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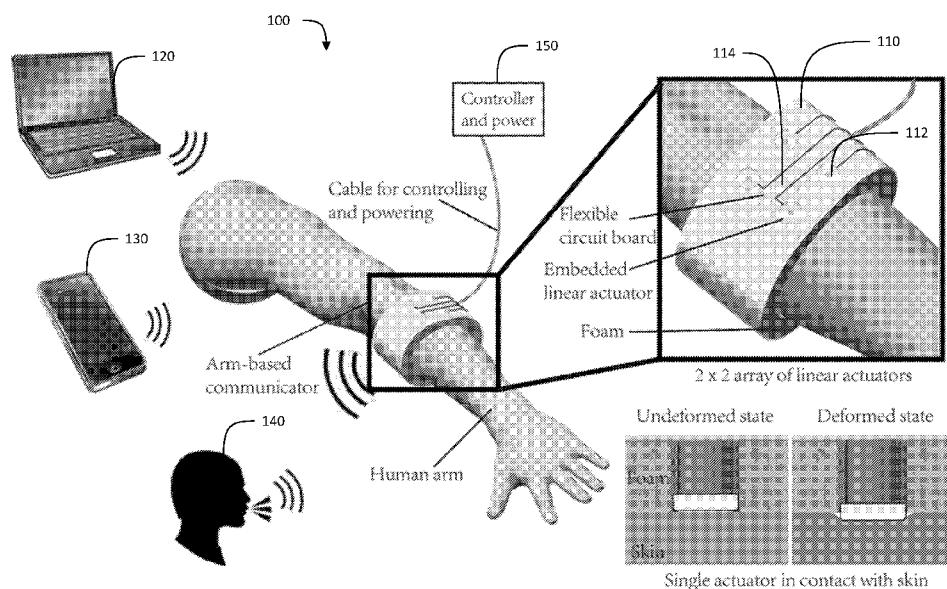


FIG. 1

(57) Abstract: A wearable haptic device and methods of operating a wearable haptic device to provide haptic stimulation to a user are described. The haptic device comprises a band configured to be worn around a portion of a user's body, circuitry coupled to a flexible substrate, wherein the flexible substrate is coupled to the band, and a plurality of dielectric elastomer actuators electrically connected to the circuitry, each of the plurality of dielectric elastomer actuators including a rolled elastomer structure having electrode elements embedded therein, wherein the plurality of dielectric actuators are coupled to the circuitry to provide haptic stimulation to the portion of the user's body when the wearable haptic device is worn on the portion of the user's body and is actuated.



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– 1 –

A WEARABLE SOFT HAPTIC COMMUNICATOR BASED ON DIELECTRIC ELASTOMER LINEAR ACTUATORS

BACKGROUND

[0001] A wide variety of haptic devices have been, and continue to be, developed for use in such social tasks as Braille communication for the blind, virtual reality/augmented reality, as well as possible future long-distance communication techniques. Such devices are often used to provide tactile stimulation to the fingers or back of the hand, which are particularly sensitive parts of the user's body.

SUMMARY

[0002] Some embodiments relate to a wearable haptic device. The wearable haptic device comprises a band configured to be worn around a portion of a user's body, circuitry coupled to a flexible substrate, wherein the flexible substrate is coupled to the band, and a plurality of dielectric elastomer actuators electrically connected to the circuitry, each of the plurality of dielectric elastomer actuators including a rolled elastomer structure having electrode elements embedded therein, wherein the plurality of dielectric actuators are coupled to the circuitry to provide haptic stimulation to the portion of the user's body when the wearable haptic device is worn on the portion of the user's body and is actuated.

[0003] In at least one aspect, the embedded electrode elements comprise at least one percolative electrode network.

[0004] In at least one aspect, the percolative electrode network comprises carbon nanotubes, metallic nanowires, or a combination of carbon nanotubes and metallic nanowires.

[0005] In at least one aspect, the percolative electrode network comprises carbon nanoparticles, metallic nanoparticles, or a combination of carbon nanoparticles and metallic nanoparticles.

[0006] In at least one aspect, the rolled elastomer structure comprises a plurality of elastomer layers, and each of the plurality of layers of the rolled elastomer structure comprises a percolative electrode network formed on a surface of the elastomer layer.

[0007] In at least one aspect, the flexible substrate comprises a flexible printed circuit board including the circuitry.

[0008] In at least one aspect, the rolled elastomer structure includes a first conductive surface electrically connected to a first portion of the flexible printed circuit board and a second

– 2 –

conductive surface electrically connected to a second portion of the flexible printed circuit board such that when a voltage is applied across the first and second conductive surfaces the dielectric elastomer actuator changes in shape along an axial dimension normal to a surface of the flexible printed circuit board.

[0009] In at least one aspect, the first conductive surface is directly electrically connected to the first portion of the flexible printed circuit board and the second conductive surface is indirectly electrically connected to the second portion of the flexible printed circuit board using at least one wire arranged within an opening of the rolled elastomer structure.

[0010] In at least one aspect, the flexible substrate comprises a flexible pad.

[0011] In at least one aspect, each of the plurality of dielectric elastomer actuators further includes a cap portion.

[0012] In at least one aspect, the cap portion comprises a flat ring, a smooth ring, or a curved surface.

[0013] In at least one aspect, the plurality of dielectric elastomer actuators comprises a first dielectric elastomer actuator including a cap portion having a first shape and a second dielectric elastomer actuator including a cap portion having a second shape, wherein the first shape and the second shape are different.

[0014] In at least one aspect, each of the dielectric elastomer actuators includes a flexible barrier arranged between the cap portion and a portion of the user's body to which haptic stimulation is provided.

[0015] In at least one aspect, the flexible barrier comprises fabric or a flexible membrane.

[0016] In at least one aspect, the flexible barrier is configured to repel fluids from skin of the user's body.

[0017] In at least one aspect, the wearable haptic device further comprises drive circuitry configured to provide a drive signal to drive one or more of the plurality of dielectric elastomer actuators by applying a differential voltage across the rolled elastomer structure.

[0018] In at least one aspect, the drive circuitry includes at least one multiplexer arranged to send the drive signal to one or more of the plurality of dielectric elastomer actuators simultaneously or separately.

[0019] In at least one aspect, the band is configured to be worn around the arm or wrist of the user.

– 3 –

[0020] In at least one aspect, the band is configured to be worn in contact with a shoulder of the user.

[0021] Some embodiments are directed to a method of providing haptic stimulation to a user. The method comprises actuating one or more of a plurality of dielectric elastomer actuators arranged on a wearable haptic device including a band configured to be worn around a portion of a user's body, wherein each of the plurality of dielectric elastomer actuators includes a rolled elastomer structure having electrode elements embedded therein.

[0022] In at least one aspect, actuating the one or more of the plurality of dielectric elastomer actuators comprises actuating at least two of the plurality of dielectric elastomer actuators simultaneously.

[0023] In at least one aspect, actuating the one or more of the plurality of dielectric elastomer actuators comprises actuating at least two of the plurality of dielectric elastomer actuators in a time sequence to simulate motion of the haptic stimulation.

[0024] It should be appreciated that all combinations of the foregoing concepts and additional concepts discussed in greater detail below (provided such concepts are not mutually inconsistent) are contemplated as being part of the inventive subject matter disclosed herein. In particular, all combinations of claimed subject matter appearing at the end of this disclosure are contemplated as being part of the inventive subject matter disclosed herein.

BRIEF DESCRIPTION OF DRAWINGS

[0025] FIG. 1 schematically illustrates a wearable haptic system in accordance with some embodiments;

[0026] FIGS. 2A-2G illustrate steps in fabricating and testing a rolled dielectric elastomer actuator implemented on an armband in accordance with some embodiments;

[0027] FIGS. 3A-C illustrate benchtop characterizations of individual dielectric elastomer actuators used in a two by two array in accordance with some embodiments;

[0028] FIG. 3D illustrates an equivalent spring and dashpot model for a dynamic response of actuators used in accordance with some embodiments;

– 4 –

[0029] FIG. 4 illustrates thermal images of an actuator when operated in accordance with some embodiments.

[0030] FIG. 5A shows an example of an actuation signal smoothly varying from 0 V DC to a sinusoidal waveform in accordance with some embodiments;

[0031] FIG. 5B shows a circuit diagram for switching high voltage sinusoidal waveforms to the desired actuator in the array in accordance with some embodiments;

[0032] FIGS. 6A and 6B illustrate an armband with a single actuator in accordance with some embodiments;

[0033] FIG. 6C shows a plot of actuation voltage at 200 Hz as a function of trial number based on testing using the armband of FIG. 6A in accordance with some embodiments;

[0034] FIG. 6D shows a plot of detection threshold voltage as a function of actuation frequency for a single actuator on a forearm based on testing using the armband of FIG. 6A in accordance with some embodiments;

[0035] FIG. 7A illustrates an armband with an array of actuators in accordance with some embodiments;

[0036] FIG. 7B shows a plot of the accuracy of position perception for subjects at different actuation frequencies using the armband of FIG. 7A;

[0037] FIG. 8A illustrates the armband of FIG. 7A with four possible directions of actuation sequence indicated; and

[0038] FIG. 8B shows a plot of the accuracy of directional perception for human subjects for the different frequencies of actuation using the armband of FIG. 8A.

DETAILED DESCRIPTION

[0039] The inventors have recognized and appreciated that some conventional haptic devices that provide tactile stimulation to a user's hand and/or fingers can limit the user's active use of the hand/fingers for other important tasks such as grasping and manipulating objects. By contrast, an arm-based wearable device would free the hands, while potentially functioning as an

– 5 –

effective haptic communication tool. However, as the arm is significantly less sensitive to touch, the forces and displacements required for an arm-based haptic device are typically higher than those for finger-based communication. Some embodiments relate to providing tactile stimulation and communication using a wearable array (e.g., a two by two array) of dielectric elastomer actuators.

[0040] Dielectric elastomer actuators exhibit an unusual combination of large displacements, moderate bandwidth, low power consumption, and impedance comparable with human skin, making them attractive for haptic devices. The physics of dielectric elastomer actuation are based on the electrostriction of a soft elastomer when an electric field is applied through the thickness of the elastomer. By creating a rolled structure, the basic biaxial expansion of a soft elastomeric dielectric sheet in response to an applied electric field can be converted into an axial expansion that can generate an actuation force. Recent work on a 10 mm-long rolled actuator has demonstrated actuation forces of approximately 1 N, displacements up to 0.8 mm, and a bandwidth from DC to over 200 Hz for applied voltages up to 1,000 V. Human testing with individual actuators demonstrated that this actuation can be perceived on the forearm, providing the basis for both the development of a wearable actuator array (e.g., a two by two array) and its use in more extensive perception evaluation, as described herein.

[0041] Some embodiments relate to an architecture of actuators and their mechanical and electrical integration into a wearable haptic device (e.g., a wearable armband). FIG. 1 illustrates an example of a haptic communication system 100 that includes an armband device 110 with an embedded actuator array 112 arranged on a flexible circuit board 114. A two-by-two array of actuators is shown. However, it should be appreciated that any size or shape of actuator array may alternatively be used. As shown, armband device 110 may be configured to communicate with one or more electronic devices including, but not limited to one or more computers 120 and/or one or more mobile devices 130. In some embodiments armband device may be configured to receive voice-based instructions from a user (e.g., the wearer of armband device 110 or some other user). In some embodiments, armband device 110 may be configured to receive control instructions and/or power from controller 150. For instance, voice-based commands provided by user 140 may be interpreted by mobile device 130 (e.g., using a speech recognition process). Commands for controlling armband device 110 may then be sent to controller 150 to provide actuation of one or more of the actuators in embedded actuator array 112. FIG. 1 also shows a single actuator of embedded actuator array 112 in two states – an

– 6 –

undeformed state in which the actuator is not in contact with the skin (or only depresses the skin slightly) and a deformed state in which the actuator compresses the skin surface relative to the undeformed state to provide tactile stimulation to the user.

[0042] An example of dielectric elastomer actuators used in accordance with some embodiments is shown in FIG. 2. Fabrication of multilayer actuators from a mix of Sylgard and Ecoflex silicone elastomer is a three-step process in accordance with some embodiments. In the first step, thin layers of a silicone elastomer are spin-cast and a percolative carbon nanotube (CNT) electrode network is stamped onto their surfaces through a mask to define the electrode shape and interconnect tabs. As an alternative to CNT or metallic nanowire electrodes, some embodiments instead use percolative electrodes made of carbon or metallic nanoparticles. In the second step, multilayers of these electroded elastomer are formed by sequential coating. In the third step, the electroded multilayers are rolled to form a “Swiss roll”. The ends of the dielectric elastomer actuators are then cut using a blade and the exposed ends are covered in colloidal silver paste to make electrical connections to the CNT electrodes. Finally, the rolled actuator is glued to a printed circuit board with copper electrical interconnects and a flat ring cap is glued to the other end – the end that will be in contact with the skin. The other set of electrodes are connected by an insulated wire through the hollow core of the actuator to a copper electrode on the other side of the printed circuit board. When a voltage is applied to the electrodes, the actuator extends in the axial direction, pushing against the relatively stiff printed circuit board, and transferring force to the skin.

[0043] To integrate multiple actuators into a wearable device, the actuators are mounted on a thin, flexible printed circuit board fixed to a textile sleeve with Velcro straps. Soft foam was placed on the inside of the sleeve with holes in which the actuators were placed. Insulated electrical cables are used to connect the conductors on the printed circuit board to the power and drive electronics. In some embodiments, one or more flexible pads may be used in place of a flexible printed circuit board. For instance, one or more discrete pads may be attached to an inner portion of a band or may be integrated with an inner band to hold in place wiring that couples the actuators to the control circuitry.

[0044] FIG. 2 further illustrates device fabrication and integration in accordance with some embodiments. FIG. 2A shows the rolling process of a multilayered dielectric elastomer actuator (DEA). FIG. 2B shows a linear actuator after rolling. FIG. 2C shows four actuators prepared for assembly. FIG. 2D shows a flat ring, made of acrylonitrile butadiene styrene (ABS)

– 7 –

attached to the top of each actuator to serve as the indenter contacting the skin. In some embodiments, a ring configuration is preferred to a hemispherical cap to minimize the height of the actuator. The insert in FIG. 2D shows how the electrode may be connected by an insulated wire to the bottom side ground electrode. The actuators are centered one inch apart on a thin, flexible printed circuit board. FIG. 2E shows a two-by-two array of actuators mounted on a flexible circuit substrate. FIG. 2F shows foam with cut holes mounted on top of circuit and encompass the actuators. FIG. 2G shows mounting of the device on a user's arm during human testing. The arm is supported by soft, adjustable pedestals at the wrist and elbow, and the wearable device is positioned on the arm as shown.

[0045] Although the wearable haptic device shown in FIGS. 1 and 2 is configured as a wearable armband configured to be worn around a user's arm, a wearable haptic device in accordance with some embodiments may be configured to be worn around or on a different portion of a user's body. For instance, in some embodiments, the wearable haptic device is configured as a patch that may be affixed to a shoulder or other portion of the user's body.

Example device testing

[0046] The force-displacement characteristics of the individual actuators were measured as a function of applied voltage and frequency. Two sets of measurement were made: free displacement and blocked force. In addition, these parameters were evaluated with the actuator pressing into a block of elastomer chosen to have a similar elastic modulus as that of skin.

[0047] The free displacement and blocked force data as a function of frequency for four nominally similar actuators are reproduced in FIG. 3. FIGS. 3A and 3B show the displacement, and blocked force, respectively, of the individual dielectric elastomer actuators of a two-by-two array during benchtop testing. Each actuator was 10 mm high, had an active (electroded) length of 8 mm and consisted of seven turns of a multilayer consisting of ten layers (with a cross sectional area of 0.66 cm²). Although nominally the same, actuator four exhibited a smaller free displacement and blocked force than the other three actuators. Some variation in the free displacements and blocked forces was observed from one actuator to another, but the fourth actuator exhibited an unusually large variation. Nevertheless, as shown in the human perception tests below, the variation in actuator four was not apparent in the recorded responses.

[0048] FIG. 3C is a plot that shows a comparison between the blocked force (e.g., as represented in FIG. 3B) with the case in which the actuator is blocked by an elastomer having

– 8 –

similar elastic properties to skin. The lower observed forces are due to the actuator displacing into the skin proxy. As shown, the blocked forces were smaller when the actuator was in contact with the artificial skin, especially at lower frequencies. It has been found previously that the frequency response of the actuator free displacement and blocked force could be well represented by a simple spring-dashpot model using measured values of the viscoelastic properties of the elastomer and the measured electrical characteristics of the actuator. For dielectric elastomer actuators used in accordance with some embodiments, it was found that the dynamic properties of the actuator pressing into an elastomer block could also be represented by the same model by incorporating additional viscoelastic and elastic elements to represent the response of the elastomer block representing skin.

[0049] FIG. 3D shows an equivalent circuit model and represents the dynamic response of an actuator in contact with the skin as two spring-dashpot-mass systems in parallel. The actuator has mass, a spring constant, and viscous properties represented by m_1 , k_1 , and η_1 , respectively. The equivalent properties of the skin are m_2 , k_2 , and η_2 . When a voltage is applied to the actuator it generates a Maxwell stress that, in turn, produces an input force F_z on this parallel system. For the combined actuator and skin system, the force equilibrium is:

$$(m_1 + m_2)\ddot{x} = F_z - (\eta_1 + \eta_2)\dot{x} - (k_1 + k_2)x \quad (1)$$

where x is the displacement of the contact point between them. Force equilibrium for the skin system is:

$$m_2\ddot{x} = F_c - \eta_2\dot{x} - k_2x \quad (2)$$

where F_c is the force at the contacting surface.

[0050] Assuming that the actuation is sinusoidal, i.e., $F_z = F \sin \omega t$, with amplitude F and frequency ω , then the amplitude of F_c (represented by F_{ca}) can be determined using equations (1) and (2):

$$F_{ca} = \frac{\sqrt{(k_2 - m_2\omega^2)^2 + (\eta_2\omega)^2}}{\sqrt{((k_1 + k_2) - (m_1 + m_2)\omega^2)^2 + ((\eta_1 + \eta_2)\omega)^2}} F \quad (3)$$

[0051] In the limit of the actuator and skin having negligible viscous responses, the force at the contact can be expressed in the simplified form:

$$F_{ca} = \left| \frac{k_2 - m_2\omega^2}{(k_1 + k_2) - (m_1 + m_2)\omega^2} \right| F \quad (4)$$

[0052] When the actuator is in contact with a rigid block, $k_2 \rightarrow \infty$:

$$F_{ca} = F \quad (5)$$

– 9 –

which is the blocked force for arbitrary ω .

In contrast, when the actuator pushes into a block having a similar stiffness to its own, $k_1 = k_2$, and a similar mass, the force drops to half:

$$F_{ca}(\omega) = \frac{1}{2} F(\omega) \quad (6)$$

[0053] Comparison between the measurements described herein and predictions from this model using the simplest possible assumptions of the same masses and stiffnesses, as well as negligible viscous losses, indicate that they are comparable. The difference between the blocked force against a rigid block is almost three times the force applied to the skin proxy, in contrast to the prediction in equation (6), however this ratio is dependent on actuation frequency. This frequency dependence indicates that the assumption of a negligible viscous response was overly simplistic – but without knowing the effective masses, a solution to equation (1) may not be feasible.

[0054] As the linear actuators are expected to be in direct contact with skin, a thermal characterization test was performed to ensure that the heat generated at high frequencies will not burn the skin or cause any harm to the wearer. For this characterization, infrared images were recorded for one actuator operated continuously for one minute at 10 Hz, 60 Hz, and 200 Hz, as shown in FIG. 4. It can be observed from the thermal images that heating increased with actuation frequency, but even at 200 Hz, the highest temperature only reached 29.1°C, which is safe for direct contact with the skin. In the human subject tests, the actuation was for only one second, so in practice the heating was considerably lower than shown in FIG. 4.

[0055] In some embodiments the actuation circuitry is designed to be able to drive the four actuators independently over a range of frequencies and voltages. Furthermore, because the sensitivity of human skin varies widely for different vibration frequencies, the actuation circuitry may be designed to avoid the generation of any harmonic signals that could be detectable and confuse the subject's perception. In some embodiments a USB-based data acquisition device (e.g., USB-6002, National Instruments Inc.) is used to generate arbitrary waveforms with a desired frequency (e.g., DC to 300 Hz) and voltage levels (e.g., 1 V peak-to-peak). The sampling frequency of the output waveform may be fixed at 4 kHz to maintain signal fidelity. A high voltage amplifier (e.g., Model 610e, Trek Inc.) may be used to amplify the low voltage output waveforms by 1000× to obtain high voltage waveforms for actuation. In the testing described herein, the current limit of the amplifier was set to 0.2 mA to ensure safe operation. The high

– 10 –

voltage waveforms may be designed so that there is a smooth transition from 0 V to a sinusoidal wave with $V_{pp}=1000$ V, for any given frequency, as shown in FIG. 5A. To obtain the smooth transition from 0 V DC to a sinusoidal wave, for example, as shown in FIG. 5A, the sinusoidal waves were voltage-shifted by $V_{pp}/2$ and phase-shifted by $-\pi/2$.

[0056] FIG. 5B shows a circuit diagram for switching high voltage sinusoidal waveforms to the desired actuator in an actuator array in accordance with some embodiments. As shown in the circuit diagram of FIG. 5B, the high-voltage waveform may be controlled using high voltage transistors acting as switches to switch the high voltage sinusoidal waveforms to the desired actuator. When the transistor switch is turned on by a control signal, a smooth high voltage sine wave drives the actuator. A switch may be used to send the control to the individual actuators. When a two-by-two actuator is used, four switches may be implemented to control the application of the high voltage waveform to the actuators in the array. Such a topology allows more than one actuator to be simultaneously actuated by turning on the corresponding transistor switches. The transistors may be biased such that their control signals are low voltage (5 V), and may be generated using a USB data acquisition device, thus, affording control of the high voltage waveform directly through a software interface. Although the circuitry shown in FIG. 5B was designed for a two by two actuator array, it is scalable to an arbitrary number of actuators.

[0057] Despite the high voltages, the current requirements of actuators used in some embodiments are relatively small (~ 100 μ A) because of their small capacitance (~ 1 nF). Consequently, the power requirements of the actuators are also small, even at high voltage levels (~ 1 kV). With such low current and power requirements, it is possible to set a strict current limit on the high voltage supply so that current does not exceed 0.2 mA at any stage of the test, even in case of a short circuit. (During human subject testing, the input and output signals were also constantly monitored using oscilloscopes and built-in displays to make sure no surge or spikes were registered). For added safety, all the electronic components, including the wires and connectors, were rated for safe operation at 2500 V, even though the maximum voltage applied during testing was limited to 1000 V.

Example psychophysical testing results

[0058] Two participants were tested to estimate the minimum actuation voltage at which the participant could barely detect the haptic signal. The absolute detection thresholds were

– 11 –

determined for four test frequencies (1, 10, 60, 200 Hz) at the volar side of the mid forearm, using a widely used three-interval forced-choice (3IFC) paradigm combined with the 1-up 3-down adaptive staircase procedure. Using this procedure, the estimated threshold corresponds to the 79.4% percentile point on the psychometric function. The procedure was repeated for each test frequency and the order of frequencies were randomized for each participant.

[0059] Participants were asked to wear an armband embedded with the single dielectric elastomer actuator (DEA). An illustration of the device with a single DEA is shown in shown in FIGS. 6A and 6B. The armband was arranged on the participant's arm such that the actuator was placed on the volar side of the upper forearm. The actuation voltage was controlled using a high voltage transistor switch (*Class A* amplifier) described in the previous section. Each trial consisted of three time intervals, and a light was used to indicate the occurrence of each time interval to the participant. The actuator was actuated in one of the three intervals at random and the participant was asked to identify the time interval of actuation. The response was recorded and the next trial resumed. The procedure continued for 50 trials at a fixed actuation frequency and voltage levels were dynamically adjusted using the following protocol:

- Initially, the voltage was set at the maximum value of 1000 V.
- If the subject response was correct three consecutive times, the actuation voltage was decreased by a factor of 1.2 (-1.58 dB) and the procedure repeated.
- If the response was incorrect, the actuation voltage was increased by a factor of 1.2 (+1.58 dB) before the procedure was repeated.

[0060] FIG. 6C shows an example plot of the actuation voltage as a function of the trial number at 200 Hz for two participants. The points at which the voltage levels were changed from increasing to decreasing, and vice-versa, are referred to as reversal points. The voltage levels at points of reversal were averaged to obtain the mean threshold voltage at that frequency, as indicated by the dashed lines.

[0061] FIG. 6D is an example plot that shows mean threshold voltage at four test frequencies for two participants. Error bars indicate the standard deviations of reversal points per run. Both participants were able to feel all test frequencies at 1000 V. The voltage thresholds decreased with frequency. The most sensitive frequency was 200 Hz, where on average 300-400 V actuation was detectable.

[0062] As all participants could reliably perceive the actuation at 1000 V, an experiment was performed to determine whether the subjects were able to identify the location of actuation

– 12 –

on the forearm. Each of the participants in the experiment wore an armband with a two by two array of actuators, as shown in FIG. 7A. Actuators were spaced 1 inch apart from their centers. Participants were asked to wear the band such that the actuator array was comfortably in contact with the volar side on the forearm. At the beginning of a session, participants were trained by activating each actuator for one second and responding with the number they believed was associated with the actuator being energized – the numbered labels for each of the actuators in the array is shown in FIG. 7A (A figure depicting the four possible actuator positions was placed in front of the subjects for reference). For the location test, one of the four actuators and a “blank” actuation was randomly actuated for one second and a light was used to indicate when the actuation was taking place. In the blank actuation case, no actuator was actuated. Participants were asked to communicate which of the actuators they believed was actuated or if no actuator was actuated. The data was recorded and the process was repeated for 50 trials for each actuation frequency. Participants completed three blocks of trials, corresponding to 10 Hz, 60 Hz and 200 Hz test frequencies. The order of each frequency block was randomized for eight participants (5 males, avg. age: 28.9 years). The voltage of each test stimulus was set to 1000 V.

[0063] A simulation-response (S-R) table was constructed to indicate participant’s response to the stimuli. The S-R table for all test frequencies and participants is shown in Table I.

TABLE I
SIMULATION-RESPONSE TABLE FOR ALL THE RECORDED RESPONSES ACROSS ALL FREQUENCIES

	S1	S2	S3	S4	S-Blank	Sum
R1	131	15	0	13	0	159
R2	6	202	41	3	0	252
R3	2	31	199	12	0	244
R4	74	3	2	194	0	273
R-Blank	1	1	1	1	268	272
Sum	214	252	243	223	268	1200

[0064] As should be appreciated from the results shown in Table I, the blank condition was easily recognizable, indicating that at 1000 V actuation, participants were able to reliably distinguish between an actuation event and a blank event for each test frequency, and they were able to do this with an accuracy of 100%. In the case of other stimuli, the response of “blank” (R-blank) was obtained in less than 1% of the trials.

[0065] Overall, the participants were correctly able to report the actuation location in 82.83% of the cases. Ignoring the blank stimulus situations, the accuracy was 77.9%. It is pertinent to note that the cross-diagonal values in S-R table are significantly higher. In particular, participants had difficulty correctly distinguishing between actuator pairs 1 and 4 (20% error), and 2 and 3 (14.5% error). This indicates that participants were more sensitive to the location on the transverse axis of the forearm than along the longitudinal axis.

[0066] FIG. 7B shows a plot illustrating the accuracy of location responses with test frequency. Error bars show the standard error across eight participants. A two-way repeated ANOVA (location and test frequency as within factors) indicated non-significant effects of frequency [$F(2,df)= 0.7883$, $p=0.47$] and a significant effect of location [$F(3,df)= 7.5689$, $p=0.001$] on the identification performance. The frequency-location interaction was also non-significant [$F(6,df)= 1.2$, $p=0.32$], indicating localization on the forearm was not affected by frequency but was affected by the position of the actuators.

[0067] Based on participants' performance in being able to detect location along the arm, the experiments with the two-by-two array were extended to ascertain whether the participants could also determine the direction of the actuation sequence relative to the location on the arm. To do this, a one second duration actuation signal was applied to two actuators 0.5 seconds apart. This actuation sequence created an illusion of motion along the direction on the arm between the two actuators. Participants were asked to communicate the direction of apparent motion they perceived with the directions encoded as shown in FIG. 8A. During a trial, a random direction of actuation was chosen and the device was actuated using the appropriate high voltage switches, as discussed above. A light was used to alert the participants as to the start and end of each trial. A blank signal was defined as when all the actuators were actuated simultaneously, thus providing no perceived direction of motion. Ten participants (8 males, avg. age: 29.4 years) completed three blocks of 50 trials, where each block was actuated with one of the three test frequencies (10 Hz, 60 Hz or 200 Hz). The order of each frequency block was randomized. The voltage of each test stimulus was set to 1000 V.

[0068] The signal-response table for all participants is shown in Table II. The second letter refers to the direction of motion, either transverse (T) or longitudinal (L) with respect to the long axis of the arm.

TABLE II

DIRECTIONAL STIMULUS-RESPONSE TABLE OF THE RECORDED RESPONSES FOR ALL FREQUENCIES

	ST1	SL2	ST3	SL4	S-blank	Sum
RT1	120	5	1	13	0	139
RL2	14	139	11	3	1	168
RT3	0	2	139	4	1	146
RL4	16	1	3	104	0	124
R-blank	2	0	10	1	160	173
Sum	152	147	164	125	162	750

[0069] As with the positional response, the blank event was recognizable with a high accuracy of 98.7%. The overall accuracy in perceiving direction was 88.2%, while it was 85.3% disregarding the blank stimulus case, showing better accuracy for directional cues than location cues. FIG. 8B shows the accuracy of direction perception as different frequencies. Error bars show the standard error across five participants. A two-way repeated ANOVA (direction and test frequency as within factors) was applied on the response accuracy yielded non-significant effects of frequency [$F(2,df)= 1.9194$, $p=0.18$] and significant effect of direction [$F(3,df)= 2.9788$, $p=0.049$], indicating direction recognition was not affected by frequency, but was marginally affected by direction itself.

[0070] As described herein, a haptic actuator device, made entirely of soft materials, can be used to communicate basic aspects of “touch” through the forearm. Additionally, a simple two by two soft-actuator array can be used to test human perception of simple elements of touch position and direction.

[0071] The use of soft actuators is in contrast to some conventional devices that have employed rigid actuators, such as electromagnetic (voice coil) actuators, piezoelectric resonators, and motors and gears. Intrinsically, being fabricated with materials having similar elastic properties as the skin, the dielectric elastomer actuators used in accordance with some embodiments are more compatible with extended periods of use in contact with the body. Furthermore, the mounted devices can flex to fit the shape of the arm.

[0072] The operating voltages used in the tests described herein are high, necessitating the use of bulky high-voltage supplies, but with further refinements in processing, in particular using thinner elastomers, smaller actuators have been developed that can produce detectable signals on the arm at voltages as low as 41 V (at 200 Hz for a single participant). These voltages are within the specified maximum voltage ranges of many standard silicon transistor-based

– 15 –

electronics. It is emphasized that although the use of high voltages is generally undesirable and considerable, caution was taken to ensure the subjects could not make contact with them, the low currents used do not pose any danger to the participants.

[0073] Based on actuator energy considerations, it may be surprising that the low power dielectric elastomer actuators used in accordance with some embodiments could create perceptible touch on the forearm, especially at high frequencies. However, this may be attributed to the similarity between the elastic properties of the actuator elastomer and human skin. This similarity minimizes the impedance mismatch and so maximizes the energy transferred from the actuator to the skin. The decrease in measured blocked force when the actuator displacement was blocked by an elastomer instead of a rigid block indicates the transmission of actuator force into the skin proxy. As described above, the measured frequency response in contact with the skin proxy can be represented by an equivalent spring and dash-pot model that incorporates additional elements that describe elastic and viscoelastic responses of the skin proxy.

[0074] Although a flat ring was used as a cap portion at the end of the dielectric elastomer actuator to contact the skin (e.g., to reduce the overall height of the device) in the examples described above, use of such a flat ring is not necessarily limiting, and any suitable shape of the portion of the actuator that contacts the skin may alternatively be used. For instance, in some embodiments, a cap portion having a smooth ring shape or a curved surface may be used. Additionally, when an actuator array is used, at least two of the actuators in the array may have cap portions with different shapes.

[0075] In some embodiments, a wearable haptic device in accordance with some embodiments includes one or more flexible barrier materials arranged between the cap portion of an actuator and the user's skin to prevent fluids (e.g., oil, sweat, or other fluids) from contacting the actuator. For instance, the flexible barrier material may be a thin cloth or fabric, a flexible membrane or another suitable material. In some embodiments, the flexible barrier material may be disposable such that it may be replaced after each use. In other embodiments, the flexible barrier material may be reusable such that the flexible barrier material may be cleaned and/or disinfected after one or more uses of the wearable haptic device.

[0076] The above-described embodiments can be implemented in any of numerous ways. For example, the embodiments may be implemented using hardware, software or a combination thereof. When implemented in software, the software code can be executed on any suitable processor or collection of processors, whether provided in a single computer or

– 16 –

distributed among multiple computers. It should be appreciated that any component or collection of components that perform the functions described above can be generically considered as one or more controllers that control the above-discussed functions. The one or more controllers can be implemented in numerous ways, such as with dedicated hardware or with one or more processors programmed using microcode or software to perform the functions recited above.

[0077] In this respect, it should be appreciated that embodiments of an electric vehicle may include at least one non-transitory computer-readable storage medium (e.g., a computer memory, a portable memory, a compact disk, etc.) encoded with a computer program (i.e., a plurality of instructions), which, when executed on a processor, performs one or more of the above-discussed functions. Those functions, for example, may include control of the motor driving a wheel of the vehicle, receiving and processing control signals from a central server, and/or displaying information to a user. The computer-readable storage medium can be transportable such that the program stored thereon can be loaded onto any computer resource to implement the aspects of the present invention discussed herein. In addition, it should be appreciated that the reference to a computer program which, when executed, performs the above-discussed functions, is not limited to an application program running on a host computer. Rather, the term computer program is used herein in a generic sense to reference any type of computer code (e.g., software or microcode) that can be employed to program a processor to implement the above-discussed aspects of the present invention.

[0078] Various aspects of the present invention may be used alone, in combination, or in a variety of arrangements not specifically discussed in the embodiments described in the foregoing and are therefore not limited in their application to the details and arrangement of components set forth in the foregoing description or illustrated in the drawings. For example, aspects described in one embodiment may be combined in any manner with aspects described in other embodiments.

[0079] Also, embodiments of the invention may be implemented as one or more methods, of which an example has been provided. The acts performed as part of the method(s) may be ordered in any suitable way. Accordingly, embodiments may be constructed in which acts are performed in an order different than illustrated, which may include performing some acts simultaneously, even though shown as sequential acts in illustrative embodiments.

[0080] Use of ordinal terms such as “first,” “second,” “third,” etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one

– 17 –

claim element over another or the temporal order in which acts of a method are performed. Such terms are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term).

[0081] The phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," "having," "containing", "involving", and variations thereof, is meant to encompass the items listed thereafter and additional items.

[0082] Having described several embodiments of the invention in detail, various modifications and improvements will readily occur to those skilled in the art. Such modifications and improvements are intended to be within the spirit and scope of the invention. Accordingly, the foregoing description is by way of example only, and is not intended as limiting. The invention is limited only as defined by the following claims and the equivalents thereto.

CLAIMS

1. A wearable haptic device, comprising:
a band configured to be worn around a portion of a user's body;
circuitry coupled to a flexible substrate, wherein the flexible substrate is coupled to the band; and
a plurality of dielectric elastomer actuators electrically connected to the circuitry, each of the plurality of dielectric elastomer actuators including a rolled elastomer structure having electrode elements embedded therein, wherein the plurality of dielectric actuators are coupled to the circuitry to provide haptic stimulation to the portion of the user's body when the wearable haptic device is worn on the portion of the user's body and is actuated.
2. The wearable haptic device of claim 1, wherein the embedded electrode elements comprise at least one percolative electrode network.
3. The wearable haptic device of claim 2, wherein the percolative electrode network comprises carbon nanotubes, metallic nanowires, or a combination of carbon nanotubes and metallic nanowires.
4. The wearable haptic device of claim 2, wherein the percolative electrode network comprises carbon nanoparticles, metallic nanoparticles, or a combination of carbon nanoparticles and metallic nanoparticles.
5. The wearable haptic device of claim 2, wherein the rolled elastomer structure comprises a plurality of elastomer layers, and wherein each of the plurality of layers of the rolled elastomer structure comprises a percolative electrode network formed on a surface of the elastomer layer.
6. The wearable haptic device of claim 1, wherein the flexible substrate comprises a flexible printed circuit board including the circuitry.
7. The wearable haptic device of claim 6, wherein the rolled elastomer structure includes a first conductive surface electrically connected to a first portion of the flexible printed circuit

– 19 –

board and a second conductive surface electrically connected to a second portion of the flexible printed circuit board such that when a voltage is applied across the first and second conductive surfaces the dielectric elastomer actuator changes in shape along an axial dimension normal to a surface of the flexible printed circuit board.

8. The wearable haptic device of claim 7, wherein the first conductive surface is directly electrically connected to the first portion of the flexible printed circuit board and wherein the second conductive surface is indirectly electrically connected to the second portion of the flexible printed circuit board using at least one wire arranged within an opening of the rolled elastomer structure.

9. The wearable haptic device of claim 1, wherein the flexible substrate comprises a flexible pad.

10. The wearable haptic device of claim 1, wherein each of the plurality of dielectric elastomer actuators further includes a cap portion.

11. The wearable haptic device of claim 10, wherein the cap portion comprises a flat ring, a smooth ring, or a curved surface.

12. The wearable haptic device of claim 10, wherein the plurality of dielectric elastomer actuators comprises a first dielectric elastomer actuator including a cap portion having a first shape and a second dielectric elastomer actuator including a cap portion having a second shape, wherein the first shape and the second shape are different.

13. The wearable haptic device of claim 10, wherein each of the dielectric elastomer actuators includes a flexible barrier arranged between the cap portion and a portion of the user's body to which haptic stimulation is provided.

14. The wearable haptic device of claim 13, wherein the flexible barrier comprises fabric or a flexible membrane.

– 20 –

15. The wearable haptic device of claim 13, wherein the flexible barrier is configured to repel fluids from skin of the user's body.
16. The wearable haptic device of claim 1, further comprising:
drive circuitry configured to provide a drive signal to drive one or more of the plurality of dielectric elastomer actuators by applying a differential voltage across the rolled elastomer structure.
17. The wearable haptic device of claim 16, wherein the drive circuitry includes at least one multiplexer arranged to send the drive signal to one or more of the plurality of dielectric elastomer actuators simultaneously or separately.
18. The wearable haptic device of claim 1, wherein the band is configured to be worn around the arm or wrist of the user.
19. The wearable haptic device of claim 1, wherein the band is configured to be worn in contact with a shoulder of the user.
20. A method of providing haptic stimulation to a user, the method comprising:
actuating one or more of a plurality of dielectric elastomer actuators arranged on a wearable haptic device including a band configured to be worn around a portion of a user's body, wherein each of the plurality of dielectric elastomer actuators includes a rolled elastomer structure having electrode elements embedded therein.
21. The method of claim 20, wherein actuating the one or more of the plurality of dielectric elastomer actuators comprises actuating at least two of the plurality of dielectric elastomer actuators simultaneously.
22. The method of claim 20, wherein actuating the one or more of the plurality of dielectric elastomer actuators comprises actuating at least two of the plurality of dielectric elastomer actuators in a time sequence to simulate motion of the haptic stimulation.

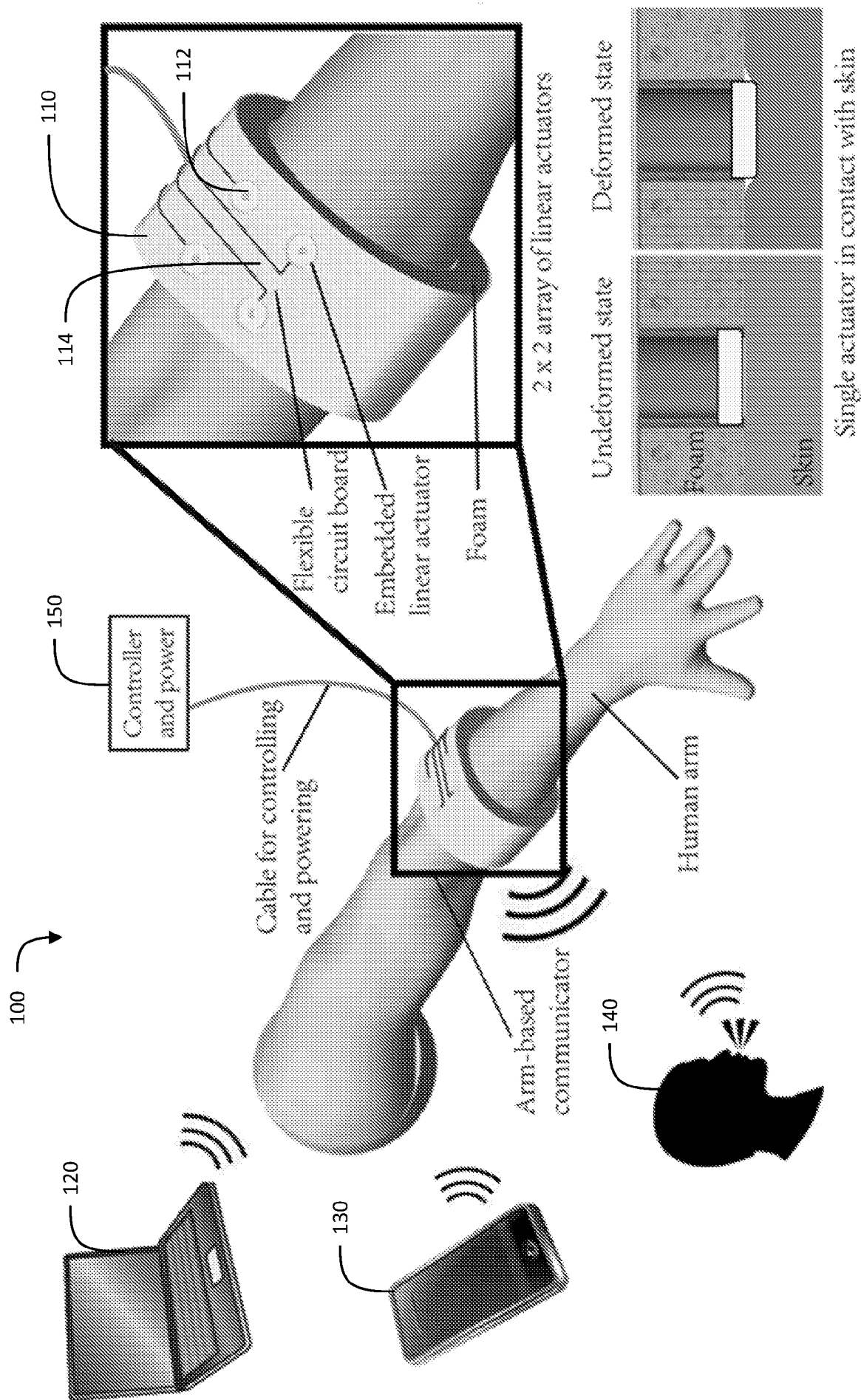


FIG. 1

FIG. 2A

FIG. 2B

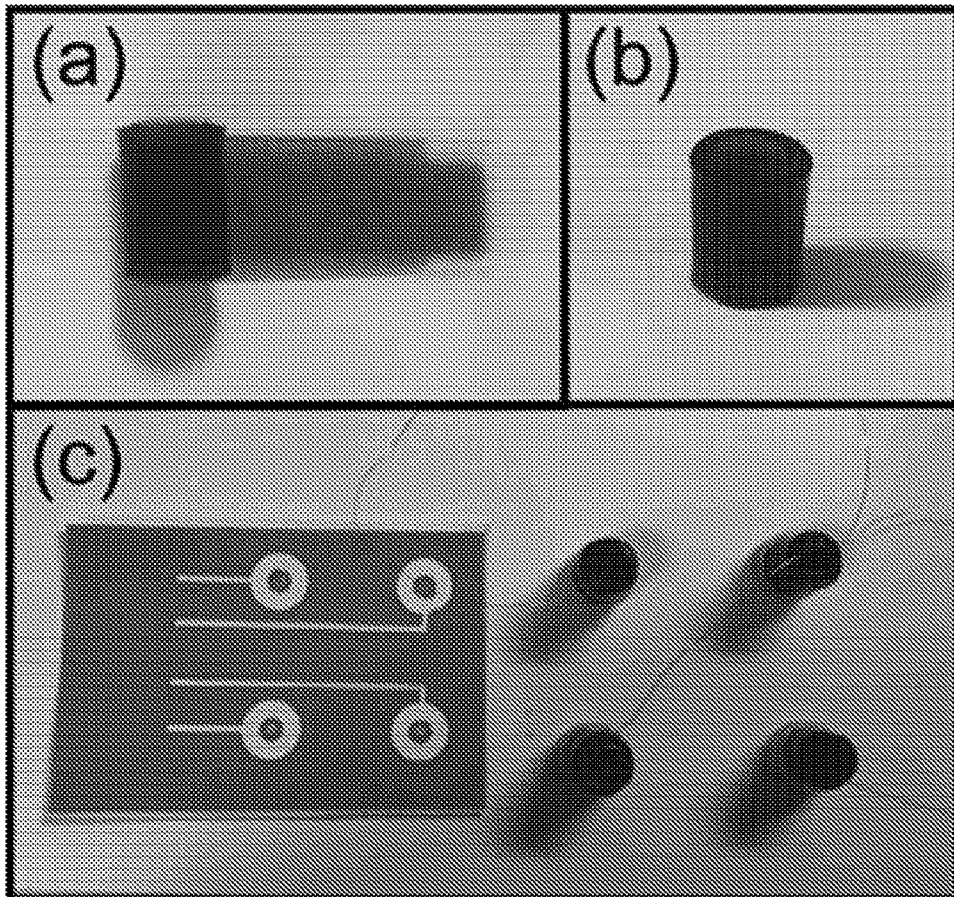


FIG. 2C

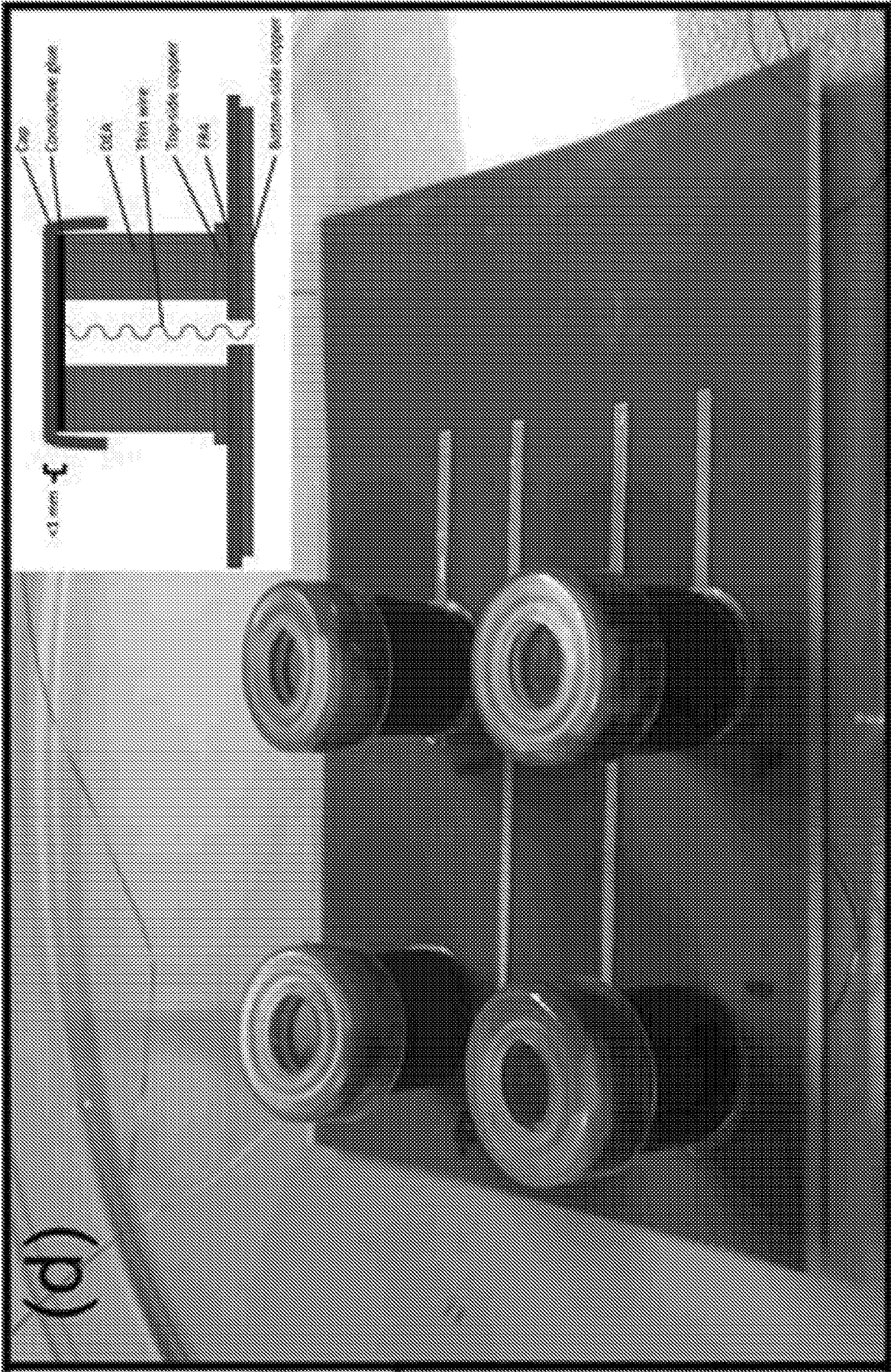


FIG. 2D

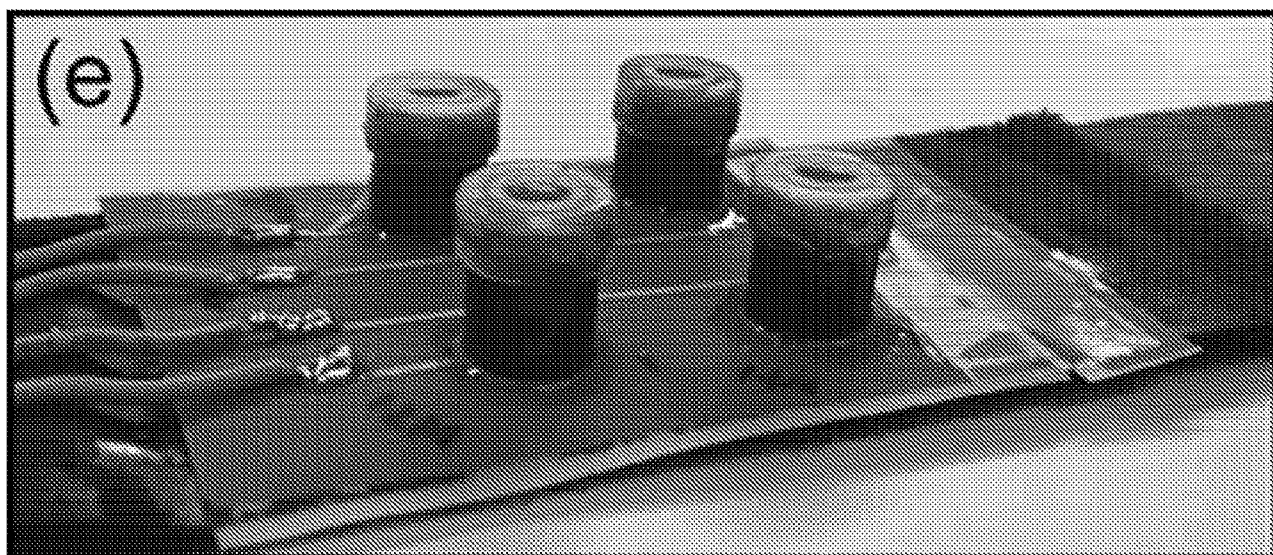


FIG. 2E

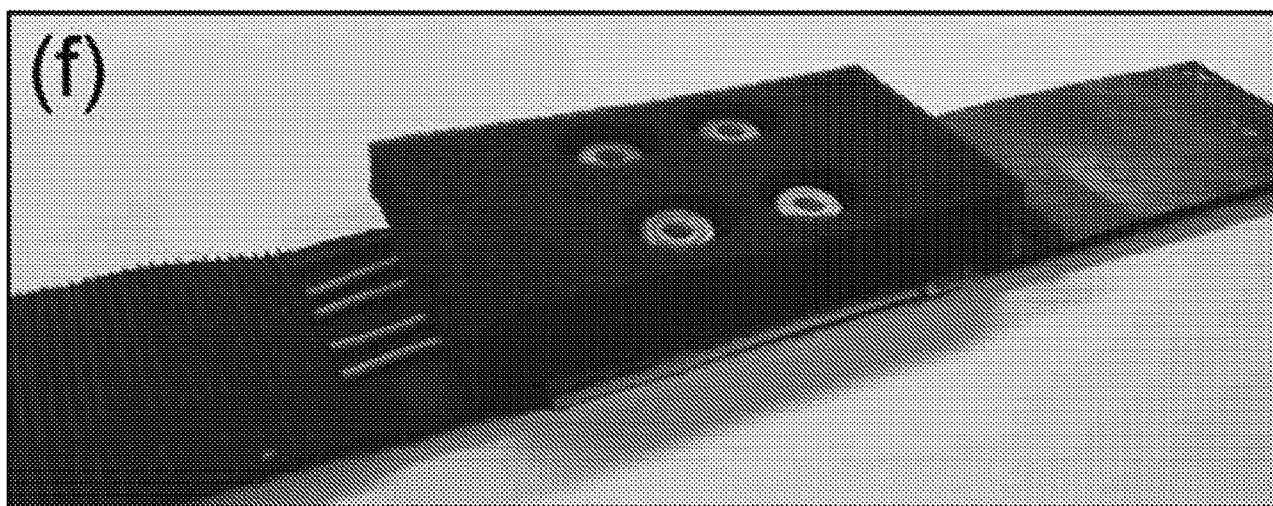


FIG. 2F

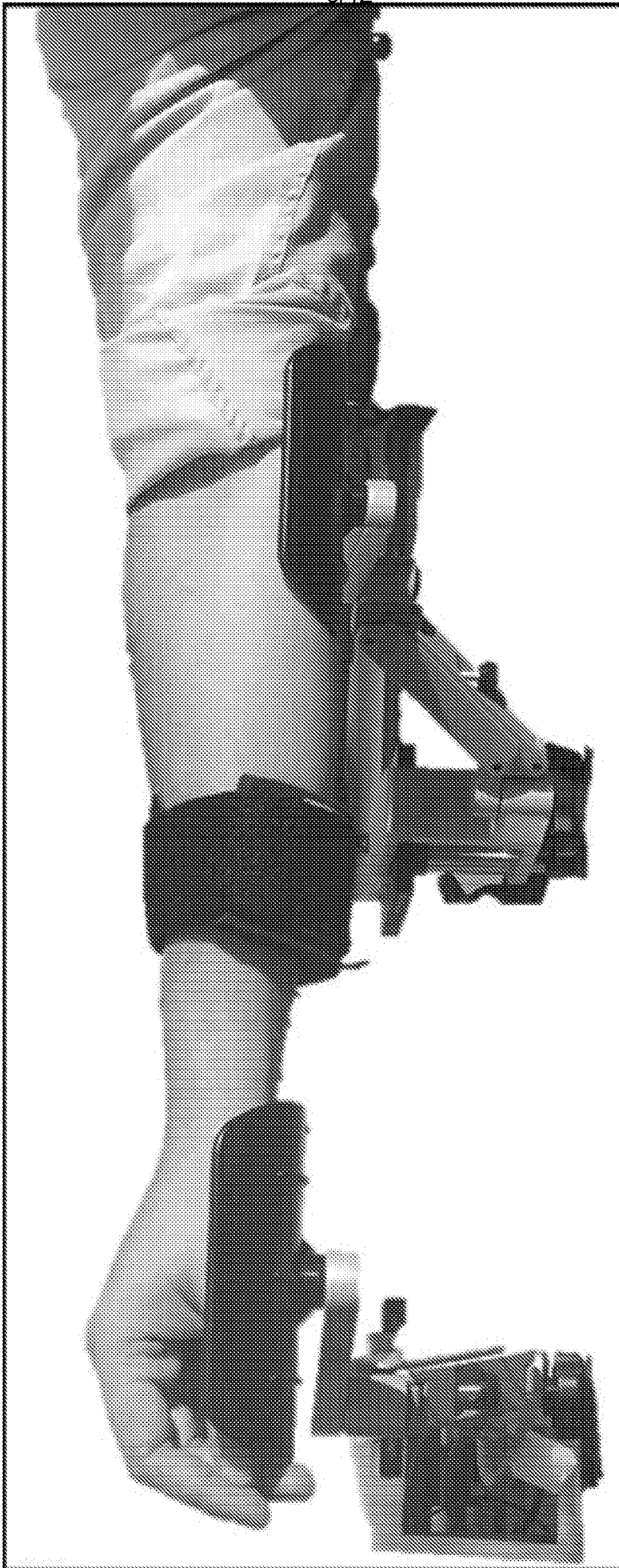


FIG. 2G

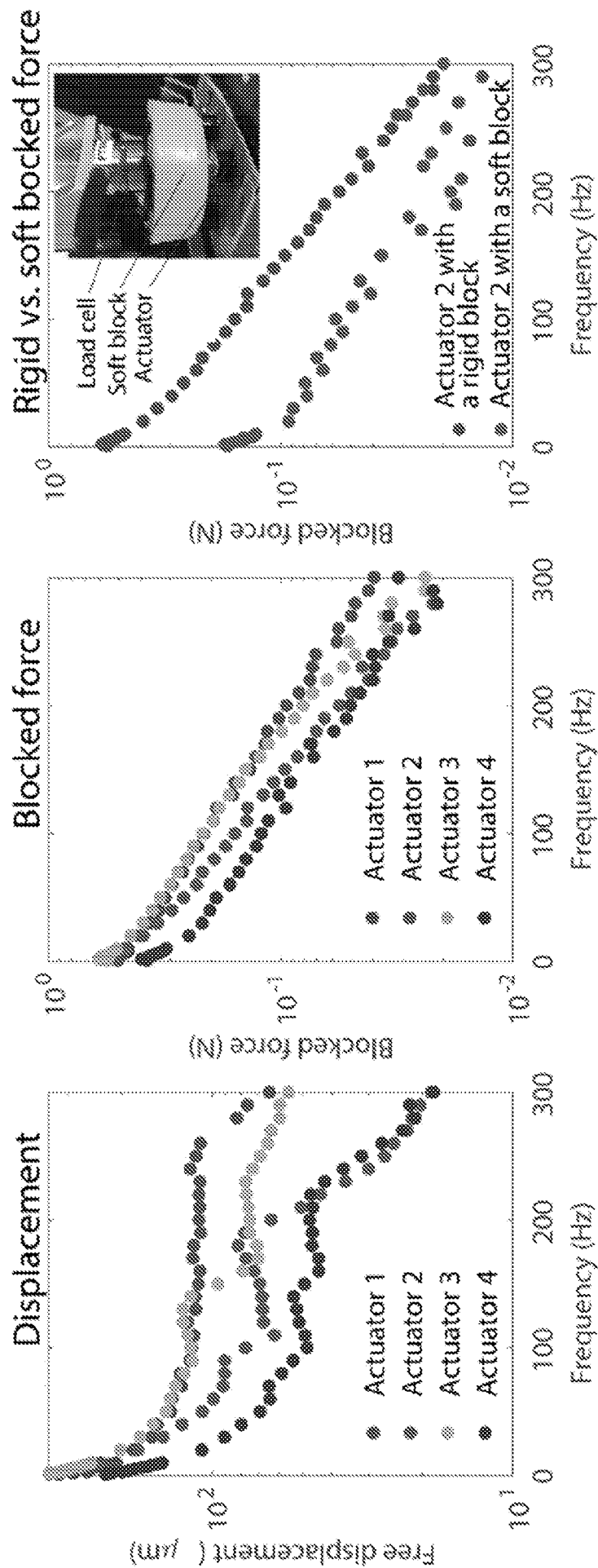


FIG. 3A

FIG. 3B

FIG. 3C

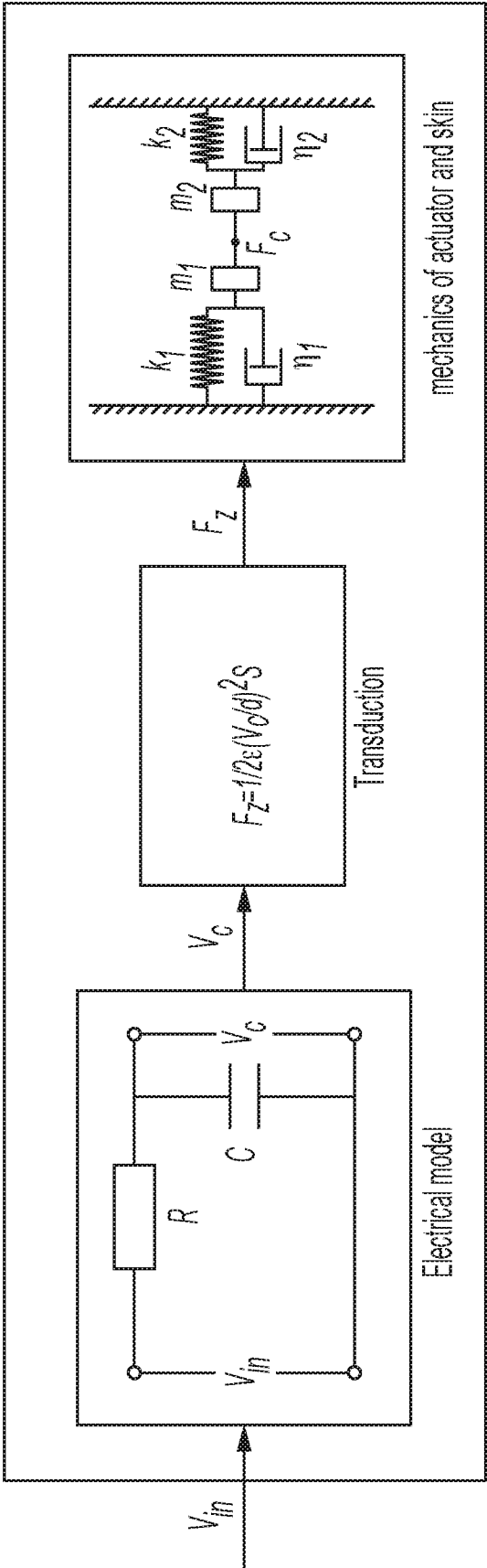


FIG. 3D

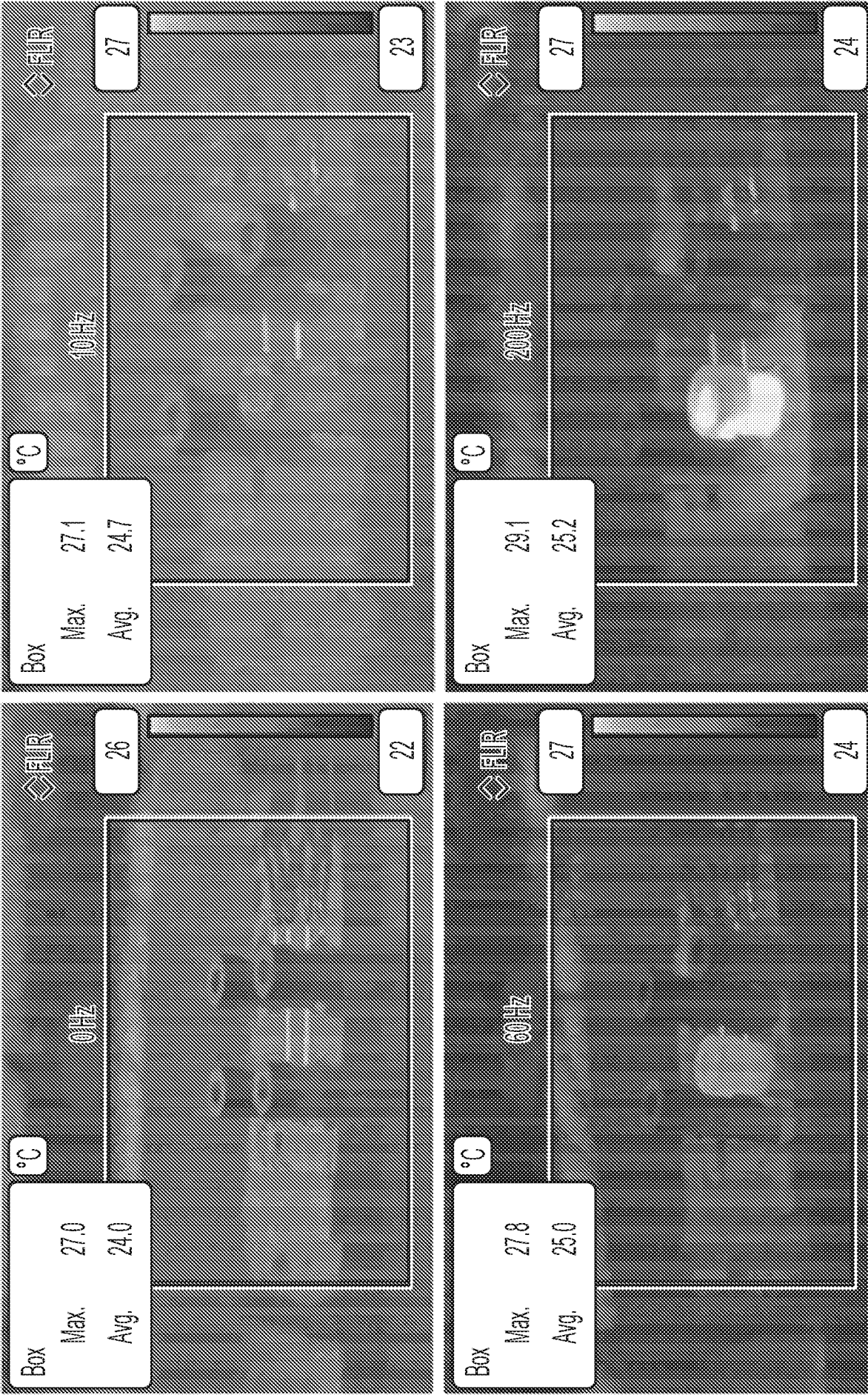


FIG. 4

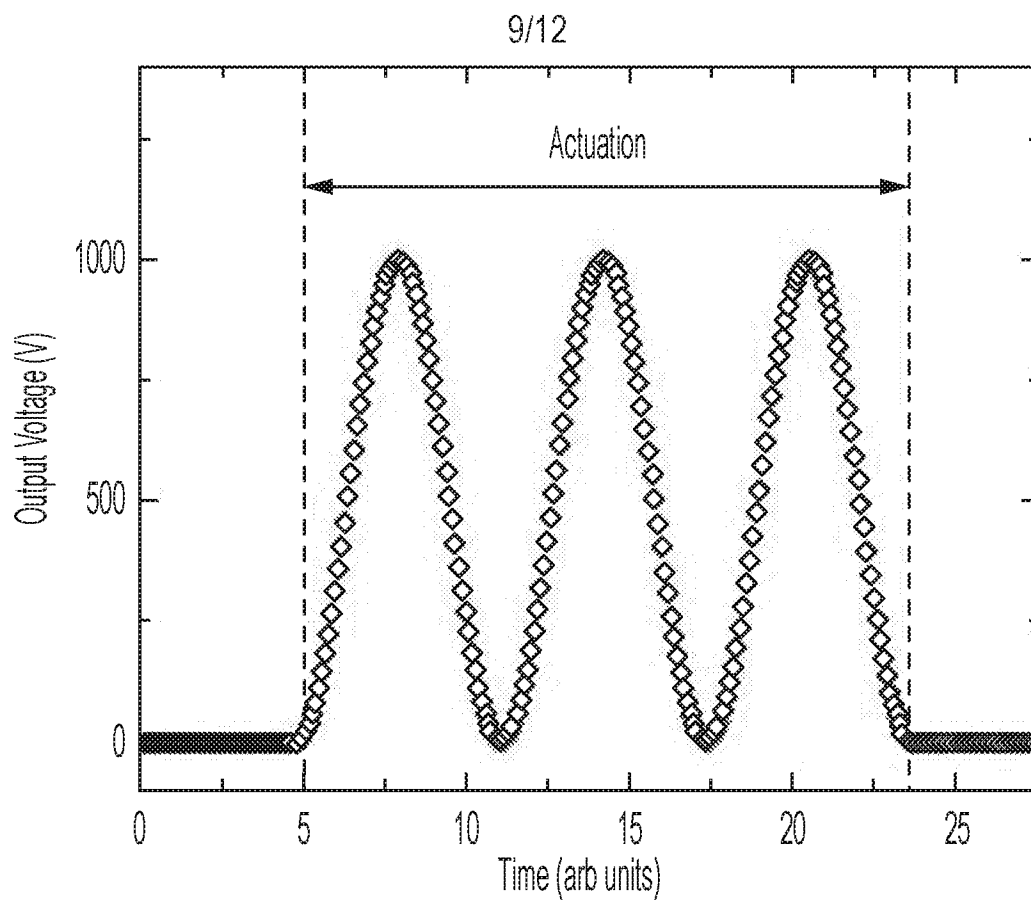


FIG. 5A

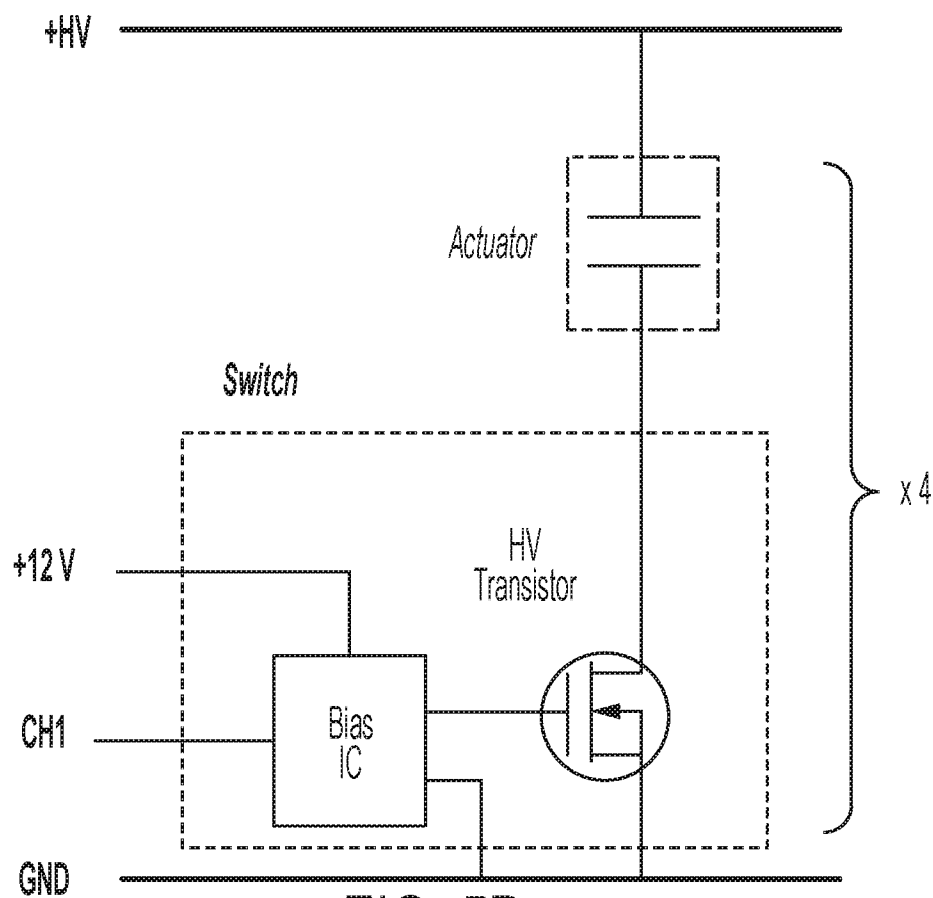


FIG. 5B

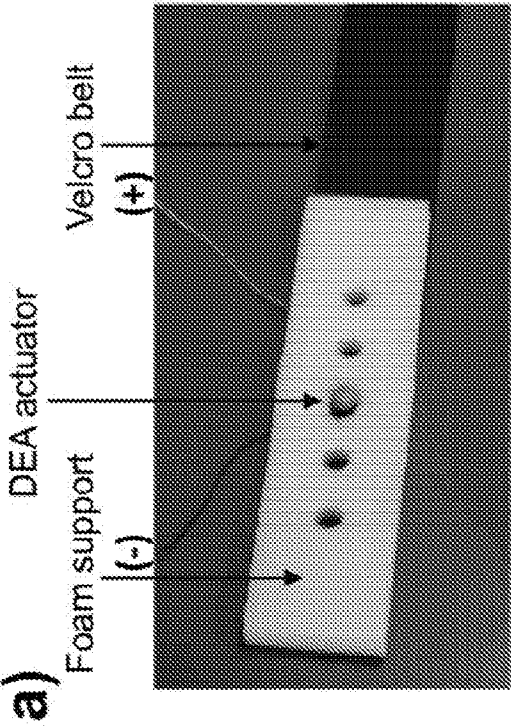


FIG. 6A

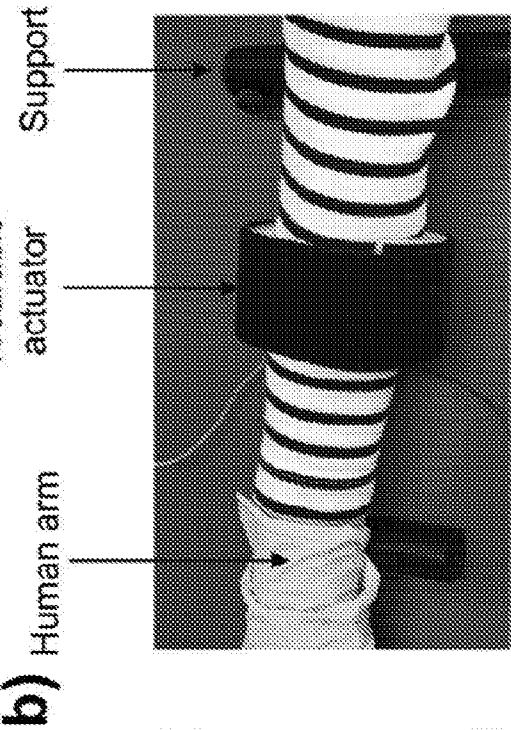


FIG. 6B

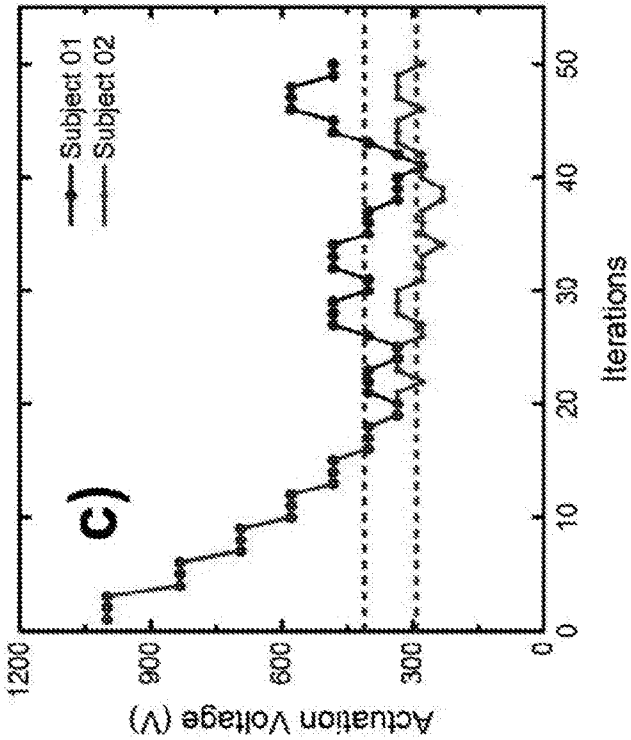


FIG. 6C

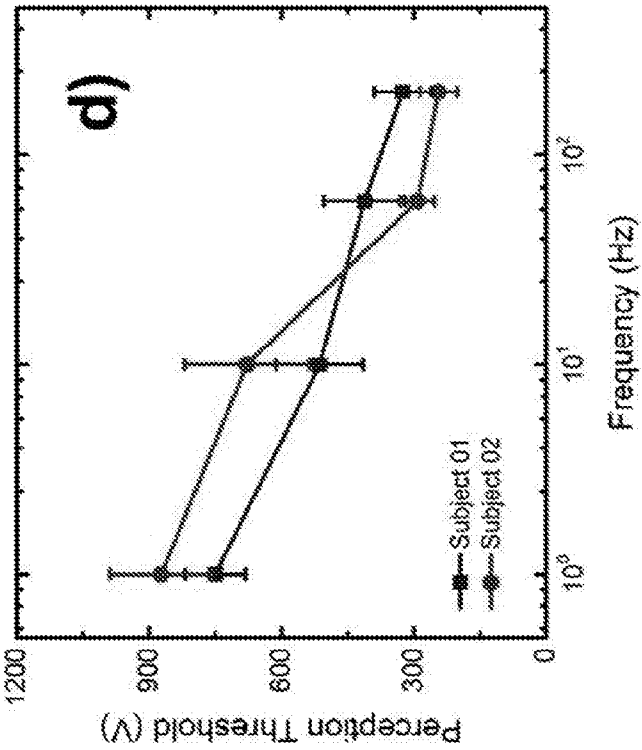


FIG. 6D

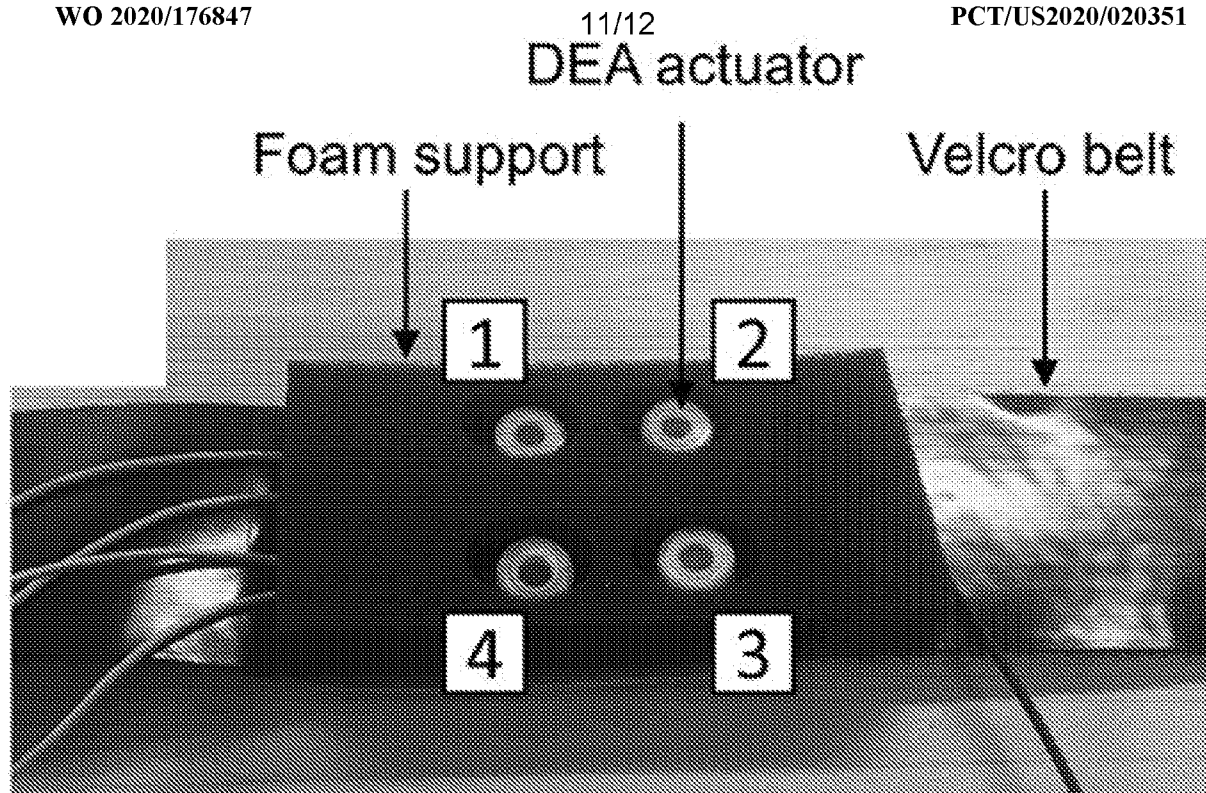


FIG. 7A

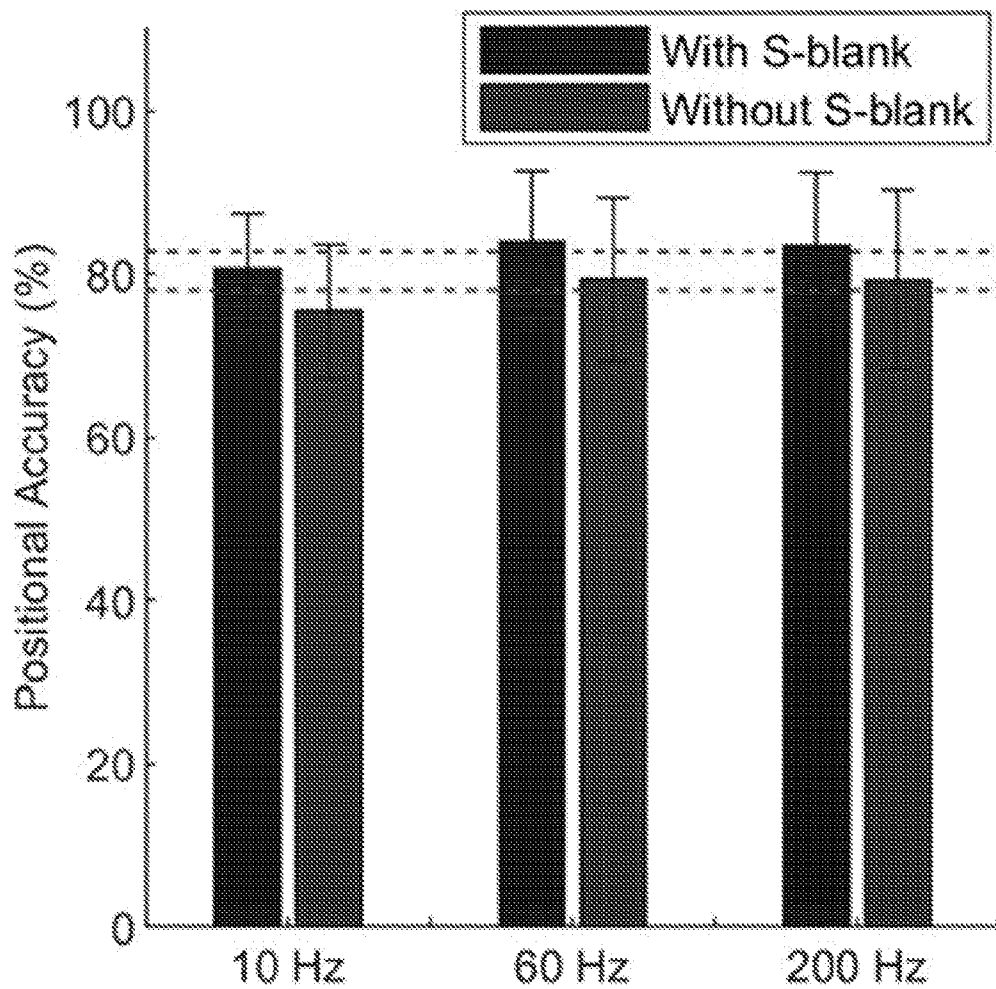


FIG. 7B

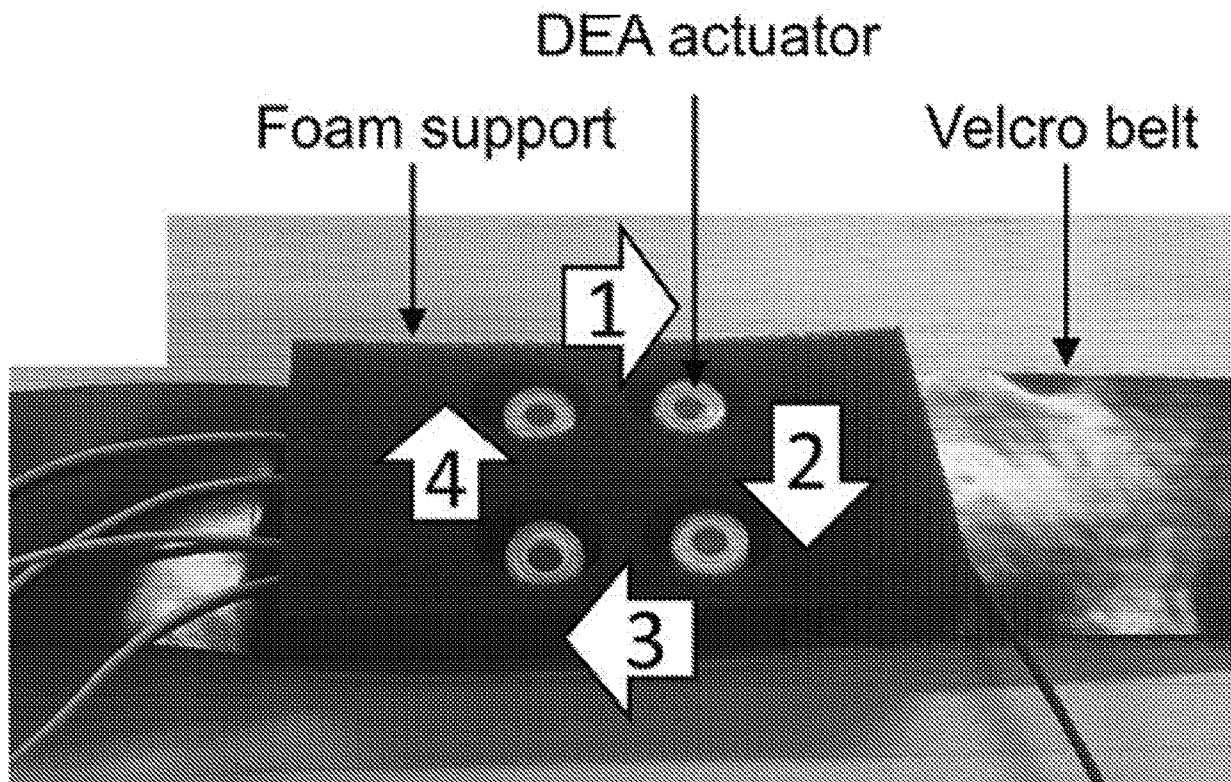


FIG. 8A

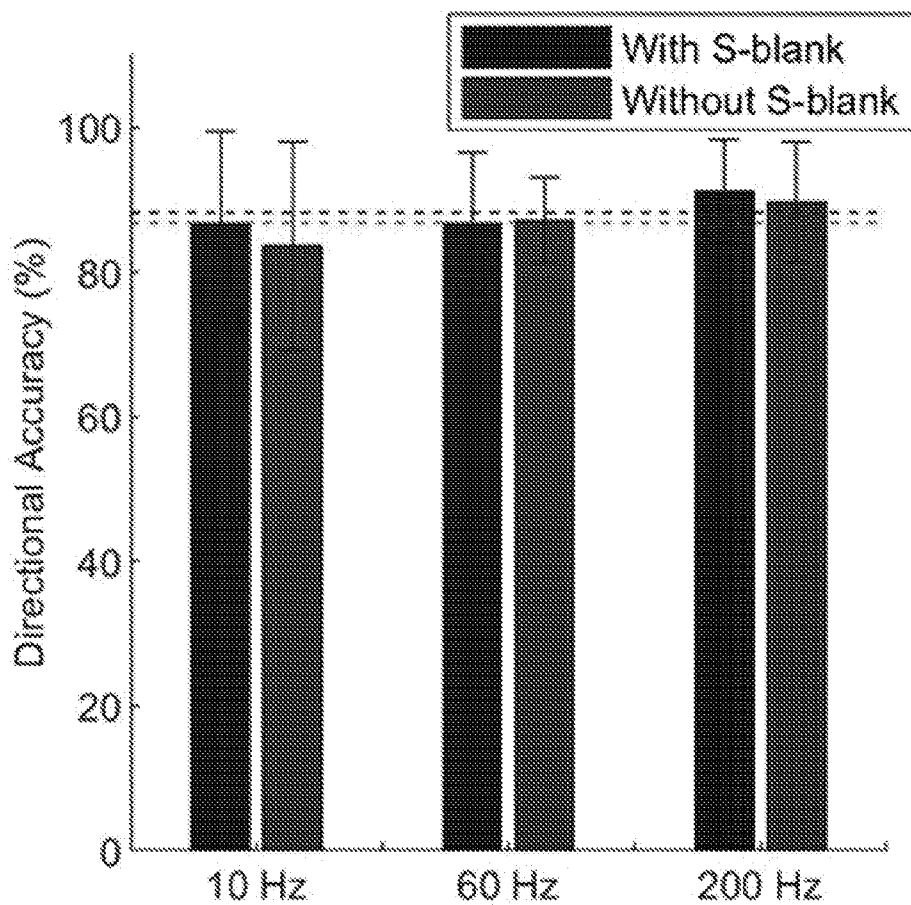


FIG. 8B

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2020/020351

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - A61B 5/11; G06F 3/01; H01L 41/193 (2020.01)

CPC - A61B 5/11; G06F 3/011; G06F 3/016; H01L 41/193 (2020.02)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

USPC - 310/328; 310/369; 340/407.1 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---	WO 2014/117125 A1 (BAYER MATERIALSCIENCE LLC) 31 July 2014 (31.07.2014) entire document	1, 6, 7, 16, 18 ---
Y		2-5, 8-15, 17, 19
X ---	US 2019/0056788 A1 (HEWLETT-PACKARD DEVELOPMENT COMPANY, L.P.) 21 February 2019 (21.02.2019) entire document	20-22 ---
Y		17
Y	WO 2017/165282 A1 (PRESIDENT AND FELLOWS OF HARVARD COLLEGE) 28 September 2017 (28.09.2017) entire document	2-5
Y	US 4,940,894 A (MORTERS) 10 July 1990 (10.07.1990) entire document	8
Y	US 2016/0346501 A1 (TEAM TURQUOISE LTD.) 01 December 2016 (01.12.2016) entire document	9
Y	US 8,093,783 B2 (ROSENTHAL et al) 10 January 2012 (10.01.2012) entire document	10-15
Y	US 2019/0009097 A1 (NALU MEDICAL, INC.) 10 January 2019 (10.01.2019) entire document	15, 19
A	WO 2017/171868 A1 (INTEL CORPORATION) 05 October 2017 (05.10.2017) entire document	1-22

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

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"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

28 April 2020

Date of mailing of the international search report

15 MAY 2020

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
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