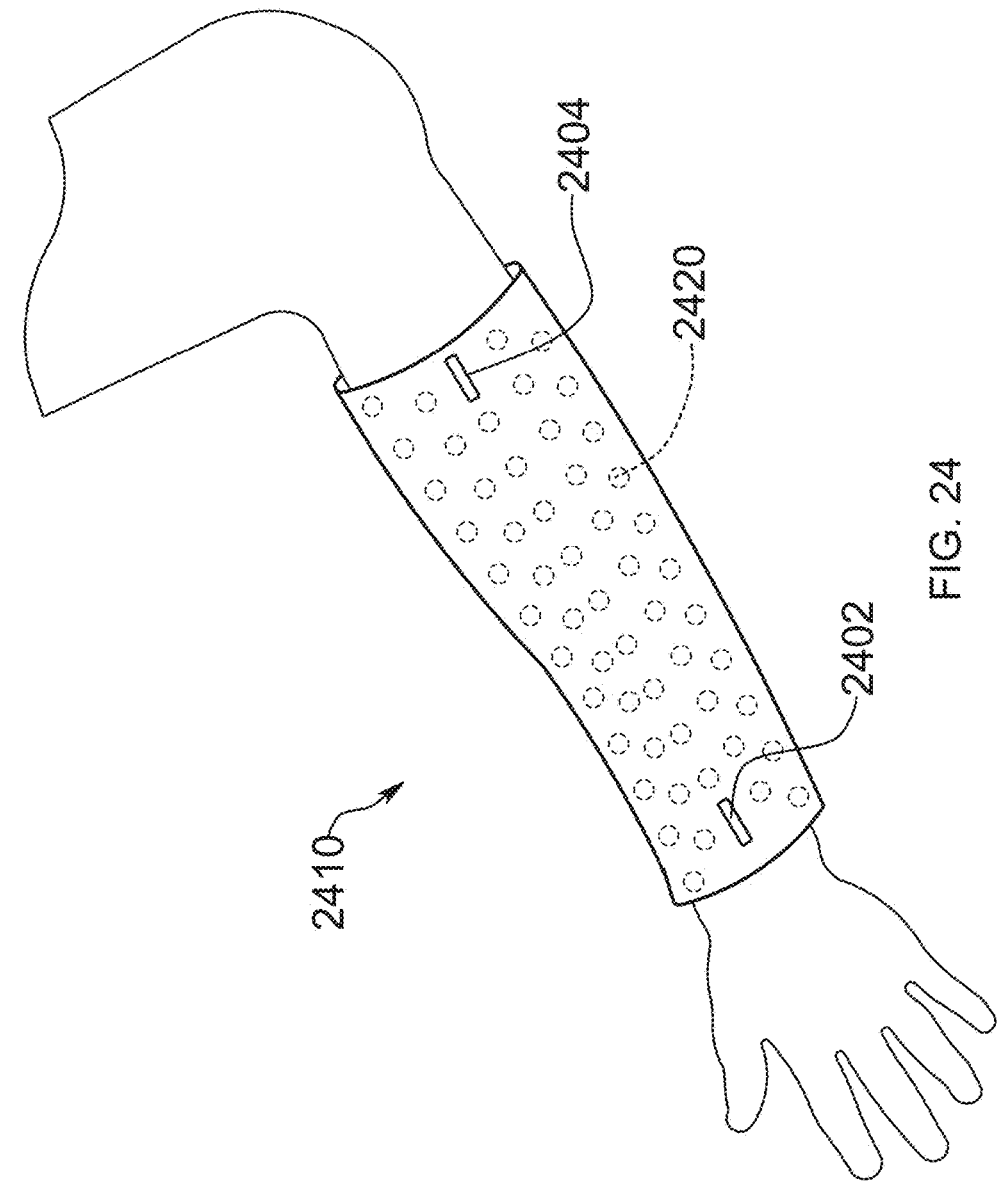


FIG. 24

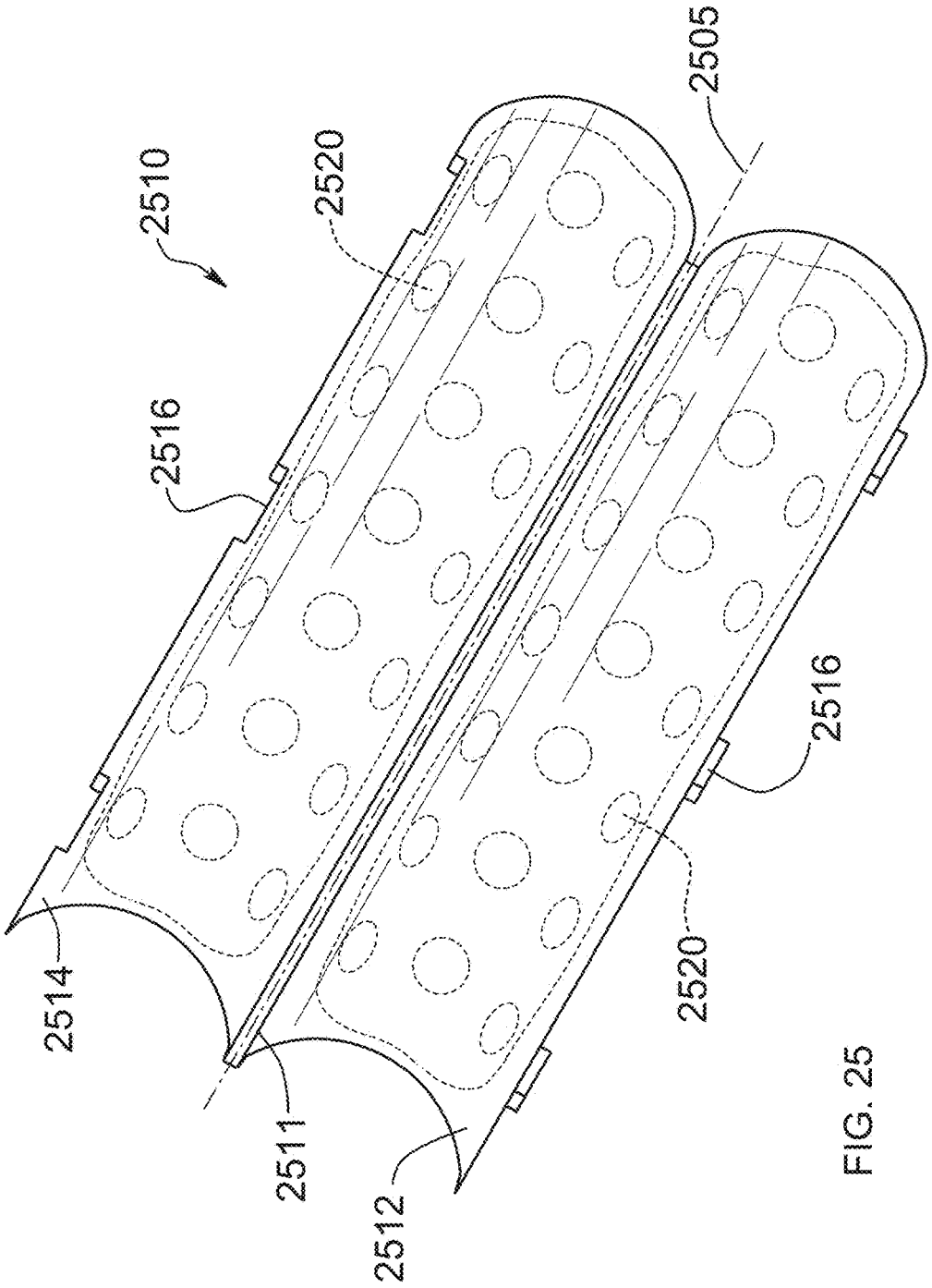


FIG. 25

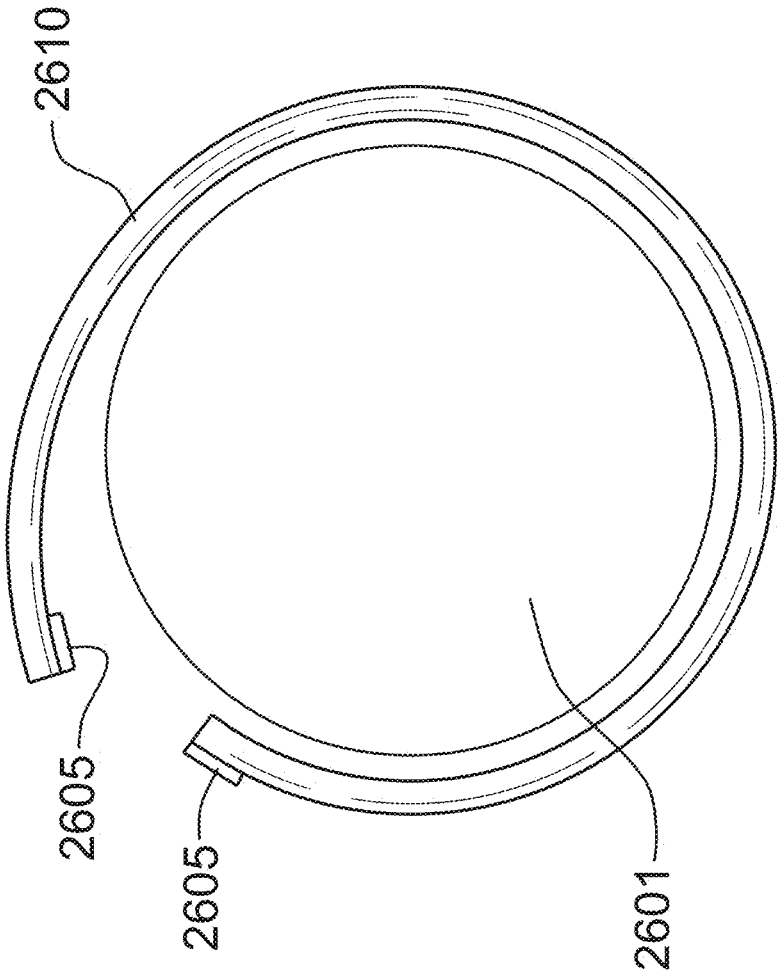


FIG. 26

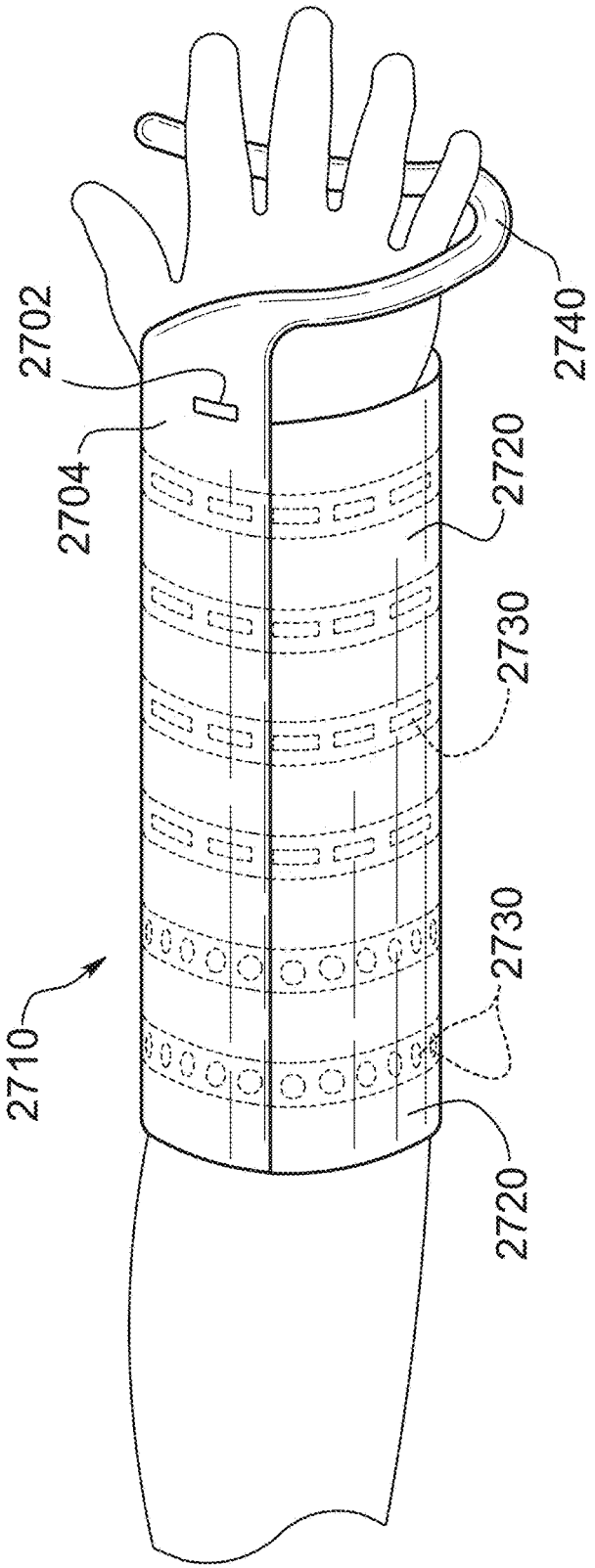


FIG. 27

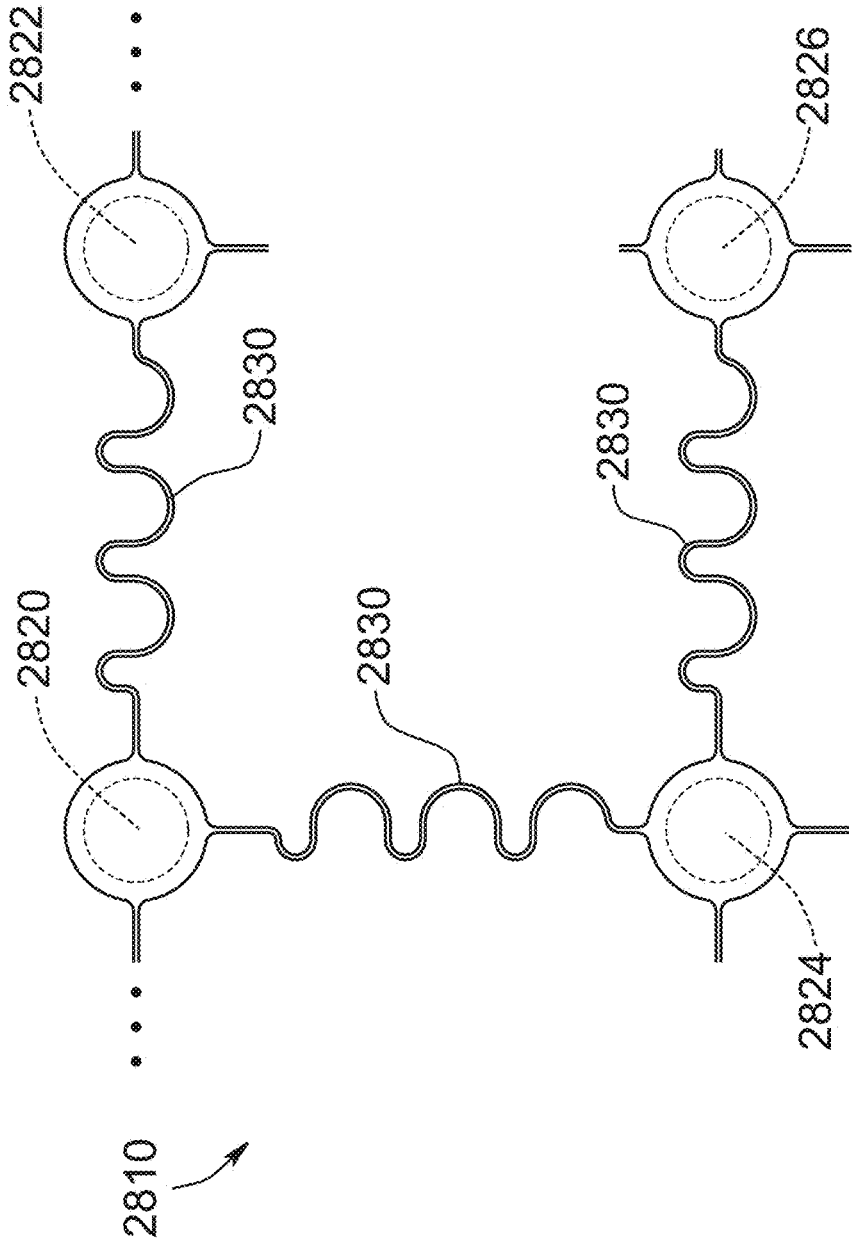


FIG. 28

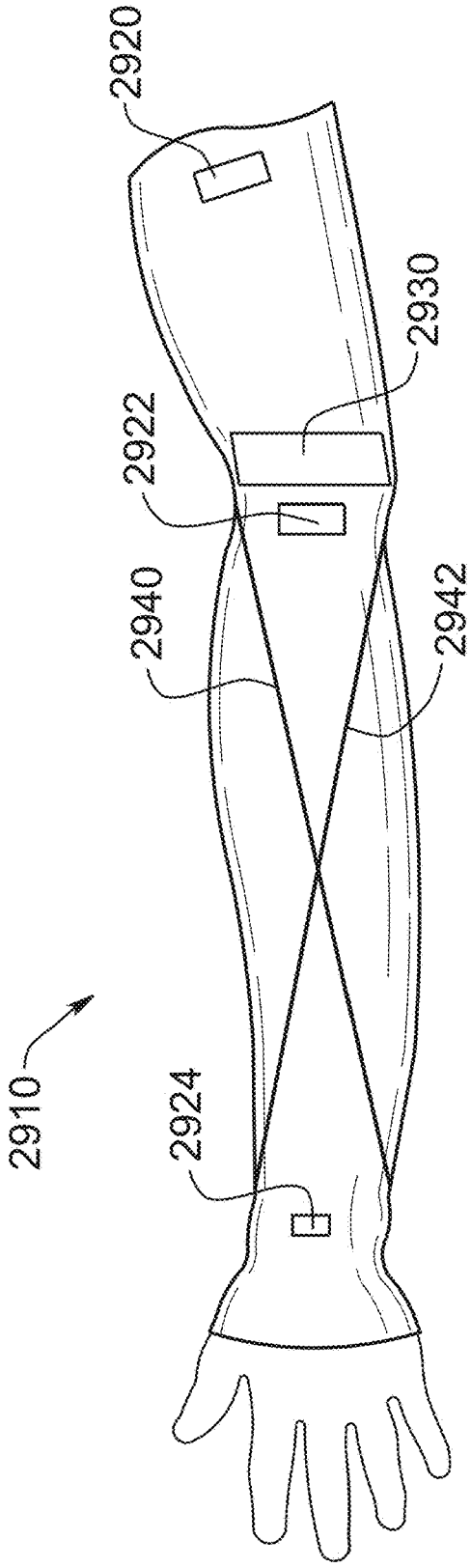


FIG. 29

NEURAL SLEEVE FOR NEUROMUSCULAR STIMULATION, SENSING AND RECORDING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. patent application Ser. No. 14/728,512, filed Jun. 2, 2015, now U.S. Pat. No. //insert later//, which was a continuation-in-part of U.S. patent application Ser. No. 14/649,025, filed on Jun. 2, 2015, now U.S. Pat. No. //insert later//, which was a 371 of PCT Application No. PCT/US2013/073247, filed on Dec. 5, 2013, which claimed priority to both U.S. Provisional Patent Application Ser. No. 61/733,736, filed on Dec. 5, 2012, and to U.S. Provisional Patent Application Ser. No. 61/734,150, filed on Dec. 6, 2012.

BACKGROUND

[0002] The following relates generally to systems, methods and devices for neuromuscular stimulation, sensing, and recording. Generally, the system may be used to receive thought signals indicative of an intended action and provide electrical stimulation to nerves and/or muscles to effectuate the intended action, thereby bypassing or assisting a damaged or degenerated region/pathway of the nervous system. The devices of the present disclosure are neuromuscular stimulation cuffs, also referred to herein as "neural sleeves," which deliver stimulation to restore movement to parts of the body not under volitional control due to damaged or degenerated neural regions/pathways from brain or spinal cord injury, stroke, nerve damage, motor neural disease, and other conditions or injuries. The system can also be used in a patient that has some local neural or muscle degeneration for therapeutic or rehabilitation purposes.

[0003] Subcutaneous implantable neurostimulation cuffs have been commonly used to block pain and to restore function to damaged or degenerative neural pathways. These implantable cuffs are wrapped around a target nerve and generally include one or more electrodes arranged to stimulate the nerve. By including more than one electrode and/or a different geometry of electrodes, implantable cuffs such as the flat interface nerve electrode (FINE) have been able to achieve stimulation selectivity at the level of individual nerve vesicles.

[0004] Transcutaneous neurostimulation cuffs behave similarly to implantable cuffs, however there are important differences. Because the electrodes are placed on the surface of the skin, rather than below it, stimulation often can better target skeletal muscle tissue or muscle groups, rather than peripheral nerves located deeper under the skin. Muscular stimulation may be preferable to stimulating major peripheral nerves, e.g. ulnar, median, radial nerves, as stimulating these nerves may cause a patient to feel a tingling sensation and it is more difficult to effect the desired movement. By increasing the number and layout of electrodes in a neuromuscular cuff, similar to the direction taken with implanted nerve cuff designs, current generation neuromuscular stimulation cuffs have been able to selectively stimulate individual muscles or muscle groups and achieve finer movements such as individual finger flexing and extension.

[0005] Flexible-like transcutaneous cuffs have been developed which fit around a human appendage such as a forearm to control the wrist or fingers. These flexible cuffs may include sensors which record muscle activity, or electromyography (EMG) signals, and stimulate in response to the EMG signals. Thin film technologies have also become important in the development of functional electrostimulation (FES) devices. Devices incorporating thin film technology are often based on a polyimide substrate covered by a chromium, gold, or platinum film.

[0006] Current transcutaneous neuromuscular stimulation electrodes (or patches) present many limitations. Such neuromuscular patches are typically large (several cm across or more) and have a single electrode (conductive surface). This does not allow selective stimulation of small muscles segments for fine wrist and finger control.

[0007] It would be desirable to provide improved devices for neuromuscular stimulation. Flexible sleeves with multiple small electrodes would allow programmable spatial stimulation patterns, which is highly desirable when attempting to restore complex muscular movements through neuromuscular stimulation.

BRIEF DESCRIPTION

[0008] The present disclosure relates to systems, methods, and devices for thought-controlled neuromuscular stimulation. Included is a neuromuscular stimulation cuff (i.e. "neural sleeve") which receives a thought signal indicative of an intended action, and in response, stimulates a damaged region/pathway of the nervous system to effectuate the intended action. The neuromuscular cuff may include a flexible design, e.g., including a plurality of electrodes arranged on flexible fingers. The flexible fingers allow for variable sized neuromuscular regions, e.g. paralyzed limbs, to fit within the neuromuscular cuff. The fingers may also allow for increased electrode positioning choices for reanimation of complex muscle movements. The neuromuscular cuff may further include an array of electrogel discs which provide enhanced electrical contact as well as keep the cuff adhered to the skin during stimulation-induced movement.

[0009] In yet other embodiments, a device for neuromuscular stimulation includes a flexible printed circuit board having at least one finger and a plurality of electrogel discs disposed on the at least one finger.

[0010] In additional different embodiments, a method for producing a neuromuscular cuff includes providing a layer of polyimide, etching a conductive copper circuit including a plurality of electrodes into the layer of polyimide to form an etched circuit layer, adhering a cover layer onto the etched circuit layer to form a flexible printed circuit board (PCB), and cutting at least one finger from the flexible PCB.

[0011] In other embodiments disclosed herein, devices for neuromuscular stimulation include: a reusable sleeve; and one or more electrodes housed within the reusable sleeve.

[0012] In particular embodiments, the reusable sleeve comprises at least two flexible fingers along which the one or more electrodes are located, each flexible finger extending in the same direction from a connector. Each finger contains one or more flexible conductive pathways that lead to the electrode(s) previously described. A plurality of conductive mediums is disposed on the flexible fingers to conduct the electrical impulses from the electrodes. As a result, each flexible finger is able to conform to different arm profiles and accommodate twisting of the arm.

[0013] The conductive medium may comprise a hydrogel, a lotion, or a conductive polymer. The flexible fingers may be oriented with respect to the connector so that they can be

wrapped helically (e.g. around a patient's limb). The device may further comprise a fabric layer disposed on an exterior of the reusable sleeve.

[0014] Each flexible finger may include a conductive circuit layer, which can be arranged in the form of one or more conductive pathways. That conductive circuit layer may be laid upon an insulating base layer, for example made of a polyimide. The flexible finger may include an insulating cover layer over the conductive circuit layer. The flexible finger may include a plurality of hydrogel discs disposed over each electrode, wherein each hydrogel disk is independently connected to a rigidizer. The rigidizer may interface with a processing device, such as a computer or other electronic device.

[0015] In other embodiments, a device for neuromuscular stimulation includes: a reusable sleeve; multiple electrodes housed within the reusable sleeve; and an inner disposable sleeve, the inner disposable sleeve comprising a conductive medium in contact with the multiple electrodes.

[0016] The conductive medium may comprise a hydrogel which is relatively more conductive in a z-direction than in a x-direction or a y-direction. The conductive medium may be less conductive in a regular state; and the conductive medium may become more conductive upon application of external pressure in a direction of the external pressure. The conductive medium may include a compressible polymer and a conductive filler dispersed in the compressible polymer. The conductive filler may be carbon-based and comprise carbon fibers. The conductive filler may comprise any of: carbon fibers, carbon nanotubes, or metallic particles (e.g. silver; gold; platinum; or palladium). The conductive medium may be dry in an initial state and then become tacky upon any one of: application of an electrical current; a change in temperature; a change in pH; or a change in moisture. The conductive medium may include a stimuli-sensitive polymer. Each electrode of the multiple electrodes may include concentric rows of teeth about 200 μm to about 300 μm in height. The reusable sleeve may include a flexible material.

[0017] In other embodiments, the reusable sleeve may include: a rigid shell; and a hinge running parallel to a longitudinal axis of the reusable sleeve. Sometimes, the reusable sleeve may include a user interface for selectively configuring electrodes and adjusting stimulation level or pattern. The reusable sleeve may be expandable.

[0018] In other embodiments, the reusable sleeve may include a compression sleeve fabric on which the multiple electrodes are printed using silk-screen technology employing conductive polycellulose or silver/carbon-based ink. The device may further include a conductive pathway including an accelerometer.

[0019] The reusable sleeve may include a flexible circuit which may include electrodes connected by electrode traces; the electrode traces may house sensors; and the electrode traces may be arranged in a zig-zag pattern to enhance flexibility and/or durability. The sensors may include any combination of pressure sensors; strain gauges; accelerometers; a micro-electro-mechanical system (MEMS) including a 3-axis accelerometer and 3-axis magnetometer; a capacitive sensor including a flexible insulating dielectric layer sandwiched between flexible electrodes; a stretch sensor including a material that changes electrical resistance when stretched or strained; a resonant bend sensor including a resistance-inductance-capacitance (RLC) circuit; a sensor including at least one bladder configured to hold a fluid or air; a fiber optic cable and a measurement tool configured to measure a bend in the fiber optic cable based on a frequency or attenuation change in a signal of the fiber optic cable; and a video motion tracking system configured to track a marker of the reusable sleeve.

[0020] The reusable sleeve may include conductive/carbon fibers and a dry fit material. The reusable sleeve may be in the form of a fingerless glove made of a stretchy material. The multiple electrodes may be woven into the reusable sleeve using conductive threads. The reusable sleeve may include buttons including light emitting diode (LED) based touchscreen displays on a back side of each of the multiple electrodes. The reusable sleeve may include an accelerometer, and may be configured for gesture control of devices. The reusable sleeve may be configured to cover both a leg portion and a foot portion of a patient; and support gait-training. The reusable sleeve may include a shirt configured to deliver electrical stimulation to a backside of a patient. The multiple electrodes may be configured to both deliver electrical simulation and sense a neural signal of a patient.

[0021] In another aspect, a device for neuromuscular stimulation may include: a reusable sleeve; and multiple electrodes housed within the reusable sleeve; wherein the reusable sleeve comprises at least two flexible fingers for housing the multiple electrodes, the flexible fingers extending in the same direction, and a plurality of conductive mediums disposed thereon.

[0022] In another aspect, a device for neuromuscular stimulation includes: a reusable sleeve comprising a continuous substrate; and multiple electrodes housed within the reusable sleeve; wherein the continuous substrate comprises a non-conductive portion and conductive, parallel pathways.

[0023] These and other non-limiting aspects of the present disclosure are discussed in more detail below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The following is a brief description of the drawings, which are presented for the purposes of illustrating the exemplary embodiments disclosed herein and not for the purposes of limiting the same.

[0025] FIG. **1** is an overview diagram of one embodiment of a system for thought-controlled neuromuscular stimulation.

[0026] FIG. **2** is a block diagram for the decoding and re-encoding architecture operating within the system of FIG. **1**.

[0027] FIG. **3** is a flow diagram for one embodiment of a method for providing thought-controlled neuromuscular stimulation.

[0028] FIG. **4** is a perspective drawing of a neural sleeve according to an exemplary embodiment, shown in place on a human arm.

[0029] FIG. **5** is a diagram for a concept design for fabricating one embodiment of the neural sleeve.

[0030] FIG. **6** is a diagram for an etched circuit layer for fabricating one embodiment of the neural sleeve.

[0031] FIG. **7** is a close-up view diagram of the etched circuit layer of FIG. **6**.

[0032] FIG. **8** is an alternative close-up view diagram of the etched circuit layer of FIG. **6**.

[0033] FIG. **9** is a diagram for a coverlay layer used in fabricating one embodiment of the neural sleeve.

[0034] FIG. **10** is a diagram for a silkscreen layer used in fabricating one embodiment of the neural sleeve.

[0035] FIG. **11** is a stack-up diagram used in fabricating one embodiment of the neural sleeve.

[0036] FIG. **12** is a flow diagram for one embodiment of a method for producing a neural sleeve.

[0037] FIG. **13** is an exemplary photograph showing individual finger movement within a system for thought-controlled neuromuscular stimulation.

[0038] FIG. **14** is an exemplary photograph showing two neural sleeve devices according to one embodiment disposed on a preparation bench.

[0039] FIG. **15** is an exemplary photograph showing two neural sleeve devices according to the embodiment of FIG. **14**.

[0040] FIG. **16** is an exemplary photograph showing two neural sleeve devices according to a different embodiment.

[0041] FIG. **17** is an exemplary photograph showing a rigidizer and the primary side of a neural sleeve device according to yet another embodiment.

[0042] FIG. **18** is an exemplary photograph showing the positioning of a patient's arm region over two neural sleeve devices according to the embodiment of FIG. **14**.

[0043] FIG. **19** is an exemplary photograph showing two neural sleeve devices according to the embodiment of FIG. **14** which are wrapped around a patient's arm region in preparation for neuromuscular stimulation.

[0044] FIG. **20** is an exemplary photograph showing two neural sleeve devices according to the embodiment of FIG. **14** which are alternatively wrapped around a patient's arm region in preparation for neuromuscular stimulation.

[0045] FIG. **21** is diagram of another exemplary embodiment of a neural sleeve. In this embodiment, conductive pathways extend from two different connectors. The fingers extend in the same direction, and taper towards a center axis.

[0046] FIG. **22** is an exemplary illustration of a fingerless neural sleeve in the form of a glove that can reach up to the elbow.

[0047] FIG. **23** is an exemplary illustration of a variation of the neural sleeve of FIG. **22**, in which the neural sleeve includes a user interface on the exterior in the form of buttons.

[0048] FIG. **24** is an exemplary illustration of a neural sleeve made of a flexible material with electrodes on the interior and implants for providing directionality to the neural sleeve.

[0049] FIG. **25** is an exemplary illustration of a neural sleeve in the form of a rigid shell having two hemicylindrical halves joined together by a hinge along the sidewall.

[0050] FIG. **26** is a cross-sectional illustration of a resuable neural sleeve, which is in the form of a flat flexible sheet that can be wrapped around the arm.

[0051] FIG. **27** is an exemplary illustration of a neural sleeve with expandable bladders for pushing the electrodes against the skin. A handle can be included with the sleeve for proper registration/orientation of the neural sleeve.

[0052] FIG. **28** is an exemplary magnified illustration of the construction of the flexible conductive pathways of the neural sleeve. These pathways can include electrodes as well as other components, for example strain gauges.

[0053] FIG. **29** is an illustrative diagram showing a neural sleeve applied to the arm of a user. This particular neural sleeve is in the form of a fingerless glove that covers the palm of the hand, extends past the wrist and the through the elbow up to the shoulder of the user. The locations of various sensors are highlighted in this diagram.

DETAILED DESCRIPTION

[0054] A more complete understanding of the processes and apparatuses disclosed herein can be obtained by reference to the accompanying drawings. These figures are merely schematic representations and are not intended to indicate relative size and dimensions of the assemblies or components thereof.

[0055] Although specific terms are used in the following description for the sake of clarity, these terms are intended to refer only to the particular structure of the embodiments selected for illustration in the drawings, and are not intended to limit the scope of the disclosure. In the drawings and the following description below, it is to be understood that like numeric designations refer to components of like function.

[0056] With reference to FIG. **1** and FIG. **2**, a system for thought-controlled neuromuscular stimulation may include a cortical implant **102** implanted into the cerebral cortex region of the brain. The cortical implant **102** in one embodiment includes a microelectrode sensing array, as depicted in FIG. **1**. The microelectrode sensing array includes multiple channels (e.g. 96 channels) and may be wired to an amplifier which further amplifies signals received by the microelectrode array. The cortical implant **102** records "brain waves," more particularly neural signals which are representative of a varied set of mental activities. Neural signals include electrical signals produced by neural activity in the nervous system including action potentials, multi-unit activity, local field potential, ECoG, and EEG. These neural signals are sent wirelessly or, alternatively, through a wired connection, from the cortical implant **102** to a receiver on a neural signal processor device **104** for processing of the neural signals. In another embodiment, a scalp based interface, headset, or other sensor **102** picks up electroencephalogram (EEG) signals and sends them to the receiver on the neural signal processor device **104**.

[0057] The neural signal processor **104** may include a processor including neural decoding algorithms **106** and/or control algorithms **108**. These algorithms **106**, **108** allow for a received neural signal input to be decoded and subsequently re-encoded for use in neuromuscular stimulation. For example, a received neural signal may be isolated to predict arm and/or hand movements a patient is thinking about. The neural signal processor **104** may also include an oscilloscope or other signal waveform viewing and/or manipulation device. The neural signal processor also preferably includes an isolated pulse stimulator **111** which receives a processed signal and generates a pulse signal for use in neuromuscular stimulation by an attached neuromuscular stimulation cuff **110**.

[0058] With reference to FIG. **2**, the system for thought control at a more complex architectural level includes the cortical implant or sensor **102** and the neural signal processor **104** which allow for the recording of neural signals and the initial processing of the signals, respectively. Initial signal processing may include analog to digital conversion, normalization, and/or other filtering and processing methods known by one having ordinary skill in the art. Initially processed signals are then decoded by the neural decoding algorithms **106**. In exemplary embodiments, the neural decoding algorithms **106** include force-based algorithms with firing-rate estimators.

[0059] The decoded signal output of the neural decoding algorithms **106** is further processed by the stimulation control algorithms **108**. In exemplary embodiments, the stimulation control algorithms **108** produce an output of peak current amplitude modulated, pulse width modulated, or frequency modulated pulse trains going to the cuff electrodes. The pulse train can also be a non-stationary Poisson type train where average pulse rate (frequency) is modulated. This may help reduce muscle fatigue as it more closely matches to the body's natural nervous system. An example of using poisson-distributed impulse trains to characterize neurons in a region of the brain is disclosed in Pienkowski et al., Wiener-Volterra Characterization of Neurons in Primary Auditory Cortex Using Poisson-Distributed Impulse Train Inputs, J. Neurophysiology (March 2009). Stimulation control algorithms **108** may be altered through input received from a training profile **107**. The training profile **107** may include training profile data representative of past user training sessions, e.g. motion demonstrations or coaching periods. Training data may be used to alter and/or define simulation control algorithms **108** during signal processing. Incorporating training data into stimulation control algorithms **108** through a model-based approach yields more accurate decoding, e.g. patient thoughts accurately translated into a complex motion, than prior position-based decoding efforts have shown. Additionally or alternatively, wrist-hand position feedback **109** may be used to alter and/or define stimulation control algorithms **108** during signal processing.

[0060] Signal control algorithm **108** output may be sent to the isolated pulse generator **111**, where the signal is converted into a waveform that is suitable for neurostimulation. Suitable waveforms may include monophasic and biphasic pulses with a voltage between 80 to 300 Volts. However, even higher voltages may be used as long as safe current levels are maintained and proper insulation is used. In exemplary embodiments, the waveform is a monophasic pulse with a peak current of 0-20 mA which is modulated to vary strength of muscle contraction, frequency of 50 Hz, and a pulse width duration of 500 ms. The output of the isolated pulse generator **111** is sent to the neuromuscular stimulation cuff **110** to deliver functional electrostimulation to the patient.

[0061] With reference to the flow diagram set forth in FIG. **3**, a method for providing thought-controlled neuromuscular stimulation S**100** starts at S**101**. At S**102** neurological signals are received from a patient indicative of an intended action. For example, neurological signals may be received though cortical implant **102**. At S**104** the neurological signals are processed, which may include analog to digital conversion or filtering. At S**106**, the digitized signals are decoded by at least one neural decoding algorithm **106**. At S**108**, the decoded signals are processed by at least one stimulation control algorithm **108**. At S**110**, the method alternatively includes altering the stimulation control algorithms **108** by training data which is stored in the training profile **107**. At S**112**, the method alternatively includes altering the stimulation control algorithms **108** based on movement data, e.g. wrist-hand position feedback **109**. At S**114**, the output of the at least one signal control algorithm **108** is converted into a re-encoded signal consisting of multiple pulse trains, each pulse train going to a corresponding electrode **114**. At S**114**, neuromuscular stimulation is delivered to the patient by sending the re-encoded signal to the neuromuscular stimulation cuff **110**.

[0062] In another embodiment, the method for providing thought-controlled neuromuscular stimulation S**100** further includes at S**117** delivering neuromuscular stimulation to the patient by selectively delivering stimulation to at least one pair of electrodes **114** within a neuromuscular cuff **110** to effectuate the intended action.

[0063] In yet another embodiment, the method S**100** further includes S**103** recording neurological signals from a patient. These neurological signals may be sensed from, e.g., a forearm or wrist region with neural pathway damage. Recording may also occur at a neurologically intact region such as a functional leg, for which stimulation pulses can be provided for stimulating commonly tied motions in damaged limbs, e.g. arms and legs. Commonly tied motions include hip and arm movements or pivoting movements. In the same embodiment, method S**100** at S**118** may further include delivering neuromuscular stimulation to the patient by selectively stimulating to at least one pair of electrodes within the neuromuscular cuff **110** based on the re-encoded signal.

[0064] With reference to FIG. **4**, an exemplary embodiment of the neuromuscular stimulation cuff **110** includes a flexible printed circuit board (PCB) **112** upon which electrodes **114** and hydrogel discs **116** are arranged in an electrogel disc array **118**. The neuromuscular stimulation cuff **110** fits over a damaged or degenerative region **120** of the nervous system, e.g. a patient's arm as illustrated. The flexible PCB **112** acts as a substrate upon which the electrodes and other conductive materials are laid. This flexible base layer may be comprised of a single layer of a flexible insulating material, for example a polyimide material. Up to approximately twenty electrodes **114** may be individually etched onto each finger **124** of the flexible PCB **112** as a copper layer. In exemplary embodiments, the flexible PCB **112** has a total of eighty electrodes **114** disposed over four fingers **124**. The electrodes **114** may be subsequently plated with a conductive metal such as gold, palladium, or silver for greater conductivity.

[0065] In some embodiments, electrodes **114** both stimulate a neuromuscular region **120** by stimulating individual muscles and/or groups of muscles, as well as monitor or record skeletal muscle activity, specifically electromyography (EMG) signals. Sensed EMG data pertaining to a sensed muscle target may be used in methods for closed or open loop stimulation of the muscle target. Sensed EMG data may also be analyzed in deciding whether to reposition the neuromuscular stimulation cuff **110** within the neuromuscular region **120** or to turn off individual electrodes **114** within the electrogel disc array **118**.

[0066] Hydrogel discs **116** may be rolled over the electrodes **114** to provide enhanced electrical and mechanical coupling. When appropriately aligned, the hydrogel discs **116** completely cover the electrodes **114** and effectively form conductive electrogel discs **117**. Put another way, the electrodes are located between the base layer and the hydrogel discs. Electrical coupling is enhanced in that hydrogel provides greater conductive contact with the skin than is achievable with a bare metal-plated electrode surface. Additionally, a carrier signal provided to any of the electrogel discs **117** in the electrogel array **118** may conduct through the tissues of a patient and be released at any other electrogel disc **117** provided in the array **118**. Enhanced mechanical

coupling is provided through the exemplary adherence characteristics of hydrogel to the skin. Hydrogel discs **116** may stay coupled to the skin even during complex patient movement. The hydrogel discs are commercially available as a tape which may be rolled on an electrode surface. One such example includes AmGel 2550 from AmGel Technologies. In the exemplary embodiment of the neuromuscular cuff shown in FIG. **4**, the hydrogel discs are provided through custom spaced hydrogel discs located on AmGel 2550 rolled hydrogel tape. In the alternative, instead of hydrogel discs, a lotion or discs of a conductive polymer could be used.

[0067] The electrogel disc array **118** is spread over a plurality of fingers **124**, wherein the fingers **124** are cut from the flexible PCB **112** to provide additional flexibility in the placement of electrogel discs **117**. Reanimation of complex motion may require stimulating muscles which are not located directly along the dimensions of a conventionally shaped neuromuscular cuff **110**. By wrapping fingers **124** around different muscular regions, e.g. the lower wrist and thumb, complex motions such as thumb movement may be reanimated more effectively than with limited placement options.

[0068] FIGS. **5-11** are views of various layers of the neuromuscular stimulation cuff, and are separated for convenience and understanding. With reference to FIG. **5**, one embodiment of the neuromuscular stimulation cuff device **110** (or neural sleeve) may be fabricated in accordance with a concept design **500**. Dimensions of and between the various components of the concept design **500** are indicated in millimeters (mm). The concept design **500** includes, as shown here, an insulating base layer, for example made of a single layer of polyimide base material **522**. In some embodiments, the polyimide base material is a DuPont AP8523E polyimide which is 50 μm (micrometers) thick and rolled-annealed copper clad at 18 μm thick. This base material serves as a substrate for the other layers of the neuromuscular stimulation cuff. This base material is formed, for example by cutting, into at least two flexible fingers. As illustrated here, the base material **522** is cut into four fingers **524**, where the electrodes will be located or housed. The fingers can be attached to each other, for example by five webbings **525** which run between adjacent fingers.

[0069] The fingers **524** extend in the same direction from the rigidizer **530**, which acts as a connector for one end of the fingers. In other words, the ends of the fingers distal from the rigidizer are all located in the same direction relative to the rigidizer, or put another way the rigidizer **530** is at one end of the device. It is noted that the fingers **524** are shown here as extending at a **90**-degree angle relative to the connector/rigidizer **530**. It is contemplated that the flexible fingers could extend at any angle from the connector **530**. Referring back to FIG. **4**, setting the flexible fingers at an angle from the rigidizer would permit the flexible fingers to be wound helically around the arm and down along the entire length of the arm.

[0070] The rigidizer **530** is used for interfacing with the neural signal processor **104**. Drilled holes **531** are additionally located on the rigidizer **530** which represent connector pin insertion points. In exemplary embodiments, eighty drilled holes **531** are approximately 1.016 mm in diameter with a tolerance of +/−0.05 mm. As illustrated here, the fingers **524** are parallel to each other along their entire length. As will be seen later, this is not a requirement.

[0071] If desired, an optional fork **526** can be located at the end of the fingers opposite the connector/rigidizer **530**. The fork connects all of the fingers, and can be provided for structural support for design and mounting. Drilled holes **527** are provided in the fork **526** for support and/or mounting purposes. In some embodiments, the four drilled holes **527** are approximately 2.387 mm in diameter with a tolerance of +/0.076 mm. Headers **528** extend between the rigidizer and the fingers. These headers are thinner than the fingers, and connect the fingers **524** to the rigidizer **530**. The headers are also part of the overall flexible finger, though they are not always required. Though not illustrated, webbings can also be provided between adjacent headers as well if desired. Again, as will be seen later, the fork **526** is optional, though the connector **530** is required.

[0072] With reference to FIG. **6**, a conductive circuit layer **600** for fabricating the neuromuscular stimulation cuff device **110** is shown. The conductive circuit layer **600** is located on the surface of the insulating polyimide substrate **622**, upon which copper electrodes **640** and connective copper traces **642** are formed to make a conductive pathway, for example by etching, deposition, ablation, etc. The electrodes **640** and traces **642** run along the four fingers **624** of the substrate **622**. The traces **642** run longitudinally down the four headers **628** to electrically connect the electrodes **642** to the connector/rigidizer **630**. Again, the connector/rigidizer **630** is used for interfacing with the neural signal processor **104**. The traces **642** continue onto rigidizer **630** and end, in this exemplary embodiment, at eighty connective points **632**, which represents twenty connective points **632** per finger **624**. Each of the eighty connective points **632** corresponds to an individual electrode **640**, electrically connected through an individual trace **642**.

[0073] FIG. **7** is a closer view of the conductive circuit layer **600** of FIG. **6**. The substrate **622**, electrodes **640**, and traces **642** are more particularly seen here. Each electrode **640** is individually connected to a single trace **642**, and the trace **642** runs down header **628** to the connector/rigidizer **630** (not shown). In some embodiments, the traces **642** are approximately 0.127 mm in width. As illustrated here, each electrode **640** includes at least one ear **641** which is used to support the electrode **640** upon the insulating substrate **622**. As seen here, each electrode includes a central area **643** and three ears **641**. The central area has a circular shape, and is used as an electrical contact. Each ear extends beyond the perimeter of the central area. As illustrated here, two ears are separated by 60 degrees, and are separated from the third ear by 150 degrees.

[0074] Referring to FIG. **8**, the conductive circuit layer illustrated in FIG. **6** may include electrodes **640** that are approximately 12 mm in diameter (not counting the ear) and spaced 15 mm apart. This 15 mm spacing between electrodes would dictate the custom spacing required for subsequent application of hydrogel discs **114**.

[0075] FIG. **9** illustrates an insulating cover or "coverlay" layer **700** which would be placed over the electrodes and traces. The coverlay layer can be made from a single layer of an insulating material such as polyimide **722**, which is preferably thinner than the substrate upon which the electrodes and traces are copper-etched or otherwise formed. In one embodiment, the coverlay layer is a DuPont LF0110 polyimide material which is a 25 μm thick coverfilm. A further thickness of 25 μm of acrylic adhesive can be used for adhering the coverlay layer **700** to the conductive circuit

layer **600**. The coverlay layer also includes a fork **726**, fingers **724**, headers **728**, and rigidizer section **730** which corresponds to these areas on the base substrate **522** and the conductive circuit layer **600**. Cutouts **740** are left in the fingers to expose the central area of the electrodes, and on the rigidizer section **730** for the electrical connectors.

[0076] The insulating cover layer **700**, when applied over the conductive circuit layer **600**, covers the copper traces **642** formed on the fingers **724** and the headers **728**. The coverlay layer **700** does not cover the central area **643** of the electrodes, but does cover the ears **641**, thus fixing the electrodes in place between the substrate and the coverlay layer. In addition, the electrical connectors in the rigidizer section **730** will remain uncovered. The exposed central areas of the electrodes **640** are preferably plated with a conductive metal such as tin, platinum, or gold. In one embodiment, exposed copper electrodes are plated with electroless-nickel-immersion-gold (ENIG) at the level of 3-8 μm gold over 100-150 μm nickel.

[0077] FIG. **10** is a diagram for a silkscreen layer **800** that can be used in fabricating the neuromuscular stimulation cuff device **110**. The silkscreen layer **800** is applied to the combination of the conductive circuit layer **600** and coverlay layer **700** to identify individual electronic elements. A first silkscreen identification number **850** is provided to each electrode **840** so that it may be more easily found after visual inspection. In one embodiment, first silkscreen identification numbers **850** span from A1-A20 and D1-D20 to represent eighty individual electrodes **840**. A second silkscreen identification number **852** identifies the connection ports for a rigidizer **830**. In one embodiment, second silkscreen identification numbers **852** span from J1-J4. Both first and second silkscreen identification numbers **850**, **852** are provided on a secondary side of the neuromuscular stimulation cuff **110**, or side facing away from exposed electrodes **740**. In an exemplary embodiment, silkscreen identification numbers **850**, **852** are provided by white epoxy nonconductive ink.

[0078] Referring now to FIG. **11**, various embodiments of the neuromuscular stimulation cuff device may be fabricated according to stack-up diagram **900**. An insulating base material (e.g. polyimide) provides a substrate **950** upon which various components are fixed. A secondary side rigidizer **830** is laminated to a secondary surface of the substrate **950**. The conductive circuit layer **600** is fabricated onto a primary surface of the substrate (opposite the secondary surface), and includes electrodes and traces that form conductive pathways on the flexible base substrate. The coverlay layer **700** is subsequently adhered to the conductive circuit layer **600** which covers the traces and leaves exposed portions of the electrodes. The combination of the substrate **950**, conductive circuit layer **600**, and coverlay layer **700** is defined as the flexible finger **912**. Primary rigidizer **730** is stacked upon the coverlay layer to complete the electrical connection required to interface the flexible finger with the neural signal processor **104**.

[0079] With reference to the flow diagram set forth in FIG. **12**, one embodiment of a method for producing a neuromuscular cuff S**200** starts at S**201**. At S**202** a single layer of polyimide base material **950** is provided. At S**204**, a conductive circuit layer is fabricated onto the polyimide base material **950** by etching a conductive copper circuit into the polyimide. At S**206** a polyimide coverlay layer **700** is adhered to the conductive circuit layer **600**. Adhering the coverlay layer **700** to the conductive circuit layer **600** completes the formation of a flexible PCB from which the flexible conductive pathways **912** will be formed. At S**208**, a plurality of flexible fingers are formed from the flexible PCB to provide additional contact points for stimulation of muscles or sensing EMG signals. At S**210**, finger webbings **725** may optionally be cut from the flexible PCB to separate the flexible fingers and provide additional flexibility, such as to accommodate limb twisting (such as the forearm) while maintaining contact. At S**212**, hydrogel may optionally be rolled over the electrodes to create electrogel discs **117**. At S**214**, a rigidizer **630**, **730**, **830** is attached to the flexible fingers **912** for interfacing with the neural signal processor **104**. At S**216**, the flexible fingers **912** are interfaced with the neural signal processor **104**.

[0080] With reference to FIG. **13**, individual finger movement within a system for thought-controlled neuromuscular stimulation **1000** is demonstrated. A neuromuscular cuff **1010** according to one embodiment is wrapped over a damaged or degenerative region **1020** of the nervous system. The neuromuscular cuff **1010** is interfaced with a neurological signal processor **1004** through attached rigidizer **1030**. The rigidizer is attached to a connection port **1005** on the neural signal processor **1004**. Received neurological signals indicative of patient thinking about moving their first two digits has been decoded and re-encoded into pulse train signals transmitted to various electrodes on the neuromuscular stimulation cuff **1010**. Using a specific number and spacing of electrodes/electrogel discs **1017** in neuromuscular stimulation cuff **1010** has allowed for high resolution and non-invasive neuromuscular stimulation which effectuates the intention of the patient.

[0081] Electrogel discs **1017** operate in pairs when reanimating motion. Individual digit movement may be effectuated through the operation of two to three pairs (4 to 6 units) of electrogel discs **1017** which are stimulating in tandem. Selecting particular pairs of electrogel discs **1017** to reanimate motion as indicated by a decoded brain signal is advantageously performed by the neuromuscular stimulation cuff **1010**, as each electrogel disc **1017** is connected to the neurological signal processor **1004** individually along a single traces etched into a conductive layer of flexible polyimide material.

[0082] With reference to FIG. **14**, two neuromuscular cuff devices **1010** according to one embodiment are disposed on a preparation bench **1070**. The preparation bench **1070** may be used to keep cuff devices **1010** flat and roll hydrogel tape across electrodes **1016**. Properly adhered hydrogel discs **116** (not shown) should fully cover the surface of electrodes **1014**.

[0083] With reference to FIG. **15**, two neuromuscular cuff devices **1010** according to the embodiment of FIG. **14** are shown. The cuff devices **1010** each include a fork **1026** for additional support when designing and/or placing the cuff devices **1010** over a damaged or degenerative region/pathway of the nervous system (not shown). Again, the fork is optional.

[0084] With reference to FIG. **16**, two neuromuscular cuff devices **1110** according to a different embodiment are shown. A fork **1126** is provided at one end of each cuff for additional design and/or structural support, similar to the fork **626** in FIG. **6**. Here, a second fork **1127** is also provided located along the headers **1128**. Put another way, the flexible fingers **1124** are bracketed by a fork on each end. The

additional fork **1127** provides additional support in combination with fork **1126** for situations when the neuromuscular cuff **1110** must be stretched flat across a surface. Additional fork **1127** can also maintains flexible fingers **1124** within the same damaged or degenerative region/pathway **1120** (not shown), which effectively concentrates stimulation and prevents flexibility.

[0085] With reference to FIG. **17**, the primary side of another embodiment of the neuromuscular cuff **1200** is shown. Hydrogel discs **1216** have been applied to electrodes **1214** (not shown, covered), forming an electrogel disc array **1218**. Two of the four flexible fingers **1224** still include the hydrogel tape before being separated from hydrogel discs **1216**. Electrogel discs **1217** are not connected to each other within the array **1218** so that the electrogel discs **1217** may be independently stimulated.

[0086] While not exposed to the air, copper traces **1242** are viewable through the polyimide cover layer **700**. A secondary side rigidizer **1230** is shown by folding the primary side over at the headers **1228**. Connectors **1234** on the secondary side rigidizer **1230** allow for the neuromuscular stimulation cuff **1200** to be interfaced with the neural signal processor **104** (not shown). Each pin **1236** within connector **1234** is electrically connected with a single electrogel disc **1217**.

[0087] With reference to FIG. **18**, a patient's arm including damaged or degenerative regions/pathways **1020** is placed over two neuromuscular cuff devices **1010** according to the embodiment of FIG. **14**. Flexible headers **1028** may be used as support while positioning the device **1010** under an arm.

[0088] With reference to FIG. **19**, two neuromuscular cuff devices **1010** in an exemplary embodiment are wrapped around a patient's arm region **1020** in preparation for neuromuscular stimulation. The two cuff devices **1010** together provide **160** separate electrodes for stimulating finger or wrist movements. The flexible fingers **1024** permit the neuromuscular cuff to fit around the arm region **1020** at points of varying circumference. Hydrogel discs **1016** (not shown) keep both cuffs **1010** adhered to the arm.

[0089] With reference to FIG. **20**, two neuromuscular cuff devices **1010** according to the embodiment of FIG. **14** are alternatively wrapped around a patient's arm region in preparation for neuromuscular stimulation. Only two flexible fingers **1024** of one of the neuromuscular cuff devices **1010** have been applied, while all of the flexible fingers **1024** on the other cuff device **1010** are already wrapped around the patient's arm. More or less electrodes can be used, as shown in FIG. **20**, depending on the nature of the damage to a patent's nervous system region/pathway **1020** and the type of movement one wishes to reanimate through neuromuscular stimulation.

[0090] In another exemplary embodiment, the flexible fingers of a neural sleeve **2110** do not need to be straight for their entire length. Referring now to FIG. **21**, flexible fingers **2124** extend from first connector **2130**, which has a rectangular shape in this illustration. The flexible conductive pathways **2124** in this embodiment "change" directions as they extend from connector **2130**. For example, an upper flexible finger **2124***a* first extends upwards from the connector **2130**, then changes direction so that its electrodes **2140** are to the right of the connector **2130**. A center flexible finger **2124***b* extends from the right-hand side of the connector **2130** off to the right of the connector. A lower flexible finger **2124***c* first extends downwards from the connector **2130**, then changes direction so that its electrodes **2140** are also to the right of the connector **2130**. Notably, none of the electrodes **2140** are present to the left of the connector **2130**.

[0091] This embodiment of a neural sleeve **2110** also contains more than one connector/rigidizer. As illustrated here, the neural sleeve **2110** has a first connector **2130** and a second connector **2131**. Flexible fingers extend in the same direction (here, to the right) of both connectors. Webbings **2135** connect flexible fingers extending from each connector **2130**, **2131**. There may be any number of webbings **2135**, and the webbings **2135** may connect the flexible fingers at any portion of their length. Here, the webbings **2135** are present along a non-electrode-containing portion **2150** of the flexible fingers (i.e. the header portion). Though not depicted, it is specifically contemplated that the flexible fingers of one connector **2130** may be of a different length from the flexible fingers of the other connector **2131**.

[0092] The electrodes **2140** may be evenly spaced apart along the length of the flexible fingers **2124**, or their spacing may vary, for example becoming shorter or longer, as the distance from the connector **2130** increases. For example, muscle segments get smaller closer to the wrist, so the electrodes need to be closer together as well. However, the electrodes do not need to be present along the entire length of the flexible fingers. As seen here, the flexible fingers **2124** may include a non-electrode-containing portion **2150** extending from the connector, which is similar to the header **528** of the embodiment of FIG. **5**. The flexible finger may also include a non-scalloped electrode-containing portion **2160**, and a scalloped electrode-containing portion **2170** at the distal end of the flexible finger (i.e. distal from the connector). It should be noted that none of the flexible fingers overlap with each other.

[0093] The electrode-containing portions **2160**, **2170** of the flexible fingers have a different shape from each other. One reason for this difference in shape is because, as seen here, the distal ends of the flexible fingers **2124** extend inwardly towards a center axis **2105** of the neural sleeve **2110**. Put another way, the flexible fingers **2124** taper inwards towards the center axis **2105**. The scalloped portions **2170** of adjacent flexible fingers permit them to fit into a smaller area while still providing a suitable number of electrodes (note the electrodes do not change in size). However, the flexible fingers **2124** all still extend in the same direction away from the connector **2130**, i.e. to the right in this figure. Put another way, the flexible fingers comprise a first portion which is transverse to the center axis **2105**, and a second portion which is parallel to the center axis. These portions are particularly seen in the flexible finger **2124***a*, which first extends upwards (i.e. transversely to the center axis), then extends parallel to the center axis.

[0094] This particular embodiment is intended to be used on a patient's arm with the two connectors **2130**, **2131** located near the shoulder, and the scalloped portions **2170** near the wrist and hand.

[0095] In other exemplary embodiments, it is contemplated that the neural sleeve will include both an outer, reusable component, and an inner, disposable component. Advantageously, this allows for a reduced per-use cost for the outer component, while permitting multiple different persons to use the outer component without hygienic concerns. The outer reusable sleeve contains the electrodes.

[0096] It is contemplated that the outer sleeve/reusable component, in several embodiments, could be made of a

flexible, stretchy, and/or compressible fabric material which would fit snugly against the user's arm. The material could also be a dry-fit material, i.e. a material which can move sweat away from the user's arm and permit the sweat to evaporate. The connector and flexible fingers would line the interior of the outer sleeve. For example, conductive threads or fibers could be woven into the fabric material. Alternatively, the conductive traces and electrodes could be printed onto the outer sleeve material using silk-screen technology, for example using conductive polycellulose, a silver-based ink, or carbon-based ink.

[0097] FIG. **22** and FIG. **23** show one exemplary embodiment of this neural sleeve. FIG. **22** is an illustration of a neural sleeve **2210** which is in the form of a fingerless glove. Not visible in FIG. **22** is an inner sleeve containing a conductive medium. FIG. **23** is an illustration of a variation on the neuosleeve outer component. As illustrated here, the neural sleeve **2310** has a user interface on the exterior reusable component, which can be used for control (including registration, activation, configuration and so forth) of individual electrodes or groups of electrodes, allowing a user to configure the electrodes or adjust a stimulation level or pattern. For example, the outer component may include buttons **2311** (e.g. in the form of LED-based touchscreens). While only four buttons are illustrated here, the user interface can include any number of buttons, and those buttons can be of any shape.

[0098] Another aspect of the present disclosure is illustrated in FIG. **24**. The neural sleeve itself may be made in a bidirectional manner, i.e. both ends of the sleeve are of the same construction. It is contemplated that directional implants **2402**, **2404** could be used to provide directional information to the neural sleeve **2410**, e.g. which end of the neural sleeve is closer to the elbow or the wrist. These implants may be located in the patient's limb, or located at opposite ends of the neural sleeve itself. Only one such implant is needed to identify the orientation/direction of the neural sleeve. It is noted that three-dimensional information can also be provided by such implants. Also depicted are the electrodes **2420**.

[0099] FIG. **25** is another embodiment of the reusable outer component. Here, the outer component is in the form of a rigid shell **2510**. The shell is separated into two hemicylindrical halves **2512**, **2514** which are joined together by a hinge **2511**. The hinge runs parallel to the longitudinal axis **2505** of the shell. A closing mechanism **2516** is located on opposite open ends of the halves for keeping the shell closed once it is closed around the user's limb. Within the shell is padding for conforming the shell to the user's limb, or a bladder that can be inflated with air. The shell houses the electrodes **2520** (which are used for both sensing and delivering neuromuscular stimulation), as well as other accompanying electronics. It is contemplated that the disposable inner component (not shown) is first applied to the inside of the shell, or reusable dry electrodes are attached to the inside of the shell. Then the limb is placed in the shell, the shell closes around the limb, and the soft padding conforms around the limb and applies pressure on the electrodes against the limb, or the air bladder is inflated to apply pressure to the electrodes against the limb.

[0100] Alternatively, as seen in the cross-sectional view of FIG. **26**, the neural sleeve can be in the form of a flexible sheet **2610** which is wrapped around the user's limb **2601**. The electrodes (not visible) are spaced throughout the flexible sheet, and a closing mechanism **2605** is present on opposite ends of the sheet. Such a mechanism may be, for example, a hook-and-loop fastener.

[0101] FIG. **27** illustrates another potential embodiment of the neural sleeve. Desirably, the electrodes are fitted snugly against the patient's limb. In this embodiment, the neural sleeve **2710** contains bladders **2720** that can be filled with air or some fluid, causing the neural sleeve to expand and push the electrodes **2730** against the limb. A pneumatic pump can be used to fill the bladders. A directional implant **2702** is also present here at a distal end **2704** of the sleeve. In addition, a handle **2740** is also present at the distal end of the sleeve. This handle is intended to help with registration of the electrodes in known positions, and also provides directionality to the neural sleeve.

[0102] The neural sleeve can incorporate several different types of sensors to provide information on data and feedback on the position and movements of the limb and other body parts. For example, desired position information from the sensors can include a **3**-dimensional location (X, Y, Z coordinates) of various points on the hand and arm relative to the body and to each other, and rotation information of the wrist, elbow, and shoulder relative to the body. Orientation of various body parts with respect to gravity can also be measured with an accelerometer (or inclinometer). Motions of the hand and arm may be derived from position sensors or from independent sensors. Other desired information includes joint angles at the elbow, wrist, thumb and fingers (or other body joints). A variety of concepts for sensors may be used to measure one or more of these data items. Broad categories of sensors include accelerometers, micro-electro-mechanical (MEMS), electronic (based on resistance, capacitance, or resonance), fluid bladders, optical fiber bend sensors, and video tracking systems. Again, these concepts can be generally applied to a neural sleeve on any body part or limb (e.g. arm, hand, leg, foot, etc.).

[0103] FIG. **28** illustrates some aspects which can be used for sensing. This is a magnified picture of a flexible conductive pathway **2810**. Electrodes **2820** are present on the flexible conductive pathway. Here, four electrodes **2820**, **2822**, **2824**, **2826** are illustrated. Electrode traces **2830** are present between the electrodes. As seen here, the trace have a zig-zag pattern, which can be used as a strain gauge.

[0104] In a first sensor aspect, integrated 6-axis MEMS (3-axis accelerometer and 3-axis magnetometer) sensors can be used to measure the position and orientation of the elbow and wrist relative to the location of the shoulder (e.g. the top of the humerus bone). When combined, these sensors can provide a reference frame utilizing the Earth's local gravitational (center of Earth) and magnetic (magnetic north) fields. Using this reference frame in conjunction with a defined 3-axis Cartesian coordinate system, different joints can be located in both position (X, Y, Z) and orientation (Ψ (yaw), θ (pitch), φ (roll)) relative to the origin of the Cartesian coordinate system at the shoulder using these same MEMS sensors. Adjacent MEMS sensors can be placed at strategic locations where the length between sensors does not change (or the change is a sufficiently small amount) when the joints are bent or rotated. For example, sensors can be placed at locations on the shoulder, elbow, and wrist where the distance between adjacent sensors remains fixed due to fixed bone lengths.

[0105] The calculation of position and orientation of each joint may use the 3-axis Cartesian coordinate system and

reference frame, the fixed distance between adjacent sensors, and the 3-axis output signals from the accelerometers or magnetometers. Calculations may involve direction cosine matrices, Euler transformations, or matrix multiplication. For sensors that are not adjacent to the origin, their coordinates may be transformed back to the coordinate system origin through intermediate transformations between adjacent sensors. For example, if there are sensors at the shoulder, elbow, and wrist then the elbow coordinates can be calculated directly relative to the origin (shoulder), but the wrist coordinates must first be calculated relative to the elbow coordinates and then calculated again relative to the origin. The reason for this is because the path lengths must be known for each sensor location and the only way to do this is by coordinate transformations along fixed length paths (e.g., wrist to elbow and elbow to shoulder).

[0106] A wide range of MEMS sensors with integrated 3-axis accelerometers and magnetometers may be used. Examples of manufacturers of these devices include Analog Devices, Bosch, Freescale, Honeywell, and ST Microelectronics. Also, 9-axis sensors available with integrated 3-axis, accelerometers, magnetomers, and gyros may be used. Additional solutions may exist for joint locations where a fixed bone length cannot be counted on such as the hand and fingers.

[0107] In a second sensor aspect, a capacitive sensor may comprise a flexible insulating dielectric layer with thin flexible electrodes on either side. A voltage differential is applied between the electrodes, creating a capacitor. When the dielectric changes shape (e.g. due to pressure or bending), the capacitance of the sensor changes and can be detected by electronic measuring techniques. Capacitive pressure sensors may be used in a variety of mechanical systems to measure barometric pressure or pressures inside equipment. Such sensors may be incorporated into the sleeve at joints (e.g. wrist, elbow) such that bending of the joint stretches or bends the dielectric layer. The sensors may also be applied away from joints (e.g. middle of the forearm) to measure the pressure of the sleeve against the arm.

[0108] In a third sensor aspect, resistive bend or stretch sensors (e.g. strain gauges) may be used. These sensors may be made from any material that changes electrical resistance when stretched or strained. This change in resistance is measured with a standard electrical circuit. Strain gauges may use metal, either alone or applied to a flexible thin film substrate. Resistive bend sensors or strain gauges also can be made from the following three general classes of materials. First, elastomers (such as silicone rubber) or polymers containing electrically conductive fillers may be used. Fillers can include carbon black, graphite, graphene, carbon nanotubes, silver nanoparticles, silver nanowires. Second, inherently conductive polymers may be used. Third, piezoelectric polymers may be used.

[0109] Resistive sensors may also be applied at joints. Bending of the joint will stretch the sensor, causing a measurable change in resistance. Pronation and supination of the wrist can be measured by using sensors in the form of long elastic bands that stretch at an angle from the wrist to the elbow. Each motion (e.g. pronation and supination) will create opposite effects in the bands, causing one to lengthen and the other to shorten.

[0110] In a fourth sensor aspect, resonant bend sensors may be used. Resonant bend sensors comprise RLC circuits that change resonance frequency when one of the three components changes its value. Rather than having a separate circuit to measure the resistance of each resistive sensor element, the resistive sensors may be wired in parallel at appropriate locations in the neural sleeve. Each sensor may have a different resistance to produce a different resonant frequency in the circuit. A sweep of voltage or current may be used to test each sensor in rapid succession; this measures changes in resonant frequency to determine changes in resistance and thus in strain of that specific sensor.

[0111] In a fifth sensor aspect, a sensor may comprise numerous trapped volumes (e.g. fluid bladders) containing air or liquid that respond to changes in motion. For each motion to be detected, a fluid bladder of a specifically designed shape would be placed at an appropriate location such that the pressure in the bladder would change only in response to that motion. For example, there may be one bladder at the wrist in a position and shape to detect wrist flexion, while a different bladder at the wrist detects pronation. Sensing elements, such as pressure transducers or strain gauges, would respond to the pressure changes.

[0112] In a sixth sensor aspect, bend sensors also can be made from fiber optics rather than electrical components. The principle is similar to the electronic bend sensors in that when the fiber is bent, a measurable property such as frequency or attenuation changes and this change can be measured. The usage would be similar to the bend sensors described above, with fiber optic bend sensors integrated into the sleeve at joints such as the wrist, such that the sensor bends with bending of the joint.

[0113] In a seventh sensor aspect, a variety of video motion tracking systems may be used to measure and track the position of the limb while using the neural sleeve. These systems are similar to the ones used for motion capture in movies and video games. One or more cameras may focus on the sleeve during use. To provide the best accuracy, these systems would include markers at key locations on the sleeve to be tracked. Depending on the type of marker selected, the camera may operate in visible light or infrared. A number of options are available for markers, including: (i) dots in a contrasting color or multiple distinct colors that can be tracked by the external camera(s) (similar to typical movie motion capture); (ii) colored light emitting diodes (LEDs); (iii) Infrared (IR) LEDs at various frequencies in the near-IR range; and (iv) thermal elements such as electrically resistive heaters that create localized warm spots to be tracked by a camera sensitive to long wavelength infrared (LWIR).

[0114] FIG. **29** is a perspective illustration of a neural sleeve **2910** showing how various sensors could be placed thereon and implemented. The neural sleeve extends from the shoulder down to the wrist. First, a trio of MEMS sensors **2920**, **2922**, **2924** are located at the shoulder, elbow, and wrist, respectively. These can be used to measure position and orientation relative to each other. Next, a capacitive sensor **2930** is located at the elbow. Resistive bend sensors **2940**, **2942** stretch at an angle from the wrist to the elbow. Motion will create opposite effects in these sensors, causing one to lengthen and the other to shorten.

[0115] As discussed above, it is contemplated that the neural sleeve will be made of a reusable outer component and an inner component that can be easily disposed of. The inner component comprises a conductive medium that con-

tacts the electrodes present in the outer component and provides a conductive interface/medium between the electrode and the user's skin.

[0116] In particular embodiments, the conductive medium can be a hydrogel, or a lotion, or a conductive polymer. In some embodiments, the conductive medium is more conductive in a z-direction and less conductive in either of a x-direction or a y-direction. Put another way, the conductive medium may become more conductive upon application of external pressure, in the direction of external pressure. This property can be obtained from a compressible polymer and a conductive filler dispersed in the compressible polymer. The conductive filler can be in the form of carbon fibers, carbon nanotubes, or metallic particles such as silver, gold, platinum, or palladium. The conductive filler is sparsely distributed in the polymer so that when pressure is applied, the conductive fillers make contact with each other and provide a conductive path from the electrode to the skin. Other conductive hydrogels include a cross-linked alginate polymer or a cross-linked polymeric hydrogel.

[0117] In alternative embodiments, to facilitate attachment to a patient, the conductive medium may be selected such that it becomes more tacky or sticky upon application of an electrical current, a change in temperature, a change in pH, or a change in moisture. The conductive medium may be a stimuli-sensitive polymer. To further facilitate attachment and/or delivery of electrical simulation, the electrodes may include concentric rows of teeth about 200 μm to about 300 μm in height.

[0118] If desired, the neural sleeve may be configured for gesture control of various devices. Examples of devices that may be controlled are: a computer cursor; an automatic remote; and a haptic interface. The gesture control aspects are also used in virtual reality applications. Gesture control is facilitated by the addition of sensors on the neuromuscular stimulation device/neural sleeve. It is noted that the electrodes present in the neural sleeve for stimulation can also be used for sensing.

[0119] In another aspect, a neural sleeve device is used to support gait-training. To facilitate this, the neural sleeve would be adapted to cover both a leg portion and a foot portion of the patient. This allows the neural sleeve to cover both the muscles and the joint of a patient, and advantageously allows for sensing of a foot flexing. A hip portion may also be covered; this allows for stimulation of additional areas to promote recovery following surgery.

[0120] In yet another aspect, neuromuscular stimulation may be delivered to the backside of the patient. To facilitate this, the neuromuscular stimulation device may be in the form of a shirt, vest, garment, belt, or so forth, with the electrodes appropriately placed to contact the backside.

[0121] The neuromuscular sleeve/neural sleeve could be operated in a wireless, battery-operated mode. In this case, the battery pack and the electronics module can be strapped on the upper arm of the subject in the form of an arm band. The device can be connected to the user's mobile device and/or PC for data transfer and real time tracking/monitoring.

[0122] It will further be appreciated that the disclosed techniques may be embodied as a non-transitory storage medium storing instructions readable and executable by a computer, (microprocessor or microcontroller of an) embedded system, or various combinations thereof. The non-transitory storage medium may, for example, comprise a hard disk drive, RAID or the like of a computer; an electronic, magnetic, optical, or other memory of an embedded system, or so forth.

[0123] The present disclosure has been described with reference to exemplary embodiments. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the present disclosure be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

1. A device for neuromuscular stimulation, comprising:
a reusable sleeve; and
one or more electrodes housed within the reusable sleeve.

2. The device of claim **1**, wherein the reusable sleeve comprises at least two flexible fingers along which the one or more electrodes are located, the flexible fingers extending in the same direction from a first connector, and one or more conductive mediums disposed on each flexible finger.

3. The device of claim **2**, wherein the conductive medium comprises a hydrogel, a lotion, or a conductive polymer.

4. The device of claim **2**, wherein the at least two flexible conductive pathways can be wrapped helically.

5. The device of claim **2**, further comprising a fabric layer disposed on an exterior of the reusable sleeve.

6. The device of claim **2**, wherein each flexible finger includes a conductive circuit layer.

7. The device of claim **6**, wherein each flexible finger includes an insulating base layer upon which the conductive circuit layer is laid.

8. The device of claim **6**, wherein each flexible finger includes an insulating cover layer over the conductive circuit layer.

9. The device of claim **2**, wherein each flexible finger includes a plurality of hydrogel discs disposed over each electrode.

10. The device of claim **9**, wherein the rigidizer interfaces with a processing device.

11. The device of claim **2**, having the first connector and a second connector, wherein at least two additional flexible fingers also extend from the second connector in the same direction as the flexible fingers extending from the first connector; and at least one webbing connects a flexible finger extending from the first connector to a flexible finger extending from the second connector.

12. The device of claim **11**, wherein the flexible fingers taper towards a center axis of the reusable sleeve.

13. The device of claim **11**, wherein each flexible finger includes:
a non-electrode-containing portion; and
a scalloped, electrode-containing portion distal from the connector.

14. The device of claim **13**, wherein each flexible finger further includes a non-scalloped, electrode-containing portion.

15. The device of claim **11**, wherein at least one flexible finger comprises:
a first portion which is transverse to a center axis of the reusable sleeve; and
a second portion which is parallel to the center axis of the reusable sleeve.

16. The device of claim **1**, comprising an inner disposable sleeve, the inner disposable sleeve comprising a conductive medium in contact with the multiple electrodes.

17. The device of claim **16**, wherein the conductive medium comprises a hydrogel which is relatively more conductive in a z-direction than in a x-direction or a y-direction.

18. The device of claim **16**, wherein:

the conductive medium is less conductive in a regular state; and

the conductive medium becomes more conductive upon application of external pressure in a direction of the external pressure.

19. The device of claim **18**, wherein the conductive medium comprises a compressible polymer and a conductive filler dispersed in the compressible polymer.

20. The device of claim **19**, wherein the conductive filler comprises carbon fibers, carbon nanotubes, or metallic particles.

21. The device of claim **16**, wherein the conductive medium is dry in an initial state and becomes tacky upon any one of: application of an electrical current; a change in temperature; a change in pH; or a change in moisture; or wherein the conductive medium comprises a stimuli-sensitive polymer.

22. The device of claim **1**, wherein each electrode of the multiple electrodes includes concentric rows of teeth about 200 μm to about 300 μm in height.

23. The device of claim **1**, wherein the reusable sleeve comprises a flexible material.

24. The device of claim **1**, wherein the reusable sleeve comprises:

a rigid shell; and

a hinge running parallel to a longitudinal axis of the reusable sleeve.

25. The device of claim **1**, wherein the reusable sleeve comprises a user interface for selectively configuring electrodes and adjusting stimulation level or pattern.

26. The device of claim **25**, wherein the reusable sleeve comprises buttons including light emitting diode (LED) based touchscreen displays on a back side of each of the multiple electrodes.

27. The device of claim **1**, wherein the reusable sleeve comprises an accelerometer; and is configured for gesture control of devices.

28. The device of claim **1**, wherein the reusable sleeve is expandable.

29. The device of claim **1**, wherein the reusable sleeve comprises a compression sleeve fabric on which the multiple electrodes are printed using silk-screen technology employing conductive polycellulose or silver/carbon-based ink.

30. The device of claim **29**, further comprising a conductive pathway including an accelerometer.

31. The device of claim **1**, wherein the reusable sleeve comprises a flexible circuit including electrodes connected by electrode traces that (i) house sensors and (ii) the electrode traces are arranged in a zig-zag pattern.

32. The device of claim **31**, wherein the sensors comprise any combination of pressure sensors; strain gauges; accelerometers; a micro-electro-mechanical system (MEMS) including a 3-axis accelerometer and 3-axis magnetometer; a capacitive sensor including a flexible insulating dielectric layer sandwiched between flexible electrodes; a stretch sensor including a material that changes electrical resistance when stretched or strained; a resonant bend sensor including a resistance-inductance-capacitance (RLC) circuit; a sensor including at least one bladder configured to hold a fluid or air; a fiber optic cable and a measurement tool configured to measure a bend in the fiber optic cable based on a frequency or attenuation change in a signal of the fiber optic cable; and a video motion tracking system configured to track a marker of the reusable sleeve.

33. The device of claim **1**, wherein the reusable sleeve comprises conductive fibers and a dry fit material.

34. The device of claim **1**, wherein the reusable sleeve is in the form of a fingerless glove.

35. The device of claim **1**, wherein the multiple electrodes are woven into the reusable sleeve using conductive threads.

36. The device of claim **1**, wherein the reusable sleeve is configured to:

cover both a leg portion and a foot portion of a patient; and

support gait-training.

37. The device of claim **1**, wherein the reusable sleeve comprises a shirt configured to deliver electrical stimulation to a backside of a patient.

38. The device of claim **1**, wherein the multiple electrodes are configured to both deliver electrical simulation and sense a neural signal of a patient.

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