



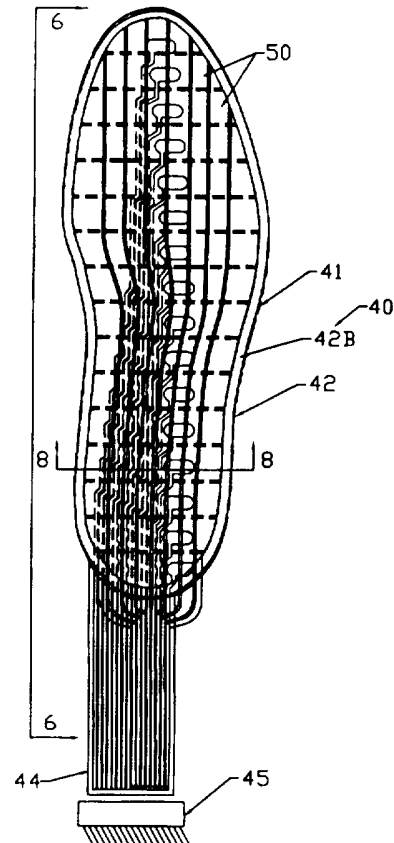
INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

<p>(51) International Patent Classification <sup>6</sup> : <b>G01L 1/20, A61B 5/103</b></p>	<p><b>A1</b></p>	<p>(11) International Publication Number: <b>WO 97/18450</b> (43) International Publication Date: 22 May 1997 (22.05.97)</p>
<p>(21) International Application Number: PCT/IB96/01467 (22) International Filing Date: 14 November 1996 (14.11.96) (30) Priority Data: 08/557,863 14 November 1995 (14.11.95) US (60) Parent Application or Grant (63) Related by Continuation US 08/557,863 (CIP) Filed on 14 November 1995 (14.11.95) (71)(72) Applicant and Inventor: TAYLOR, Geoffrey, L. [US/CA]; 211 Oak Street, Winnipeg, Manitoba R3M 3P7 (CA). (74) Agent: CHAPIN, William, L.; 8732 Squires Circle, Huntington Beach, CA 92646 (US).</p>		<p>(81) Designated States: AL, AM, AT, AU, AZ, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DE (Utility model), DK, EE, ES, FI, GB, GE, HU, IL, IS, JP, KE, KG, KR, KZ, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, US, UZ, VN, ARIPO patent (KE, LS, MW, SD, SZ, UG), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).</p> <p><b>Published</b> <i>With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i></p>

(54) Title: PIEZORESISTIVE FOOT PRESSURE MEASUREMENT METHOD AND APPARATUS

(57) Abstract

A method and apparatus (68, 40) for measuring pressures exerted on human feet or horses' hooves comprises a rectangular array of piezoresistive force sensors encapsulated in a thin polymer package (40) that is inserted into a shoe, or incorporated into a sock that may be pulled over a foot or hoof. The preferred embodiment employs novel piezoresistive normal force or pressure sensing elements (36) which include a polymer fabric mesh impregnated with conductive particles suspended in an elastomeric vehicle, preferably silicone rubber. The piezoresistive mesh layer (33) is sandwiched between an array of row (34) and column (31) conductor strip laminations, preferably made of a nylon mesh impregnated with printed metallic paths. In a variation (100) of the basic embodiment, each normal force sensor element (30) is bordered by laterally and longitudinally disposed pairs (80) of shear force sensor elements, each of the latter comprising a pair of adjacent resilient piezoresistive pads (83) that have longitudinally contacting lateral surfaces. The pads are slidably movable, and when urged into more or less intimate contact in response to shear forces directed normal to their tangent contact plane, the electrical resistance between the pads varies in a predetermined way as a function of the shear forces.



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**PIEZORESISTIVE FOOT PRESSURE MEASUREMENT  
METHOD AND APPARATUS**

Background of the Invention

5     A. Field of the Invention

The present invention relates to methods and apparatus for measuring pressures exerted on the feet of standing humans or animals such as horses. More particularly, the invention relates to a method and apparatus for providing a two-  
10 dimensional map of pressures exerted on the bottom of a human foot by a shoe, for example, or on the hoof of an animal, particularly, a horse.

      B. Description of Background Art

People who must be on their feet for long periods of  
15 time, whether standing or walking, are well aware of the discomfort and fatigue that may be brought on by reaction pressures exerted on the bottoms of the feet by the ground or other surface supporting the weight of the person. Accordingly, substantial efforts have been exerted by  
20 manufacturers of shoes, ski boots and other footwear, in an effort to more uniformly distribute the pressures exerted by footwear on the feet of the wearer. In conjunction with these efforts, a variety of devices for measuring the forces applied to the foot by footwear have been disclosed in the following  
25 United States patents:

Levin et al., 4,121,453, October 24, 1978, Foot Force Transducer, which discloses an apparatus for measuring foot forces during walking that uses a specially configured spring seated in a transducer plate to transmit static and dynamic  
30 forces on the foot during walking to strain gauges mounted on the transducer plate, which in turn, may be monitored and recorded for diagnostic purposes, particularly to aid in treating patients with lower extremities dysfunction.

Confer, 4,745,930, May 24, 1988, Force Sensing Insole For Electro-Goniometer, which discloses a force sensing insole  
35 that is adapted to be used in association with an electro-goniometer for analyzing the gait of a patient. The insole

includes a body member composed of three overlying sheets of thin plastic material which are bonded together, with the intermediate sheet having cut-outs in each of the heel, ball and toe portions so as to define three separate internal chambers. A contact switch is positioned in each of the open chambers, and which comprises a plurality of parallel fingers formed of conductive ink on the inwardly facing surface of one of the outer sheets, and an area of conductive material on the inwardly facing surface of the outer sheet. The body member includes a laterally extending flexible strip, and which is adapted to flex and extend outwardly from the wearer's shoe. Also, lines of conductive ink are provided in the body member which extend from each of the contact switches to a terminal positioned at the end of the strip. In the preferred embodiment, switch closures are input to a radio frequency transmitter strapped to the waist of a subject, a remote receiver being used to monitor switch closures.

Franks, 4,858,621, August 22, 1989, Foot Pressure Measurement System, which discloses a foot pressure measurement system in which pressure measurements are obtained from the variation of light output from an illuminated glass or transparent plate. A reflective material on the top surface of the plate causes an increase in light intensity escaping from the plate when pressure is applied to the reflective material. The accuracy and resolution of the pressure measurements are improved by obtaining a reference measurement of the background light intensity and distribution before pressure is applied and subsequently subtracting this background light from the light patterns produced when pressure is applied. The reflectance characteristics of the system are improved by using a photographic paper as the reflective material.

Seitz, 4,862,743, September 5, 1989, Device For Measuring The Areal Distribution Of Compressive Forces, which discloses a device for measuring the areal distribution of compressive forces which act substantially vertically with respect to a deformable measuring surface. A matrix

arrangement of force sensors is provided, each of which is formed as a capacitance at crossings of substantially perpendicular conductor paths. The conductor paths are fixed on the opposed surfaces of an elastically deformable area-type dielectric and adapted to be connected by conductive elements to evaluator electronics. The conductor paths are printed on plastic substrate films.

Podoloff et al., 5,033,291, July 23, 1991, Flexible Tactile Sensor For Measuring Foot Pressure Distributions And For Gaskets, which discloses a force and pressure sensor having two sets of parallel electrodes which are positioned facing one another and arranged so that electrodes of one set cross the electrodes of the second set at an angle to create a plurality of electrode intersections. Pressure-sensitive resistive material lies between the electrodes at each intersection. An adhesive layer is applied to at least one of the electrode sets in areas between electrode intersections to secure the first and second electrode sets in facing relationship, the adhesive layer preferably being applied in a pattern which provides passages where the adhesive layer does not exist to allow air to escape from interior areas of the electrode set. The thickness of the adhesive layer may be adjusted to permit preloading or to provide a threshold level for the sensor. In order to permit electrodes of the electrode set to be trimmed around their periphery, electrical contact to each electrode of the electrode sets is made intermediate the ends of the electrodes. This is accomplished by providing an insulating layer over the rear of each electrode set having holes therein at the desired intersection points and having a plurality of connecting conductors on the back of the insulating sheet, one for each electrode, which make contact with the corresponding electrode through the hole in the insulating sheet.

Fullen et al., 5,323,650, June 28, 1994, System For Continuously Measuring Forces Applied To The Foot, which discloses a self-contained system for measuring forces applied to the foot of a user that includes a force sensor array

positioned within the user's shoe between the foot and the inner sole of the shoe, the force sensor array including a multiplicity of individual force sensors arranged in a hexagonal pattern that covers the entire area of contact  
5 between the sole of the user's foot and the inner sole of the shoe, an electronic circuit module removably attached to the side of the shoe, and a flat interconnecting cable for electrically coupling the force sensor array to the electronic circuit module. The electronic circuit module includes a  
10 central processing unit, read-only memory, random access memory, and scanning circuitry for electronically continuously scanning the force sensor array to obtain information indicative of an instantaneous force sensed by each one of the multiplicity of individual force sensors of the force sensor  
15 array, for processing that information to obtain force data, and for storing the force data in the random access memory. An annunciator audibly signals the user when a force on the foot greater than a predetermined threshold force is sensed.

In addition to the aforementioned references, the  
20 following United States patents disclose devices generally adapted to the measurement of pressures exerted on body parts:  
Bourland et al., 5,010,772, April 30, 1991, Pressure Mapping System With Capacitive Measuring Pad, which discloses  
25 a capacitive measuring pad for measuring the pressures exerted by various portions of a patient's body on a mattress. The pad is constructed of transverse conductive strips separated by a compressible insulator to form a matrix of pressure sensitive capacitive nodes. The nodes are repetitively scanned in sequence by a microcomputer to measure their  
30 respective capacitances, from which measurements a pressure map is then derived. The resulting pressure map may be displayed on a color graphics monitor with different colors representing different pressures. Node capacitance is found by measuring the response of the node to a driving signal of  
35 a known voltage. This measurement is accomplished by connecting one of the node's transverse conductive strips to a sense amplifier. In order to isolate the node of interest

from the influence of surrounding nodes, all of the conductive strips except the two intersecting the selected node are connected to ground. Furthermore, the input impedance to ground of the sense amplifier is made negligibly small with respect to the other system impedance. In this way, only the conductive strip connected to the driving source has a voltage impressed on it, and the conductive strips of all other nodes in the system are maintained at ground potential, thus allowing an accurate measurement of the one capacitance.

10        Tamori, 5,079,949, January 14, 1992, Surface Pressure Distribution Detecting Element, which discloses a detecting element for sensing surface pressure distributions comprising a substantially rigid insulating substrate, a plurality of scanning row electrodes, formed by metal deposition on said substrate, etched to form a pattern of substantially parallel electrodes which are spaced apart and oriented along a first axis, a thin resistive film, deposited on said substrate, having a resistance which varies as a function of contact area, a substantially resilient deformable surface layer, a plurality of scanning column electrodes, formed by metal deposition on said surface layer, etched to form a pattern of substantially parallel column electrodes which are spaced apart, said surface layer being bonded to said substrate by an anisotropic adhesive so that said column electrodes are oriented along a second axis which is perpendicular to said first axis, said surface layer transmitting pressure distribution to said row electrodes, resistive film, and column electrodes to form a matrix of variable contact resistances to provide analog information relating to the distribution of surface pressure applied to said surface layer.

25        Rincoe et al., 5,253,656, October 19, 1993, Apparatus And Method For Monitoring Contact Pressure Between Body Parts And Contact Surfaces, which discloses an apparatus and method for monitoring pressure between the surface of a body part and a contact surface employing a plurality of pressure sensors disposed in a matrix array between the contact surface and the

body part. The sensors produce analog force signals proportional to pressure, and a monitor receives the analog signals and produces output signals, preferably digital, having pressure data corresponding to the pressure at each  
5 sensor. A computer processor receives the output signals from the monitor to create a force profile for the sensor array. The sensors may be scanned as a read event in variety of manners, including periodic continuous and triggered scanning. Where triggered scanning is desired, one or more switches act  
10 to initiate a read event. This monitoring apparatus and method is used, for example, to fit prosthetics, to monitor bed-ridden and wheelchair-bound patients, to reduce pain and sores caused by uneven distribution of pressure and to monitor pressure between a cast and a person. The sensors may be  
15 mounted on a single sheet or on strips for positioning along the body, and monitoring is accomplished by multiplexing and digitizing the analog force signals.

In addition to the references cited above, the present inventor disclosed in U.S. Patent Application Serial No.  
20 08/254,918, filed 06/06/94, novel Multi-Directional Piezoresistive Shear And Normal Force Sensors For Hospital Mattresses And Seat Cushions. Although the sensors disclosed in the aforementioned application are an important advancement in the field, the required characteristics of foot pressure  
25 sensors are somewhat different from those for hospital mattresses and seat cushions.

In addition to the problem of accurately mapping pressures exerted on human feet, a need exists for performing such measurements on the hooves of animals, particularly  
30 horses. Since the substantial weight of a horse is concentrated on relatively small portions of the horse's hooves, it should be the goal of the farrier who fits horseshoes to hooves to trim the hoof in a manner causing the weight of the horse to be distributed relatively uniformly  
35 over both those portions of the hoof in contact with the shoes, and those portions in contact with the ground. The present inventor is unaware of any prior art devices that are



intended for, or particularly well adapted to, mapping pressures exerted on the hooves of an animal.

#### OBJECTS OF THE INVENTION

An object of the present invention is to provide an apparatus for measuring pressures exerted on various portions of the bottom of a foot by a shoe, in response to the weight of a body.

Another object of the invention is to provide a two-dimensional pressure sensing array for providing a quantitative two-dimensional map of pressures exerted on various portions of a foot by a shoe or other footwear.

Another object of the invention is to provide a planar piezoresistive pressure sensing array for measuring pressures exerted on various portions of a foot pressing down on the array.

Another object of the invention is to provide a thin, flexible piezoresistive foot pressure sensing array that may be fitted between the upper inner surface of a shoe or other item of footwear, and the lower surface of a foot.

Another object of the invention is to provide a sock containing in the sole surface thereof a thin, flexible array of pressure sensors, the sock being wearable over a foot and providing measurements of pressure exerted on various portions of the bottom of a foot, when the foot is placed in contact with ground or other supporting surface.

Another object of the invention is to provide a sock adapted to fit over the hoof of a horse, the sock having in the sole portion thereof a thin, flexible array of pressure sensors, thus adapting the sock to measuring the pressures exerted on various portions of the bottom of a standing horse's hoof, and thereby providing data permitting a farrier to trim the hoof in a manner resulting in more even distribution of pressures on the horse's hooves.

Various other objects and advantages of the present invention, and its most novel features, will become apparent to those skilled in the art by perusing the accompanying specification, drawings and claims.

It is to be understood that although the invention disclosed herein is fully capable of achieving the objects and providing the advantages described, the characteristics of the invention described herein are merely illustrative of the preferred embodiments. Accordingly, I do not intend that the scope of my exclusive rights and privileges in the invention be limited to details of the embodiments described. I do intend that equivalents, adaptations and modifications of the invention reasonably inferable from the description contained herein be included within the scope of the invention as defined by the appended claims.

#### SUMMARY OF THE INVENTION

Briefly stated, the present invention comprehends apparatus and methods for measuring the pressures exerted on the bottoms of feet of standing or running humans and animals, particularly horses.

In a basic embodiment of a pressure measuring apparatus according to the present invention, piezoresistive pressure sensors are arranged in a two-dimensional array having an outline shape similar to that of a footprint, and encapsulated in a thin, flexible polymer sandwich. Each sensor includes a resiliently deformable piezoresistive pad, the electrical resistance of which varies inversely with pressure or normal forces exerted on the pad. The piezoresistive sensors are arranged in rows and columns, each of which is electrically conductively connected to a separate wire at the input end of a flexible electrical cable. At the output end of the cable, each wire is connected through a multiplexer to an electrical resistance measuring module such as a bridge. In response to electrical control signals, the multiplexer momentarily connects each piezoresistive sensor in the sensor array to the resistance measuring module, thus producing a sequence of resistance measurements proportional to pressures exerted on various portions of the foot by the array, and thereby permitting the plotting of a two-dimensional map of pressures exerted on the foot.

/ / /

In the preferred embodiment of pressure sensing arrays according to the present invention, piezoresistive pads are regions of a piezoresistive mesh layer made by impregnating a fabric mesh, preferably made of mono-filament strands of a polymer such as polyester or polyethylene, with a piezoresistive material comprising electrically conductive particles, such as carbon black, suspended in an insulating elastomeric vehicle, such as silicone rubber. The piezoresistive mesh layer is sandwiched between a pair of thin polymeric conductor strip laminations, preferably made of nylon. Inner facing surfaces of the two conductor strip laminations have formed thereon adjacent rows of spaced apart row and column conductors, respectively. Peripheral contacting surfaces of the conductor strip laminations are heat sealed or otherwise bonded to encapsulate the piezoresistive mesh layer, thereby forming a thin, flat, flexible laminated sensor array. Each region of piezoresistive material sandwiched between a row conductor and a column conductor comprises an individual normal force or pressure sensor in a rectangular array of sensors.

In a variation of the basic embodiment of a sensor array according to the present invention, each normal force sensor element constructed as described above is bordered by laterally and longitudinally disposed pairs of shear force sensor elements. The novel shear force sensor according to the present invention comprises a pair of adjacent resilient piezoresistive pads that have longitudinally contacting lateral surfaces. The pads are slidably movable, and when the pads are urged into more or less intimate contact in response to shear forces directed normal to their tangent contact plane, the electrical resistance between the pads varies in a predetermined way as a function of the shear forces. The shear force sensors in the pair laterally adjacent to a normal force sensor preferably have their sensitive axes laterally disposed, while the shear force sensor elements in the longitudinally disposed pair adjacent to a normal force sensor have their sensitive axes longitudinally disposed. This

arrangement permits measurement of shear forces in two perpendicular directions in the plane of the sensor array.

In the preferred embodiment of the shear force sensor elements alternating with normal force sensors according to the present invention, each element is fabricated by forming mesh impregnated regions of piezoresistive material that are laterally or longitudinally separated, and in tangential contact along longitudinally or laterally disposed contact zones, respectively.

10 In another embodiment of the invention, a sock is made of concentric flexible fabric tubes comprising row conductive strips, column conductive strips and piezoresistive normal force and/or shear force sensor elements fabricated similarly to the corresponding parts of the novel planar sensor arrays  
15 according to the present invention. Thus constructed, the sock may be fitted over the foot of a person, or hoof of a horse, and measurements made of forces exerted on the foot or hoof, using the force sensing elements contained in the sock.

#### BRIEF DESCRIPTION OF THE DRAWINGS

20 Figure 1 is an upper perspective view of a normal force sensor element according to the present invention.

Figure 2 is a first transverse sectional view of the sensor element of Figure 1, taken along line 2-2.

Figure 3 is a second transverse sectional view of the  
25 sensor element of Figure 1, taken along line 3-3.

Figure 4 is a lower plan-view of the sensor element of Figure 1.

Figure 5A is a graph of resistance versus normal force or pressure for the sensor element of Figure 1.

30 Figure 5B is a graph of resistance versus shear force for the sensor element of Figure 15.

Figure 6 is a fragmentary upper perspective view of a rectangular array of normal force sensors of the type shown in Figure 1.

35 Figure 7A is an upper plan-view of a normal force sensor array of the type shown in Figure 6, the array being adapted for measuring normal forces exerted on a human foot.

Figure 7B is a lower plan-view of the sensor array of Figure 7A.

Figure 7C is a lower plan-view of the upper, column lamination of the array of Figure 7A.

5 Figure 7D is an upper plan-view of the lower, row lamination of the array of Figure 7A.

Figure 7E is an upper plan view of a row lead-out lamination used to make electrical connections to the row lamination of Figure 7D.

10 Figure 7F is a fragmentary, magnified view of a conductive mesh fabric used in an alternate construction of the array shown in Figure 7A.

Figure 7G is a lower plan-view of a lower, row lamination employing the fabric shown in Figure 7E.

15 Figure 7H is a plan-view of a piezoresistive lamination comprising part of the sensor array of Figure 7A.

Figure 8 is a transverse sectional view of the sensor array of Figure 7A, taken along line 8-8.

20 Figure 9 is a longitudinal sectional view of the sensor array of Figure 7A, taken along line 9-9.

Figure 10 is an expanded side sectional view of the sensor array of Figure 7A, showing the array bent to fit in a shoe.

25 Figure 11 is a rear elevation view of the sensor array of Figure 7A, in which upper and lower lead-out laminations thereof are folded away from one another.

Figure 11A is a transverse sectional view of a lower lead-out lamination of Figure 11, taken along line 11A-11A.

30 Figure 12 is an exploded plan-view of an alternate embodiment of a normal force sensor array similar to the one shown in Figure 7A, in which Figures 12A-12E illustrate the lowermost, intermediate, and uppermost laminations comprising the sensor array.

35 Figure 13 is an exploded plan-view of a variation of the normal force sensor array shown in Figure 12, in which Figures 13A-13E illustrate the lowermost, intermediate, and uppermost laminations comprising the sensor array

Figure 14 is a partially diagrammatic block diagram of the sensor array of Figure 7A, showing the array interconnected with processing and display circuitry.

Figure 15 is an upper perspective view of a shear force sensor element according to the present invention.

Figure 16 is a first transverse sectional view of the sensor element of Figure 15, taken along line 16-16.

Figure 17 is a second transverse sectional view of the sensor element of Figure 15, taken along line 17-17.

Figure 18 is a lower plan-view of the sensor element of Figure 15.

Figure 8A is a fragmentary, magnified view of a piezoresistive pad comprising part of the shear force sensor element of Figure 15, the pad being fabricated from a mesh fabric.

Figure 18B is an upper plan-view of a rectangular array of shear force sensors of the type shown in Figure 15.

Figure 19 is a fragmentary exploded view of a sensor array comprised of normal force sensors of the type shown in Figure 1, alternating with shear force sensors of the type shown in Figure 15, and showing a portion of an upper lamination thereof peeled away to reveal the sensors.

Figure 20A is a schematic diagram showing the relative orientation of sensors comprising the array of Figure 19.

Figure 20B is a fragmentary transverse sectional view of the array of Figure 19, taken along line 20B-20B.

Figure 20C is a fragmentary lower plan-view of the sensor array of Figure 19.

Figure 20D is an upper plan-view of the array of Figure 19.

Figure 20F is a lower plan-view of the array of Figure 19.

Figure 21 is an exploded upper perspective view of an array of combined (stacked) shear and normal sensor elements according to the present invention.

Figure 24 is an upper perspective view of a normal force sensor array comprising normal force sensors of the type shown

in Figure 1, the array being adapted for measuring normal forces exerted on the hoof of a horse.

Figure 25 is a lower plan-view of the sensor array of Figure 23.

5 Figure 25A is a lower plan-view of the upper, column lamination of the array of Figure 23.

Figure 26 is an upper perspective view of another sensor array adapted for measuring shear forces as well as normal forces exerted on the hoof of a horse, the array comprising  
10 normal force sensors of the type shown in Figure 1, alternating with shear force sensors of the type shown in Figure 15.

Figure 27 is a perspective view of a sock incorporating force sensors according to the present invention.

15 Figure 28 is a perspective view of an inner, column conductor tube comprising part of the sock shown in Figure 27.

Figure 29 is a longitudinal sectional view of the sock shown in Figure 27.

Figure 30 is a view similar to that of Figure 29, but  
20 showing the sock in a folded position.

Figure 31 is a partly dissected view of the inner, column conductor tube of Figure 28, showing the tube cut longitudinally and folded flat.

Figure 32 is a cut and folded-flat view of an outer, row  
25 conductor tube comprising part of the sock shown in Figure 27.

Figure 33 is a fragmentary perspective view of a piezoresistive tube comprising part of the sock of Figure 27.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to Figures 1-33, piezoresistive foot/hoof  
30 pressure measurement apparatus and methods according to the present invention are shown.

Referring first to Figures 1-4, a basic embodiment of a piezoresistive normal force sensor element usable to measure foot pressure is shown. As shown in Figures 1-4, normal force  
35 sensor element 30 includes a first, elongated rectangularly-shaped electrically conductive strip 31 made of a thin, flexible, electrically conductive fabric, such as Flectron

brand nickel/copper plated woven nylon mesh fabric made by Monsanto, The Chemical Group, 800 N. Lindberg, St. Louis, Missouri. Normal force sensor element 30 also includes a second conductive strip 32 disposed in a plane parallel to  
5 first conductive sheet 31. Conductive strip 32 is spaced apart from strip 31 in a direction normal or perpendicular to strip 31. As shown in Figures 1-4, conductive sheet 32 is located above strip 31, with its longitudinal axis oriented in a first, X direction, while lower conductive sheet 31 is  
10 oriented perpendicularly to the longitudinal axis of the upper sheet in a Y direction. Other orientations of the upper and lower conductive strips are of course possible. Whatever the orientation of conductive strips 31 and 32, sensor element 30 includes a piezoresistive layer 33 sandwiched between the  
15 conductive strips. The construction details of piezoresistive layer 33 will now be described.

Referring now to Figure 4, piezoresistive layer 33 of sensor 30 may be seen to preferably include a supporting matrix made of thin, open mesh fabric sheet 34. Fabric sheet  
20 34, which is preferably electrically non-conductive, is preferably woven from monofilament strands of a polymer such as polyethylene or polyester. In an exemplary embodiment of the invention, the present inventor has found that a 300 mesh fabric sheet made of 0.002 inch diameter monofilament strands  
25 of polyester proved to be a satisfactory material for fabric sheet 34.

Piezoresistive layer 33 of normal force sensor element 30 is fabricated by impregnating mesh fabric sheet 34 with a resiliently deformable, partially conductive substance 35 that  
30 has an electrical resistance inversely proportional to normal forces or pressures exerted on the layer, a property which may be referred to as volume or bulk piezoresistivity. As will become apparent from the ensuing description, partially  
35 conductive substance is defined herein as finely divided particles of an electrically conductive material. According to the present invention, mesh sheet 34 is impregnated with piezoresistive substance 35, the mesh providing a durable and



dimensionally stable support matrix for piezoresistive substance 35. The present inventor has found that a suitable substance 35 for impregnating mesh 34, thus forming piezoresistive layer 33, is an ink composed of about 50% milled carbon black having a grain size of 2-5 microns, 30% unpolymerized liquid nitrile rubber, type BUNA N, and 20% ABS plastic resin/hardener, or silicone rubber (e.g., Dow Corning RTV 732) and no hardener. Piezoresistive layer 33 is formed by mixing the aforementioned components thoroughly, applying the mixture to a thickness of about .004 in. with a spatula, and allowing the mixture to air cure at room temperature.

The volume resistivity of piezoresistive layer 33 of normal force sensor element 30 can be varied to a desired cured value by varying the amount of carbon black added to the liquid rubber, and monitoring the resistivity as those two components are being mixed together. The present inventor has found that a suitable range of volume resistivities for piezoresistive layer 33 is about 5 ohm-cm to 100,000 ohm-cm for measurement of normal forces in the approximate range of 0-5 psi, and 100-300,000 ohm-cm for measurement of forces in the approximate range of 5-30 psi. Figure 5A shows the variation of resistivity versus pressure for a typical sensor element 30.

In example embodiments of normal force sensor element 30, conductive strips 31 and 32 were cut from a conductive fabric consisting of nickel/copper coated nylon taffeta and marketed under the brand name FLECTRON by Monsanto, The Chemical Group, 800 N. Lindberg, St. Louis, Missouri. This material has a thickness of 3.8 to 4 mils, is flexible and drapable, and has a surface resistivity of less than 0.05 ohms per square. Preferably, each conductive strip 31 and 32 has slits 36 cut perpendicularly inward from opposite longitudinal edges of the strip, to allow stretching of the strip in a direction parallel to its longitudinal axis. As shown in Figure 1, slits 36 are located in laterally spaced apart pairs, one pair being spaced laterally outwards from each side of piezoresistive layer 33. Figure 5A illustrates a typical

variation of the electrical resistance between lower and electrode conductor strips 31 and 32 of sensor element 30, as a function of pressure or force directed normally to the sensor element, i.e., in the Z direction in Figure 1.

5 Figure 6 illustrates a planar array 37 of normal force sensor elements 30 in which a plurality of column conductive strips 31 and row conductive strips 32 form a rectangular matrix of normal force sensor elements. In regions exterior to piezoresistive layers 33 of sensor elements 30, column and row  
10 conductive strips 31 and 32 are electrically isolated from one another, to prevent short circuiting, by means of thin column and row insulating strips 38 and 39, respectively. The insulating strips may be made of any suitable electrically insulating material, such as nylon. In the preferred  
15 embodiment, insulating strips 38 and 39 are integral with conductor strips 31 and 32, and formed therefrom by photoetching conductive plating on the strips where insulating areas are required.

Figures 7A-11 illustrate a normal force sensor array 40  
20 that is particularly well adapted for measuring normal forces or pressures exerted on the bottom surfaces of human feet. Foot pressure sensor array 40 employs normal force sensor elements 50 substantially similar in construction to the normal force sensor elements 30 shown in Figures 1-4 and  
25 described above, with the sensor elements arrayed in a rectangular array similar to array 37 shown in Figure 6. However, foot pressure sensor array 40 contains additional novel and advantageous structural and functional features, as will now be described.

30 Referring now first to Figures 7A and 7C, foot pressure sensor array 40 may be seen to include an upper, column conductor strip lamination 41 having a substrate 42 made of a thin, flexible sheet of electrically insulating material such as woven nylon having a thickness of about 4 mils. As may be  
35 seen best by referring to Figure 7A, lamination 41 has the approximate outline shape of a human foot. As may be seen best by referring to Figure 7C, column lamination 41 has

formed on the lower surface thereof a plurality of generally longitudinally disposed, laterally spaced apart column conductive strips 51.

Referring still to Figure 7C, column conductive strips 51 may be seen to have a generally rectangular, longitudinally elongated plan-view, and are disposed longitudinally between the toe and heel ends of column substrate 42. Preferably, as shown in Figures 7A and 7C, the longitudinal edges of conductive strips 51 curve somewhat to parallel the curved longitudinal edges of foot-shaped column substrate 42. As is also shown in Figure 7C, the width of conductive strips 51 decreases towards the rear of substrate 42, the rear or heel portions of conductive strips 51 tapering or "necking" down into thin rectangular "tail" traces 43. Preferably, this necking down is located close to the rear edge of the heel portion of substrate sheet 42, to ensure that sensor elements 50 will have sufficient area to be operable as close as possible to the heel edge of sensor array 40.

As shown in Figures 7A and 7B, column substrate 42 preferably has an integral, rectangularly-shaped tab or tongue 44 that protrudes rearward from the heel edge of the substrate sheet. Tongue 44 provides support for traces 43, and has a transversely disposed rear edge adapted to be insertably received by a ribbon cable connector 45, as shown in Figure 10.

As may be seen best by referring to Figure 7D, sensor array 40 may be seen to include a lower, row conductor strip lamination 46 having a substrate 47 made of a sheet of a thin, flexible electrically insulating material such as woven nylon having a thickness of about 4 mils. Row conductor strip lamination 46 preferably has the same foot-shaped outline as column conductor strip lamina 41. As shown in Figure 7D, row conductor strip lamination has formed on the upper surface thereof a plurality of generally laterally disposed, longitudinally spaced apart row conductive strips 52.

Referring still to Figure 7D, row conductive strips 52 may be seen to have a generally rectangular, laterally

elongated plan-view shape, and are disposed laterally between inner and outer longitudinal edges of shoe-shaped row substrate 47.

An individual electrical connection is made to each row of conductor strips 52 by a separate longitudinally disposed conductive trace 48, as follows.

Referring now to Figure 7E, it may be seen that row conductor strip lamination 46 is overlain by a thin, longitudinally elongated, lead-out lamination 49, having a thin, flexible insulating substrate 57. As shown in Figure 7A, lead-out substrate 57 is longitudinally disposed over the central longitudinal portion of row conductor strip lamination 46. Substrate 57 is fastened to the upper surface of row conductor lamination 46 by any suitable means, such as adhesive regions 58 between the lower surface of the lead-out substrate and the upper surface of the row conductor lamination.

As shown in Figure 7E, a plurality of thin, narrow longitudinally elongated, rectangular-shaped lead-out traces 48 are adhered to the upper surface of lead-out lamination 49. Lead-out traces 48 are laterally spaced apart from one another, and terminated at the upper or toe end thereof by a laterally elongated, oval plan-view "flag" appendage 58 that is in electrically conductive contact with the lead-out trace. Flags 58 protrude laterally outwards from a longitudinal edge of lead-out lamination 49, and are longitudinally aligned and spaced apart so as to each be centered over a separate row conductor strip 52. Each flag conductor 58 is conductively coupled to a separate row conductor strip 52. In the preferred embodiment, flag conductors 58 are adhered to row conductor strips 52 by an electrically conductive adhesive such as R17012 neoprene-type adhesive, manufactured by Stockwell Rubber Company, 4749 Talbut Street, Philadelphia, Pennsylvania 19139.

Referring still to Figure 7E, lead-out lamination 49 may be seen to have an integrally formed rectangular tongue 59 that protrudes rearward from the heel edge of the substrate

sheet. Tongue 59 provides support for row lead-out traces 48, and has a transversely disposed rear edge adapted to be insertably received by ribbon cable connector 45.

In the embodiment of normal force sensor array 40 employing upper column, conductor lamination 41 and lower, row conductor lamination 46 constructed as described above, the lead-out traces 43 and 48 are on the lower and upper facing surfaces of the respective laminations. Thus, the rearwardly protruding tongues 44 and 59 supporting the lead-out traces must be bent away from one another to prevent the upper and lower traces from contacting one another, and to permit separate electrical connections to be made to the respective row and column lead-out traces.

In this embodiment of the row, column and lead-out laminations of normal force sensor array 40, each of the laminations was fabricated as photo-etched printed circuits from a thin sheet of 0.002 inch thick rip-stop nylon having on one surface thereof a layer of electroless deposited copper. The copper-coated sheet was cut to the desired plan-view shape, as shown in Figures 7A and 7B, and the copper layer coated with a photo-sensitive, photo-resist emulsion. Next, a photographic film positive containing an image of a desired conductor pattern, e.g., column conductive strips, row conductive strips, or lead-out conductive strips or traces was placed in contact with the photo-sensitized surface, and exposed to light. The exposed substrate was then placed in a solvent bath to remove the non-exposed emulsion, and subsequently placed in an ammonium persulfate bath to etch away the copper from those regions of the substrate where no conductors paths appear. The exposed copper conductors on the surface of the substrate were then plated with nickel in an electroless bath, to reduce the oxidation rate of the exposed copper surfaces, and to increase the mechanical strength of the conductive strips on the substrate.

In a variation of the photo-etched construction of the column, row and lead-out substrates described above, the copper coated nylon sheet was overcoated with an electroless

deposited layer of nickel prior to photo-etching. In this case, a ferrous chloride etching solution was used to remove both copper and nickel from non-conductive portions of the substrates. In both cases, it was found that a suitable material for the substrate was copper coated or copper and nickel coated nylon having a thickness of about 0.004 inch and a total plating thickness of about 0.002 inch.

In the preferred embodiment of normal force sensor array 40, upper and lower laminations 41 and 46 are fabricated by a novel construction that allows lead-out traces to be on outer, upper and lower surfaces of the upper and lower laminations, respectively, rather than on inner, facing surfaces. The novel construction eliminates the requirement for separate electrically conductive feed-throughs required by conventional two-sided printed circuits, as will now be described.

According to the present invention, a novel construction of upper and lower laminations 41 and 46 utilizes a substrate made of a material consisting of woven mesh of non-conductive strands, in which all of the outer surfaces of each of the strands are plated with a conductive material. An example of such a material is Flextron brand nickel/copper plated nylon mesh fabric, part number 3050-226, manufactured by Monsanto.

The aforementioned material has substantial electrical conductivity through its thickness dimension as well as in the plane of the fabric. Therefore, as shown in Figures 7F and 11A, the material M may have insulating paths P etched entirely through the thickness dimension of the substrate, thus forming conducting islands, such as A and B, having identical upper and lower conductive regions that are in electrical contact with one another. In this embodiment, as shown in Figure 7G, row connector lead-out lamination 49 is attached to the lower, outer side of row conductor strip lamination 46, rather than to the upper, inner side of the lamination. This arrangement permits inner facing surfaces of laminations 41 and 46 to have row or column conductive strips electrically in contact with lead-out strips on the outer

surfaces of tongues 44 and 49. With an insulating sheet 44A slid between the inner facing surfaces of the tongues to prevent short circuiting, as shown in Figure 10, the two tongues may be inserted into a single edge card connector 45 provided with upper and lower connectors contacting upper and lower lead-out traces, respectively.

Referring now to Figures 8-11 in addition to Figures 7A, 7B, and 7H, normal force sensor array 40 may be seen to include a piezoresistive lamination 63 sandwiched between row conductor lamination 46 and column conductor lamination 41. Piezoresistive lamination 63 can be comprised of individual, generally rectangularly-shaped piezoresistive cells similar to piezoresistive layers 33 shown in Figures 1-4 and described above. Preferably, however, piezoresistive lamination 63 of sensor array 40 is fabricated as a unitary lamination forming an array of rectangular sensor elements 63A.

Thus, as shown in Figures 7H and 8-11, an example piezoresistive lamination 63 of sensor array 40 includes a mesh fabric matrix sheet 64 made of a 300 mesh fabric woven from 0.002 inch diameter mono-filament strands of polyester fiber and cut to the same plan-view outline shape as that of column substrate 42 and row substrate sheet 47, but of slightly smaller size. In an example embodiment tested by the present inventor, matrix sheet 64 had an outer perimeter that was inset about 1/16th inch from the perimeter of column substrate 42 and row substrate 47, forming a border 65 of the same width. As will be described below, this perimeter border facilitates encapsulating piezoresistive lamination 63.

In an example embodiment of normal force sensor array 40, mesh fabric matrix sheet 64 was cut from a 300 mesh fabric sheet made of 0.002 inch diameter monofilament strands of polyester. Matrix sheet 64 was impregnated with an elastomeric piezoresistive substance 66 having a volume resistivity of about 120,000 ohm-cm, a composition of 50% carbon and 50% RTV 732 silicone rubber and a thickness of about 0.002 inch. The present inventor has found that a suitable method for impregnating matrix sheet 64 with

piezoresistive substance 66 is by spreading the substance in the form of a viscous, uncured paste, using a spatula similar to those sometimes used in screen printing.

After piezoresistive lamination 63 has been fabricated as described above, and piezoresistive substance 66 allowed to cure at about 20°C for about 4 hours, the lamination is positioned concentrically between row substrate 47 and column substrate 42. The peripheral borders 47B and 42B of the row and column substrates are then pressed firmly together and thermally fused to one another by the application of heat and pressure, thus hermetically encapsulating piezoresistive lamination 63. So constructed, sensor array 40 is impervious to the effects of moisture and air.

In an alternate construction that seals piezoresistive lamination 63 between row and column substrates 47 and 42 against moisture and air, the three laminations are positioned between upper and lower latex rubber sheets 53 and 54, as shown in Figure 10. Upper and lower latex sheets 53 and 54 have a plan-view shape similar to the plan-view shapes of the substrate, but are slightly larger, providing upper and lower border areas, respectively, that may be sealed to each other. In a preferred embodiment of the alternate construction, the latex sheets have a thickness of about 0.004 inch, and are sealed to each other by strips of two-sided (double-stick) adhesive tape, such as 3M 950.

In the embodiments of foot pressure sensor array 40, shown in Figures 7A-7H, the sensor array includes an upper column, conductor strip lamination 41 and a lower, row conductor strip lamination 46 having the shape of a left human foot, thus adapting the sensor array to be placed in a shoe to measure pressures exerted on a person's left foot. A mirror image sensor array having upper column conductor could be constructed for measuring pressures on the right foot. However, the present inventor has found that a single type sensor array may be used for both left and right feet by turning over the array as required.

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Figures 12A-12E illustrates an alternate embodiment of the foot pressure or normal force sensor array 40 shown in Figures 7A-11 and described above. The alternate embodiment employs a novel construction using an aperture mask lamination which eliminates the need for conductively adhering lead-out lamination trace termination flags to row conductive strips, as will now be described.

Referring first to Figure 12A, foot pressure sensor array 300 may be seen to include a bottom, column conductor strip lamination 301 comprising a insulating substrate sheet 302 on which are formed a plurality of longitudinally disposed, laterally spaced apart column conductive strips 311. Column conductive strips 311 terminate at the rear or heel end of substrate 302 in narrowed-down conductive lead-out traces 303 located on a rearwardly protruding, rectangularly-shaped tab or tongue portion 304 of substrate sheet 30. Preferably, column conductive strip lamination 311 is made from an etched-through fabric sheet, as shown in Figure 7F and described above. Using this arrangement, the conductive lead-out traces 303 are electrically continuous through the thickness dimension of the substrate sheet 302, allowing electrical contact to be made to the lead-out traces by lower contacts of a ribbon cable connector 305.

Referring now to Figure 12B, sensor array 300 may be seen to include a piezoresistive lamination 323. Piezoresistive lamination 323 comprises a mesh matrix sheet 324 supporting a piezoresistive substance 326, in a construction substantially similar to that of piezoresistive lamination 63 described above. Preferably, matrix sheet 324 of piezoresistive lamination 323 has a rearwardly protruding tongue 324A which provides electrical insulation between column conductive traces 303 below the piezoresistive lamination, and the lamination above it.

Referring now to Figure 12C, sensor array 300 may be seen to include a row conductor strip lamination 306 having an insulating substrate sheet 307 made of a thin, flexible, electrically insulating material. Row conductor strip

lamination 306 has formed on a surface thereof a plurality of generally rectangularly shaped, laterally disposed, longitudinally spaced apart row conductive strips 312. Preferably, row conductive strip lamination 306 is made from an etched-through mesh fabric sheet, as shown in Figure 7F and described above. With this arrangement, the lower surfaces of row conductive strips 312 may be in electrical contact with piezoresistive layer 323, while lead-out connections may be made to the upper surfaces of the conductive strips protruding upwards through the mesh substrate sheet 307. The novel manner of making the aforementioned connections will now be described.

Referring now to Figure 12D, sensor array 300 may be seen to include an aperture mask lamination 314, made of a thin sheet of flexible, electrically insulating material such as Mylar or nylon. Aperture mask lamination 314 consists of a sheet 315 of the above-described material, that has been cut to the same plan-view shape as column and row lamination substrates 302 and 307. A plurality of laterally elongated, longitudinally aligned and spaced apart apertures 316 is provided through the thickness dimension of sheet 315. One such aperture 316 is longitudinally centered on the laterally disposed center line of each row conductive strips 312, when aperture mask lamination 314 is stacked on top of row conductor strip lamination 306. Thus located, apertures 316 allow electrically conductive contact to be made through insulating substrate 315 to the row conductors 312, by a lead-out lamination located above the substrate, as will now be described.

Referring now to Figure 12E, sensor array 300 may be seen to include a lead-out lamination 309, made of a thin substrate sheet 317 of electrically insulating material, cut to approximately the same plan-view shape as aperture mask lamination 309.

A plurality of thin, narrow conductive lead-out traces 308 are provided on a surface of substrate sheet 317. Lead-out traces 308 are laterally spaced apart from one another,

and each is terminated at the upper end thereof by a laterally elongated, oval plan-view "flag" appendage 318 that is in electrically conductive contact with the lead-out trace. Flags 318 of lead-out lamination 309 protrude laterally  
5 outwards from corresponding lead-out traces 308, and are so located as to each be vertically aligned with a separate aperture 316 of aperture mask lamination 314, with the lead-out lamination overlying and vertically aligned with the aperture mask lamination. Therefore, when lead-out lamination  
10 309 is pressed down and adhered to aperture mask lamination 314, flags 318 conductively contact row conductor strips 312.

Preferably, lead-out lamination 309 is made from an etched-through mesh fabric sheet, as shown in Figure 7F and described above. With this arrangement, the lower surfaces of  
15 flags 318 may be in conductive electrical contact with row conductor strips 312, while lead-out traces 308 on the upper surface of lead-out substrate 317 may be electrically contacted by upper contacts of a ribbon cable connector 305.

Laminations 301, 323, 306, 314, and 315 are stacked  
20 vertically and sealed together by 3M double-stick tape to form foot pressure sensor array 300.

Figures 13A-13E illustrate a modification of the alternate embodiment 300 of the foot pressure sensor array depicted in Figures 12A-12E and described above. Modified  
25 foot pressure sensor array 300A shown in Figures 13A-13E is substantially identical in structure and function to sensor array 300 shown in Figures 12A-12E and described above, except for the spacing between row conductor strips 312A, and corresponding apertures 316A and flags 318A. By varying the  
30 longitudinal spacing between row conductor strips 312A, modified foot pressure sensor array 300A may be constructed so as to have thinner, more densely spaced conductor strips where greater sensitivity and spatial resolution are required, such as toe region T and heel region H identified in Figure 13.  
35 Conversely, conductive strips 312 may be wider and less densely spaced in regions such as instep region I where less sensitivity and spatial resolution are required.

Figure 14 is a partially diagrammatic view of a planar foot pressure measuring and mapping apparatus 68 according to the present invention. As shown in Figure 14, apparatus 68 includes a foot pressure sensor array 40 comprised of sensor elements 30 of the type shown in Figure 1, and signal processing and display circuitry 70. In the preferred embodiment, foot pressure sensor 40 is connected to signal processor and display circuitry 70 by means of a thin, flat, flexible multi-conductor ribbon cable 71 that is terminated at one end thereof by ribbon cable connector 45. As was described previously and shown in Figure 10, ribbon cable connector 45 is adapted to insertably receive rearwardly protruding tongue 44 of sensor 40, and has individual conductors that frictionally and electrically conductively contact a separate one of each of the row and column lead-out conductor traces on the upper and lower surfaces of the tongue.

As shown in Figure 14, interface cable 71 is connected at the other end thereof to an interface module 72 containing means for applying an electrical sampling signals between a selected column conductive strip 51 and a selected row conductor strip 52, to measure the resistance value of selected sensor element 30. Resistance is measured by applying a known voltage across a sensor resistance element, and measuring the resulting current, or applying a known current, and measuring the voltage drop. Although a d.c. sampling signal may be used for measuring resistances of sensor elements 30, preferably, an a.c. signal is used, to avoid polarizing effects on the sensor elements.

Interface module 72 preferably contains a multiplexer 73, which sequentially outputs a sequence of  $m \times n$  signals, each signal being representative of the resistance value for a particular sensor element 30 at the intersection of the  $m$ th row conductive strip with the  $n$ th column conductive strip. Also in the preferred embodiment, an analog-to-digital converter (ADC) 74 is connected between an analog resistance measuring circuit 75 and multiplexer 73, which is then of the

digital variety, outputs a serial digital data signal on an RS232 port 76. In the preferred embodiment, RS232 port 76 of interface module 72 is connected to serial data port 77 of a computer 78.

5           Computer 78 is used to control interface module 72, directing the sequence of addressing sensors 30 in array 40. Computer 78 also performs signal processing functions, using predetermined scaling factors to convert the resistance values of sensor elements 30 to digital values representing normal  
10 forces and pressures exerted on the sensors. In the preferred embodiment, digital numbers representing the pressures on each of the  $m \times n$  sensors 30 in array 40 are utilized to produce area maps of those pressures, which are displayed on a monitor 79 and stored in digital memory if desired.

15           Figures 15-18 illustrate a shear force sensor element 80 according to the present invention. For reasons to be stated later, it would be desirable in some applications to be able to measure shear forces as well as normal forces or pressures exerted on a foot.

20           Referring now to Figures 15-18, but especially to Figures 15 and 16, shear force sensor element 80 may be seen to include a first elongated, rectangularly-shaped electrically conductive strip 81 made of a thin flexible, electrically conductive fabric, such as Flectron. Shear force  
25 sensor element 80 also includes a second conductive strip 82 spaced apart from strip 81 in a direction normal or perpendicular to strip 81.

          Shear force sensor element 80 includes at least one pair of elastomeric piezoresistive pads 83A and 83B located between  
30 conductive strips 81 and 82. As may be seen best by referring to Figures 13 and 14, piezoresistive pads 83A and 83B have surfaces 84A and 84B, respectively, which tangentially contact one another. Pad 83A is in electrically conductive contact with lower conductive strip 81, and pad 83B is in electrically  
35 conductive contact with upper conductive strip 82. Thus, when contacting surfaces 84A and 84B of pads 83A and 83B are urged into more intimate contact in response to shear forces

directed normal to their tangent contact plane, the electrical resistance between the conductive strips is reduced, a phenomenon which may be referred to as tangential or surface piezoresistivity.

5 As shown in Figure 16, to electrically isolate lower piezoresistive pad 83A, which is conductively coupled to lower conductive strip 81, from upper conductive strip 82, a thin, flexible insulating sheet 85A is positioned between that portion of the lower surface of the upper conductive strip  
10 that overlies pad 83A, and the upper surface of the pad. In the preferred embodiment, insulating sheet 85A is made of a slippery material such as TEFLON, the lower surface of the sheet thereby facilitating sliding lateral motion of lower piezoresistive pad 83A relative to upper conductive strip 82,  
15 in response to lateral or shear forces exerted on lower strip 81 relative to upper strip 22. Similarly, a slippery insulating sheet 85B is located between the upper surface of lower conductive strip 81 and upper piezoresistive pad 83B, to electrically isolate upper piezoresistive pad 83B from lower  
20 conductive strip 81, while permitting slidable motion of the pad with respect to the strip.

Referring now to Figures 15, 16 and 18A, each piezoresistive pad 83 of shear force sensor element 80 may be seen to preferably include a supporting matrix made of a thin,  
25 open mesh fabric sheet 86. Fabric sheet 86, which is preferably electrically non-conductive, is preferably woven from mono-filament strands of a polymer such as polyethylene or polyester. In an example embodiment of shear force sensor element 80, fabric sheet 86 was a 300 mesh fabric sheet made  
30 of 0.002 inch diameter mono-filament strands of polyester.

Mesh fabric sheet 86 is impregnated with a resiliently deformable, partially conductive substance 87 that has an electrical resistance inversely proportional to compressive forces exerted on the surfaces 84 of the pads in response to  
35 shear forces on the pads, mesh sheet 86 provides a durable

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and dimensionally stable support matrix for piezoresistive substance 87. The present inventor has found that a suitable piezoresistive substance 87 for impregnating mesh 86, thus forming piezoresistive pad 83, is an ink composed of about 50% milled carbon black having a grain size of 205 microns, 30% unpolymerized liquid nitrile rubber, type BUNA N, and 20% ABS plastic resin/hardener, or silicone rubber (e.g., Dow Corning RTV 732) and no hardener. Piezoresistive pads 83 are formed by mixing the aforementioned components thoroughly, applying the mixture to a thickness of about 0.004 in. to matrix mesh 86, using a spatula or flat plastic knife, and allowing the mixture to air cure at room temperature.

The volume resistivity of piezoresistive pad 83 of shear force sensor element 80 can be varied to a desired cured value by varying the amount of carbon black added to the liquid rubber, and monitoring the resistivity of the liquid mixture as those two components are being mixed together. The present inventor has found that a suitable range of volume resistivities for piezoresistive pad 83 is about 5 ohm-cm to 100,000 ohm-cm for measurement of shear forces in the approximate range of 0-5 psi, and 100-300,000 ohm-cm for measurement of shear forces in the approximate range of 5-30 psi.

A suitable material for conductive strips 81 and 82 of shear force sensor 80 is a conductive fabric consisting of nickel/copper coated polyester taffeta and marketed under the brand name FLECTRON by Monsanto, The Chemical Group, 800 N. Lindberg, St. Louis, Missouri. This material has a thickness of 3.8 to 4 mils, is flexible and drapable, and has a surface resistivity of less than 0.05 ohms per square. Preferably, each conductive strip 81 and 82 has slits cut perpendicularly inward from opposite longitudinal edges of the strip, to allow stretching of the strip in a direction parallel to its longitudinal axis. As shown in Figure 13, slits 88 are located in laterally spaced apart pairs, one pair being spaced laterally outwards from each side of a pair of opposed piezoresistive pads 83. Figure 5B illustrates a typical

variation of the electrical resistance between lower and electrode conductor strips 81 and 82, of sensor element 80, as a function of shear force directed normally to contacting surfaces 84 of piezoresistive pads 83 of the sensor element, 5 i.e., in the X or Y direction in Figure 15.

Figure 18B illustrates a planar array 89 of shear force sensor elements 80 in which a plurality of column conductive strips 81 and row conductive strips 82 form a rectangular matrix of shear force sensor elements. In regions exterior to 10 piezoresistive pads 83 of sensor elements 80, column and row conductive strips 81 and 82 may be electrically isolated from one another, to prevent short circuiting, by means of thin column and row insulating strips 90 and 91, respectively. The insulating strips may be made of any suitable electrically 15 insulating material, such as nylon. Preferably, however, insulating strips 90 and 91 are integral with the non-conductive fabric substrates of conductive strips 81 and 82. In this case, conductive material on the Electron fabric is stripped away from insulating areas 90 and 91 by photo-etching 20 using a ferrous chloride solution.

In the embodiment 89 of a planar shear force sensor array shown in Figure 18B, the sensitive or "S" axis of each shear force sensor element 80 is oriented perpendicularly to the S axis of each of its neighbors. This arrangement of 25 shear force sensor array 89 affords a capability for mapping shear forces in two orthogonal, X and Y directions parallel to the plane of the sensors.

After mesh fabric matrix sheets 86 have been impregnated with piezoresistive substance 87 and the latter allowed to 30 cure, the piezoresistive pads 83 thus formed are positioned between upper and lower conductive strips 82 and 81. In the preferred embodiment, a rectangular array of spaced apart contacting pairs of piezoresistive pads 83A and 83B is formed on a pair of lower and upper fabric matrix sheets 86A and 86B, 35 as for example, by screen printing piezoresistive ink onto the matrix sheets. The matrix sheets are then positioned between upper and lower column and row laminations having on the inner



facing surfaces thereof spaced apart column and row electrode conducting strips, of the type illustrated in Figures 7A-7D and described above. Row and column laminations are then sealed to one another to encapsulate matrix sheets 86A and 86B and pairs of piezoresistive shear force sensing pads 83A and 83B, in a manner similar to that described above for normal force sensor 40.

Figures 19-20E illustrate a modification 100 of a foot pressure sensor array 40 according to the present invention, in which shear force sensor elements similar to elements 80 described above, are interspersed with normal force sensor elements similar to elements 30 described above.

As may be seen best by referring to Figures 19 and 20C, foot pressure/shear sensor array 100 includes a rectangular array of generally rectangular plan-view normal force sensor elements 30, in which each normal force sensor is bordered on either lateral side by a pair of shear force sensor elements 80, with their sensitive axes S aligned in a first horizontal direction, and on either longitudinal side by a pair of shear force sensors having their sensitive axes S aligned in a second horizontal direction perpendicular to sensitive axes of the first pair of shear sensor elements. Aside from the interspersing of shear force sensor elements 80 with normal force sensor elements 30, the construction of foot pressure/shear sensor array 100 is substantially similar to that of foot pressure sensor array 40. Thus, sensor array 100 has elements numbered 101-119 that are exactly analogous in structure and function to elements 41-59 of the pressure sensor array 40. Accordingly, a complete understanding of the structure and function of elements 101-119 may be obtained by referring to the previous description of elements 41 through 59.

Thus, as shown in Figure 20E, foot pressure/shear force sensor 100 includes a lower, row conductive strip lamination 106 having row conductive strips 112. As may be seen best by referring to Figure 20D, sensor array 100 also includes an upper, column lamination 101 having column conductive strips

111 that overlie piezoresistive normal force sensor elements 30, the latter alternating in a rectangular array with shear force sensor elements 80.

In the combined shear/normal force sensor array 100 depicted in Figure 19 and 20C, normal force sensor elements 30 are preferably fabricated by impregnating a mesh fabric matrix sheet 34 with square areas of piezoresistive material 35, the squares being arranged in parallel diagonal rows, such as rows 92 in Figure 19. As shown in Figures 19 and 20C, diagonal rows 92 of normal force sensor elements 30 alternate with diagonal rows 93 of shear force sensor elements 80. As is also shown in Figures 19 and 20C, the sensitive axes S of shear force sensor elements 80 in each diagonal row alternate between the X and Y directions.

One method of fabricating array 100 of normal force sensors 30 alternating with shear force sensors 80 consists of perforating normal force sensor array matrix sheet 34 with square apertures 120 aligned with diagonal rows 93 of shear force sensor elements 80. Preferably, apertures 120 are slightly larger than shear sensor elements 80. With this arrangement, perforated normal force matrix sheet 34 may be vertically aligned with a pair of matrix sheets 86A and 86B on which are formed the pairs 83A and 83B of piezoresistive pads of shear force sensor elements 80. Thus configured, normal force matrix mesh sheet 34 could be located above or below shear force matrix sheet pair 86A and 86B. Preferably, however, normal force matrix mesh sheet 34 is located between lower and upper shear force matrix sheets 86A and 86B.

Figure 21 illustrates an array 130 of combined shear/normal force sensor elements according to the present invention. The embodiment of the invention shown in Figures 19 and 20 includes normal force sensor elements 140 that are substantially similar in structure and function to normal force sensor element 30 shown in Figures 1-4 and described above, stacked above or below shear force sensor elements 150 which are substantially similar in structure and function to shear force element 80 shown in Figures 16 and 18 and

described above. Thus, as shown in Figure 21, stacked shear/normal force sensor array 130 includes a planar array 130A of shear force sensor elements 80 which have a common first, lower lamination 80A having on the upper surface thereof inner column or row conductive strips 81 and, a second, upper lamination 82A having on the lower surface thereof row or column conductive strips 82. As shown in Figure 21, each shear force sensor element 80 of array 130A includes a pair of elastomeric piezoresistive pads 83A and 83B located between conductive strips 81 and 82. Piezoresistive pads 83A and 83B have surfaces 84A and 84B, respectively, which tangentially contact one another. Pad 83A is in electrically conductive contact with lower conductive strip 81, and pad 83B is in electrically conductive contact with upper conductive strip 82. Thus, when contacting surfaces 84A and 84B of pads 83A and 83B are urged into more intimate contact in response to shear forces directed normal to their tangent contact plane, the electrical resistance between the conductive strips is reduced, a phenomenon which may be referred to as tangential or surface piezoresistivity. As shown in Figure 21, shear force sensor element pads 83A and 83B preferably are arranged in array 130A so that the tangent planes of adjacent shear force sensor elements 80 are perpendicular to one another. This arrangement permits measurement resolution of shear forces in any direction parallel to array 130A into two mutually orthogonal components.

To electrically isolate lower piezoresistive pads 83A, which are conductively coupled to lower conductive strips 81, from upper conductive strips 82, thin, flexible insulating strips 85A are positioned between that portion of the lower surface of the upper conductive strip that overlies pads 83A, and the upper surface of the pads. In the preferred embodiment, insulating strips 85A are made of a slippery material such as TEFLON, the lower surface of the sheet thereby facilitating sliding lateral motion of lower piezoresistive pad 83A relative to upper conductive strip 82,

in response to lateral or shear forces exerted on lower strip 81 relative to upper strip 22. Similarly, slippery insulating strips 85B are located between the upper surface of lower conductive strips 81 and upper piezoresistive pad 83B, to electrically isolate upper piezoresistive pad 83B from lower conductive strip 81, while permitting slidable motion of the pads with respect to the strip. In the preferred embodiment, each piezoresistive pad 83A and 83B is fabricated integrally with conductive strip 81 or 82 was described above with reference to Figures 15, 16 and 18A.

Stacked shear/normal force sensor element array 130 also includes normal force sensor elements 30 which have a common first, lower lamination 31A having on the upper surface thereof column or row conductive strips 31. Lower conductive strips 31 may be adhered to the upper surface of an insulating sheet positioned over shear force array upper lamination 82A. Alternatively, lamination 82A may be a double-sided printed circuit, the lower surfaces of the insulating sheet having formed thereon traces comprising the upper, column conductive strips 82 of shear force sensor elements 80, and having formed on the upper surface thereof traces comprising the lower, row conductive traces 31 of normal force sensor elements 30. However, in the most preferred embodiment, lamination 82A is fabricated with conductive strips extending through the thickness dimension of the lamination, according to the novel construction employing etched, plated fabric described above. With this arrangement, upper, column conductive strips 82 of shear force sensor elements 80 may be common with lower column conductive strips 31 of normal force sensor elements 30.

Sensor array 130 also includes an upper lamination 132A having on the lower surface thereof a plurality of column or row conductive strips 132, that are disposed perpendicularly to conductive strips 31. A piezoresistive layer 133 is positioned between column and row conductive strips 31 and 132, and functions in response to normal forces exerted thereon as has been previously described.

/ / /

Thus constructed, combined shear/normal force sensor elements 130 can be arranged in a rectangular array similar to that shown in Figures 7A-7D. However, in this case, one or two additional lead-out tongues 144A, 144B must be brought out  
5 from the array, as indicated by the dotted lines in Figure 7A. The additional lead-out tongues are required to accommodate the two additional layers of conductors required for the stacked configuration of shear and normal force sensors.

In the arrangement of stacked shear/normal force sensor  
10 element 130 shown in Figures 19 and 20, normal force sensor element 30 is positioned above shear force sensor element 80. This order could of course be reversed.

Figures 24-25A illustrate a normal force sensor array  
15 160 that is particularly well adapted for measuring normal forces or pressures exerted on the bottom surfaces of horses' hooves, by horseshoes, for example. Hoof pressure sensor array 160 employs normal force sensor elements 170 substantially similar in structure and function to the normal  
20 force sensor elements 30 shown in Figures 1-4 and described above, with the sensor elements arranged in a rectangular array similar to array 37 shown in Figure 6. Also, hoof pressure sensor array 160 is substantially similar in structure and function to foot pressure sensor array 40. Thus, hoof pressure sensor array 160 has elements 161-187  
25 substantially similar in structure and function to elements 41-67 of foot pressure sensor array. Since the structure and function of the latter elements were described in detail above, a thorough understanding of the corresponding elements of hoof pressure sensor array 160 may be obtained by referring  
30 to that description.

As may be seen by referring to Figures 24-25A, some of the construction details of hoof pressure sensor 160 differ somewhat from those of foot pressure sensor 40. Thus, as shown in Figures 23-24B, the laminations comprising hoof  
35 pressure sensor 160 have in plan-view a shape approximating a horse's hoof print rather than a human foot print. Also, the piezoresistive substance 186 used to impregnate mesh fabric

matrix sheet 184 differs from piezoresistive material 66 used in foot pressure sensor array 160 by having a higher volume resistivity of about 500,000 ohm-cm versus 100,000 ohm-cm, thus resulting in a piezoresistive layer 183 that has greater  
5 linearity and minimum hysteresis for the larger pressure ranges of 1,000 to 6,000 psi resulting from the larger weight of horses.

It will be recalled that a planar foot pressure measuring and mapping apparatus 68 illustrated in Figure 12  
10 was described above. That apparatus includes a foot pressure sensor array 40, which may be replaced by hoof pressure sensor array 160, thus enabling apparatus 68 to measure and map hoof pressures rather than foot pressures.

Figure 26 is a lower plan-view of a modification 200 of  
15 a hoof pressure sensor array 160 according to the present invention, in which shear force elements similar to elements 80 described above, are interspersed with normal force sensor elements similar to elements 30 described above. Modified hoof pressure/shear sensor array 200 is substantially similar  
20 in structure and function to modified foot pressure/shear sensor array 100 illustrated in Figures 17-18B and described above. Thus, hoof pressure/shear force sensor array 200 has elements 201-219 substantially similar in structure and function to elements 101-119 of foot pressure/shear force  
25 sensor array 100. Since the structure and function of the latter elements were described in detail above, a thorough understanding of the corresponding elements of hoof pressure/shear force sensor array 200 may be obtained by referring to that description.

30 As was described above, stacked, combined shear/normal force sensor elements 130 can be substituted for alternating normal force sensor elements 30 and shear forced elements 80 in foot pressure/shear force sensor array 100. This substitution could of course also be made in hoof  
35 pressure/shear force sensor array 200.

/ / /

Figures 27-33 illustrate a sock 220 that may be fitted

with any of the sensor arrays 40, 100, 160, or 200 described above. The construction of sock 200 is as follows: The sock is made up of three conductive tubular laminations, an inner tube 221 with longitudinal conductor strips, a center tube 222 bearing piezoresistive material and an outer tube 223 containing lateral or circumferentially disposed conductor strips which wrap around the sock. A fourth, lead-out layer/strip 224 is provided to make electrical contact with each of the lateral conductor strips.

10 In the preferred embodiment of force sensing and mapping sock 220, each of tubes comprising the sock is made of a mesh fabric material. Thus, inner, column conductor lamination 221, row conductor lamination 223, and row lead-out lamination 224 are preferably made of a conductive mesh fabric such as  
15 the Flectron material described above.

As shown in Figure 31, inner column conductor tubular lamination 221 comprises a tubular Flectron sock base or matrix 231, having etched through the thickness dimension thereof, longitudinally disposed insulating paths 232 defining  
20 longitudinally disposed, laterally spaced apart column conductors 233 terminating at the opening of the sock in lead-out traces 234.

As shown in Figure 32, outer, row conductor tubular lamination 223 comprises a tubular Flextron sock base or  
25 matrix 241 having etched through the thickness dimension thereof circumferentially disposed insulating paths 242 defining circumferentially disposed, longitudinally spaced apart row conductors 243.

As shown in Figures 29 and 33, piezoresistive tubular  
30 lamination 222 comprises a tubular sock made of a non-conducting mesh fabric impregnated with piezoresistive material, in a manner previously described.

Referring now to Figures 27 and 29, force sensing and mapping sock 220 may be seen to include an outer tubular row  
35 lead-out tubular lamination 224. Lead-out tubular lamination 224 is made from Flextron material having etched through the thickness dimension thereof circumferentially and

longitudinally disposed insulating paths 262 and 263 defining laterally disposed longitudinally flag appendages 264 connected to longitudinally disposed lead-out traces 265.



Figures 34 and 35 illustrate an alternate embodiment of a force sensor array according to the present invention, which utilizes a variation of the shear force elements previously described.

5 As shown in Figures 34A-34C and 34E, alternate shear force sensor array 400 has laminations 401A, 423, 426, and 401B, substantially identical in structure and function to those previously described with reference to Figures 12, 20D and 20E. However, in the embodiment 400 of a force sensor  
10 array, shear force sensors 480 are arrayed in a separate layer using the horizontal conductive elements from a normal force sensor as a first conductive array on a first side of the shear force sensor elements, and a second layer of vertical conductive elements as a second, perpendicular conductive  
15 array for the second side of the shear force sensor elements.

As shown in Figure 34D, each shear force sensor element 480 includes a pair of mating right-triangularly-shaped piezoresistive pads 483A and 483D having mating hypotenuse surfaces 484A and 484B, the two pads thus defining a square  
20 shape. Each shear force sensor element pad 483A, 483B has a teflon coating or sheet 485A, and 485B adhered to one side thereof. The other side of each pad is in electrically conductive contact with a row or column conductor strip. Shear forces imposed on the pads 483A and 483B urge the pads into  
25 more or less intimate contact, thus varying the electrical resistance between the pads.

With pads 483A and 483B slidably movable towards one another, without any pre-load forcing the pads together, sensor element 480 is more sensitive to forces tending to urge  
30 the pads into more intimate contact than to forces tending to separate the pads. This somewhat non-bilateral characteristic may also be present in the basic embodiment of shear force sensor element according to the present invention and described above. Thus, in the absence of a pre-load force  
35 tending to bias pads 483A and 483B together, it is preferable to employ diagonally opposed pairs of sensor elements 480A and 480B as shown in Figure 34, assuring adequate bilateral

sensitivity of the sensor element pad array, as shown in Figure 35.

In another shear force sensor array embodiment shown in Figure 36, circularly-shaped, piezoresistive pads 503 are placed on multi-conductor flat cable 500. Spots 502 are bared on (hc flat cable to coincide with placement of the four circular pads 503 of the shear sensor 499. This allows the pads to contact the flat cable and these are adhered to the cable using a conductive adhesive. There are also two additional bared areas which make up the normal force sensor element. One of the central normal force elements acts as the common electrical contact and the other is covered with a layer of piezoresistive normal force sensing material 501. A central round aluminum element 504 comes into contact with the central piezoresistive layer 501, allowing it to act as the normal force sensing element. Element 504 also tangentially contacts pads 503 and serves as the common element for those pads. The tops of the four pads 503 are covered with Teflon sheet 505 to reduce friction with the plastic cover plate 506. The whole assembly is covered with latex rubber 507 to ensure a good friction to surrounding surfaces.

What is claimed is:

1. A device for measuring forces exerted on discrete locations of a surface, said apparatus comprising a planar two dimensional array of normal force sensing elements, said  
5 elements containing a piezoresistive material defined as having a bulk electrical resistance that varies in a predetermined way with normal forces exerted thereon, said piezoresistive material being in the form of a resilient pad sandwiched between a pair of first and second conductor strip  
10 laminations comprising thin, flexible insulating sheets having formed on the inner facing surfaces thereof adjacent rows of spaced apart row and column conductor strips, respectively, said row and column conductor strips being in electrically conductive contact with opposite sides of said piezoresistive  
15 pad, whereby the resistance between a selected row and column conductor intersection defining a particular region in said array may be determined by measuring the electrical current flowing through said piezoresistive material in response to a voltage applied between said selected row and column conductor  
20 strips, thereby determining the normal force exerted on said region.

2. The device of Claim 1 wherein said row and column conductors define therebetween regions of piezoresistive pads of known transverse sectional area thereby providing means for  
25 measuring pressures exerted on said regions by measuring the resistance thereof.

3. The device of Claim 1 wherein said piezoresistive pads are each further defined as comprising an insulating matrix impregnated with a piezoresistive substance.

30 4. The device of Claim 3 wherein said matrix is further defined as being a woven fabric mesh.

5. The device of Claim 1 wherein said piezoresistive substance is further defined as comprising a suspension of conductive particles in a resilient material.

35 6. The device of Claim 5 wherein said resilient material is further defined as being an elastomer.

/ / /

7. The device of Claim 6 wherein said elastomer is further defined as being silicone rubber.

8. The device of Claim 5 wherein said conductive particles are further defined as being composed of carbon.

5 9. The device of Claim 1 wherein said row and column conductor strips extend through the thickness dimension of said first and second conductor strip laminations, whereby electrical contact may be made with said inner facing row and column conductor strips in contact with said piezoresistive  
10 elements by contacting elements on the outer surfaces of said cover sheets.

10. The device of Claim 9 wherein said first and second, row and column conductor strip laminations are further defined as comprising a conductive fabric sheet consisting of a non-  
15 conducting fabric mesh composed of woven strands of non-conductive fibers which are plated on the outer surfaces thereof with a conductive metallic coating, said coating being etched through the thickness dimension of said mesh to produce insulating paths defining conductive strips that extend  
20 through the thickness dimension of said mesh.

11. A device for measuring shear forces exerted on discrete locations of a surface which the apparatus may be placed in contact with, said device comprising a planar two dimensional array of individual shear force sensing elements,  
25 each of said shear force sensing elements comprising a pair of laterally adjacent piezoresistive pads having tangentially contacting peripheral surfaces, the electrical resistance between said pad pair members varying in a predetermined way with shear forces directed perpendicularly to the tangent  
30 plane and urging said contacting surfaces of said pad pair into greater or lesser conductive contact, said pairs of pads being sandwiched between a pair of first and second conductor strip laminations comprising thin, flexible electrically insulating sheets having formed on the inner facing surfaces  
35 thereof adjacent rows of spaced apart row and column conductor strips, respectively, said row and column conductor strips being in electrically conductive contact with a separate one

of each pair of pads, whereby the resistance between the pads of a selected pair of said pads may be measured by applying a voltage between said selected row and column conductor strips, thereby determining shear forces exerted on said pad pair.

5 12. The device of Claim 11 wherein at least one of said halves of a pad pair is slidably supported by an electrically non-conductive sheet on the surface opposite to that surface in electrically conductive contact with said pad.

10 13. The device of Claim 11 wherein said piezoresistive pads of said shear force sensing elements are each further defined as comprising an insulating matrix impregnated with a piezoresistive substance.

15 14. The device of Claim 13 wherein said piezoresistive substance is further defined as comprising a suspension of conductive particles in a resilient material.

15 15. The device of Claim 14 wherein said resilient material is further defined as being an elastomer.

16 16. The device of Claim 15 wherein said elastomer is further defined as being silicone rubber.

20 17. The device of Claim 14 wherein said conductive particles are further defined as being composed of carbon.

25 18. The device of Claim 11 wherein said row and column conductor strips extend through the thickness dimension of said first and second conductor strip laminations, whereby electrical contact may be made with said inner facing row and column conductor strips in contact with said piezoresistive pads by contacting elements on the outer surfaces of said laminations.

30 19. The device of Claim 11 wherein said first and second, row and column conductor strip laminations are further defined as comprising a conductive fabric sheet consisting of a non-conducting fabric mesh composed of woven strands of non-conductive fibers which are plated on the outer surfaces thereof with a conductive metallic coating, said coating being  
35 etched through the thickness dimension of said mesh to produce insulating paths defining conductive strips that extend through the thickness dimension of said mesh.

20. A device for measuring pressures exerted at various locations on the bottom of a foot in response to weight placed on the foot comprising a thin, flexible laminated structure containing a plurality of piezoresistive pressure sensing elements arranged in a planar two-dimensional array, said laminated structure comprising a first, column conductor strip lamination including a substrate made of a thin, flexible sheet of electrically insulating material having formed on a surface thereof a plurality of longitudinally disposed, laterally spaced apart column conductor strips, a second, piezoresistive lamination comprising a thin substrate matrix supporting a thin layer of resilient piezoresistive material having an electrical resistance measured normal to said layer that varies with normal forces exerted thereon, said piezoresistive layer having a first planar surface which is in electrical contact with said column conductor strips, a third, row conductor strip lamination including a substrate made of a thin, flexible sheet of electrically insulating material having formed on an inner surface thereof a plurality of laterally disposed, longitudinally spaced apart row conductor strips in electrically conductive contact with a second planar surface of said piezoresistive layer, and means for making electrically conductive contact with a selected pair of row and column conductor strips whereby the resistance of a selected piezoresistive element defined by that portion of said piezoresistive layer between said strips may be measured, said resistance being related in a predetermined way to pressure exerted on said element.

21. The device of Claim 20 wherein said row and column conductor strip laminations are further defined as having longitudinally elongated lead-out tongues supporting lead-out traces in electrically conductive contact with said respective row and column conductor strips, said tongues protruding away from the pressure sensor area defined by said piezoresistive lamination.

/ / /

22. The device of Claim 21 where said lead-out tongues

are further defined as being vertically aligned and splayed vertically apart, thereby allowing separate edge card connectors to electrically contact separate lead-out traces on the inner facing surfaces of said tongues.

5       23.    The device of claim 20 wherein at least one of said column and row conductor strip laminations is further defined as comprising a conductive fabric sheet consisting of a non-conducting fabric mesh composed of woven strands of non-conductive fibers which are plated on the outer surfaces  
10 thereof with a conductive metallic coating, said coating being etched through the thickness dimension of said mesh to produce insulating paths defining conductive strips that extend through the thickness dimension of said mesh.

15       24.    The device of Claim 20 wherein said column and row conductor strip laminations are further defined as comprising a conductive fabric sheet consisting of a non-conducting fabric mesh composed of woven strands of non-conductive fibers which are plated on the outer surfaces thereof with a  
20 conductive metallic coating, said coating being etched through the thickness dimension of said mesh to produce insulating paths defining conductive strips that extend through the thickness dimension of said mesh.

25       25.    The device of Claim 24 wherein said column and row conductor strip laminations are further defined as having longitudinally elongated lead-out tongues supporting lead-out traces in electrically conductive contact with said respective  
30 column and row conductor strips, said lead-out tongues protruding away from the pressure sensing area defined by said piezoresistive laminations and being vertically aligned in a parallel relationship with an insulating strip between the inner surfaces of said tongues, said lead-out traces being located on the outer surfaces of said tongues.

35       26.    The device of Claim 1 wherein at least one of said row and column strips is further defined as being made of an electrically conductive, woven fabric that is flexible and drapable.

27. The device of Claim 1 wherein at least one of said conductor strips is further defined as having formed therein at least one transversely disposed slit spaced apart from said piezoresistive pad, said slit facilitating longitudinal stretching of said strip.

5

28. The device of Claim 4 wherein said woven fabric mesh is further defined as being flexible and drapable.



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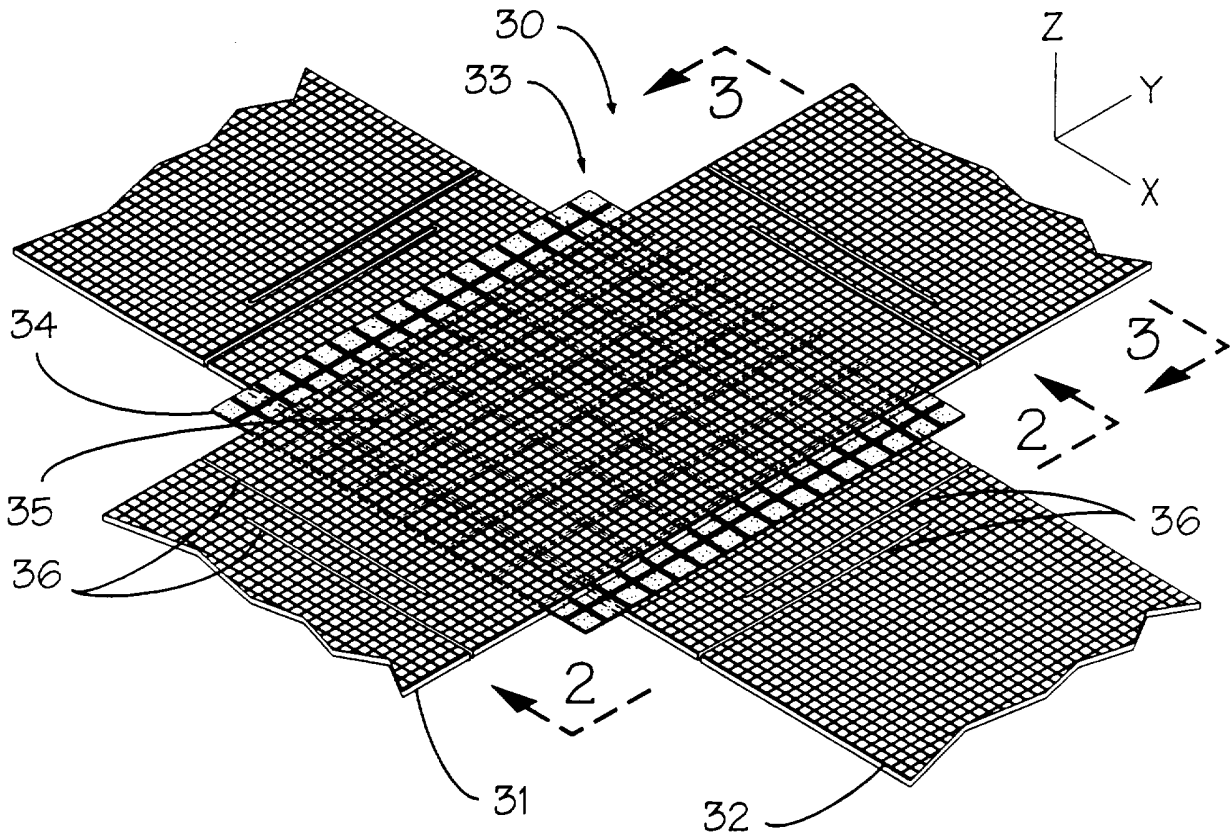


FIG. 1

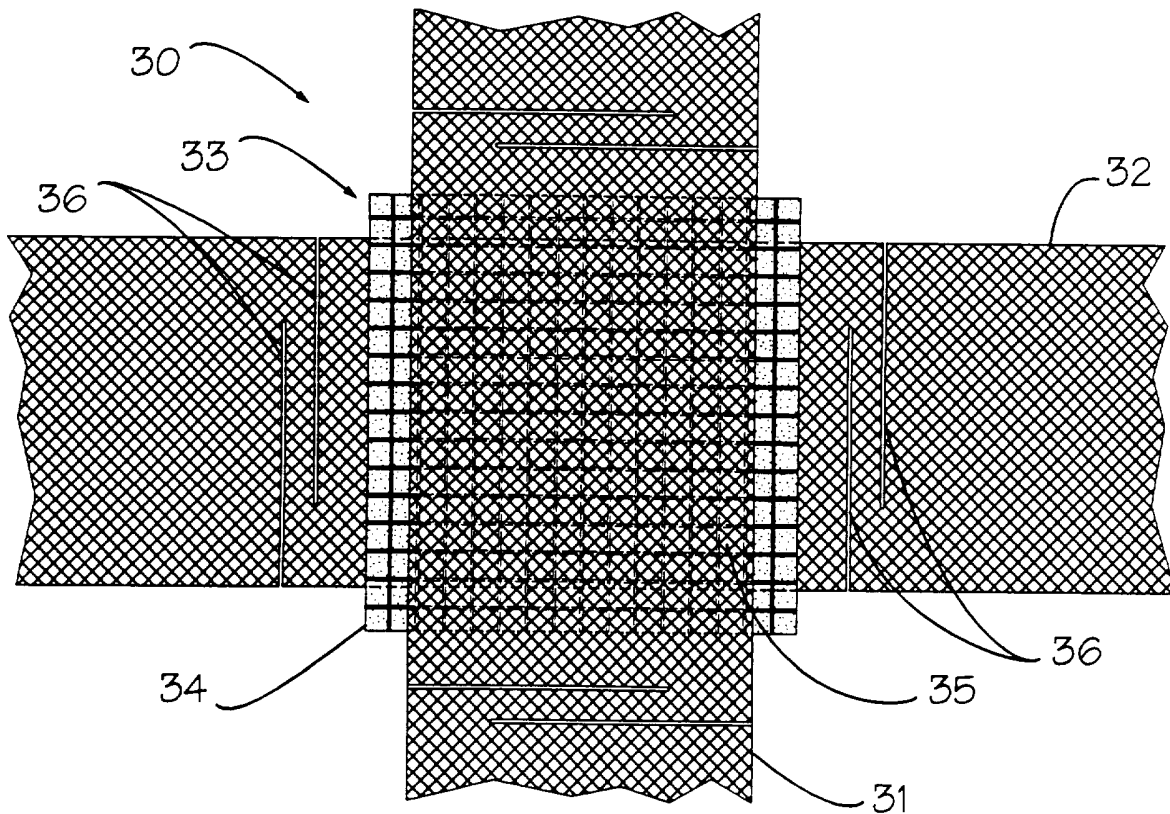


FIG. 4

SUBSTITUTE SHEET (RULE 26)

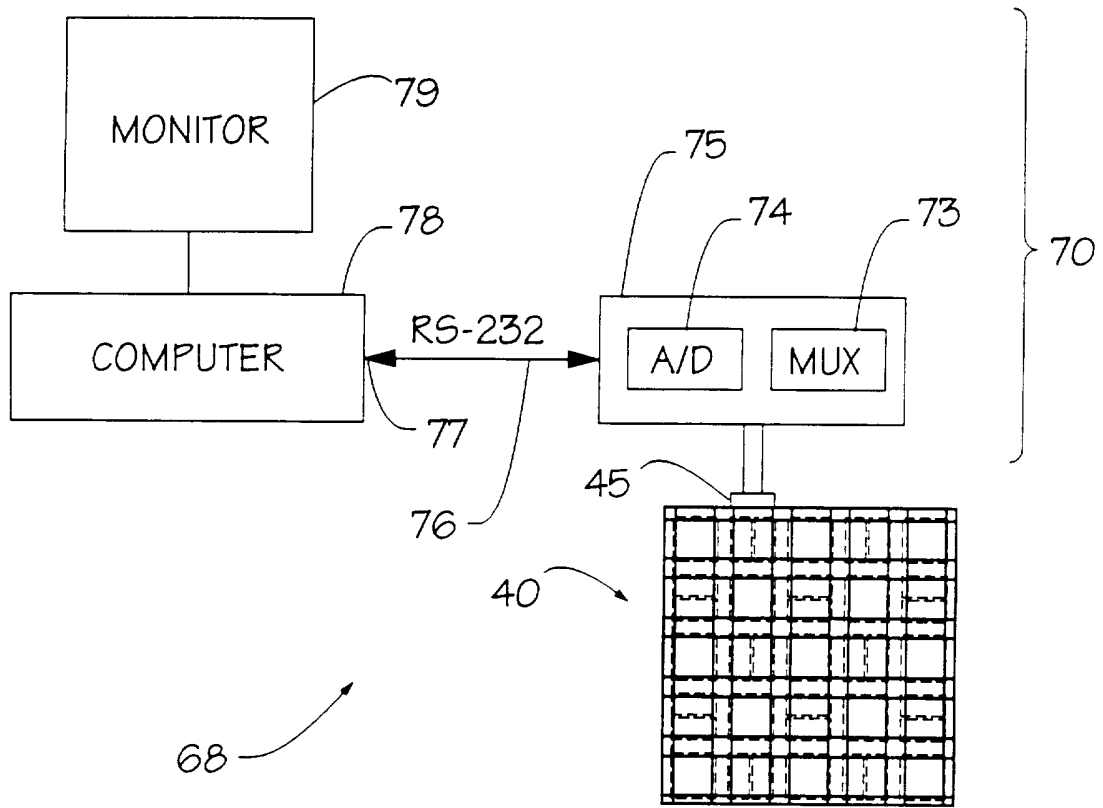


FIG. 14

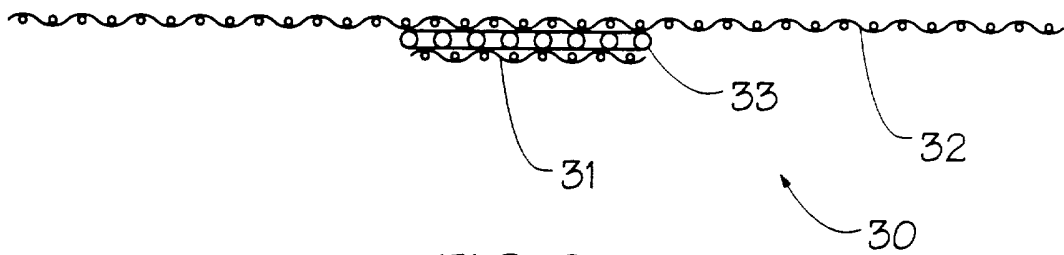


FIG. 2

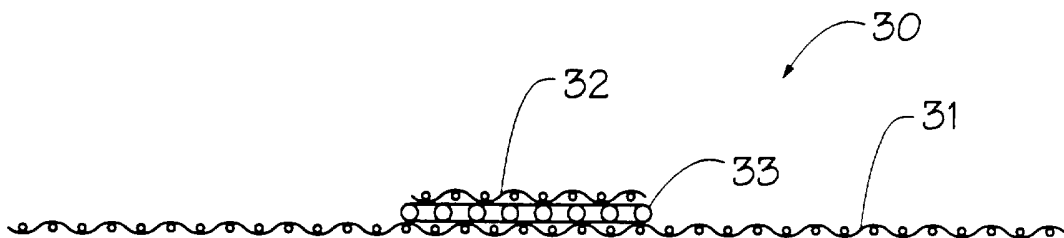
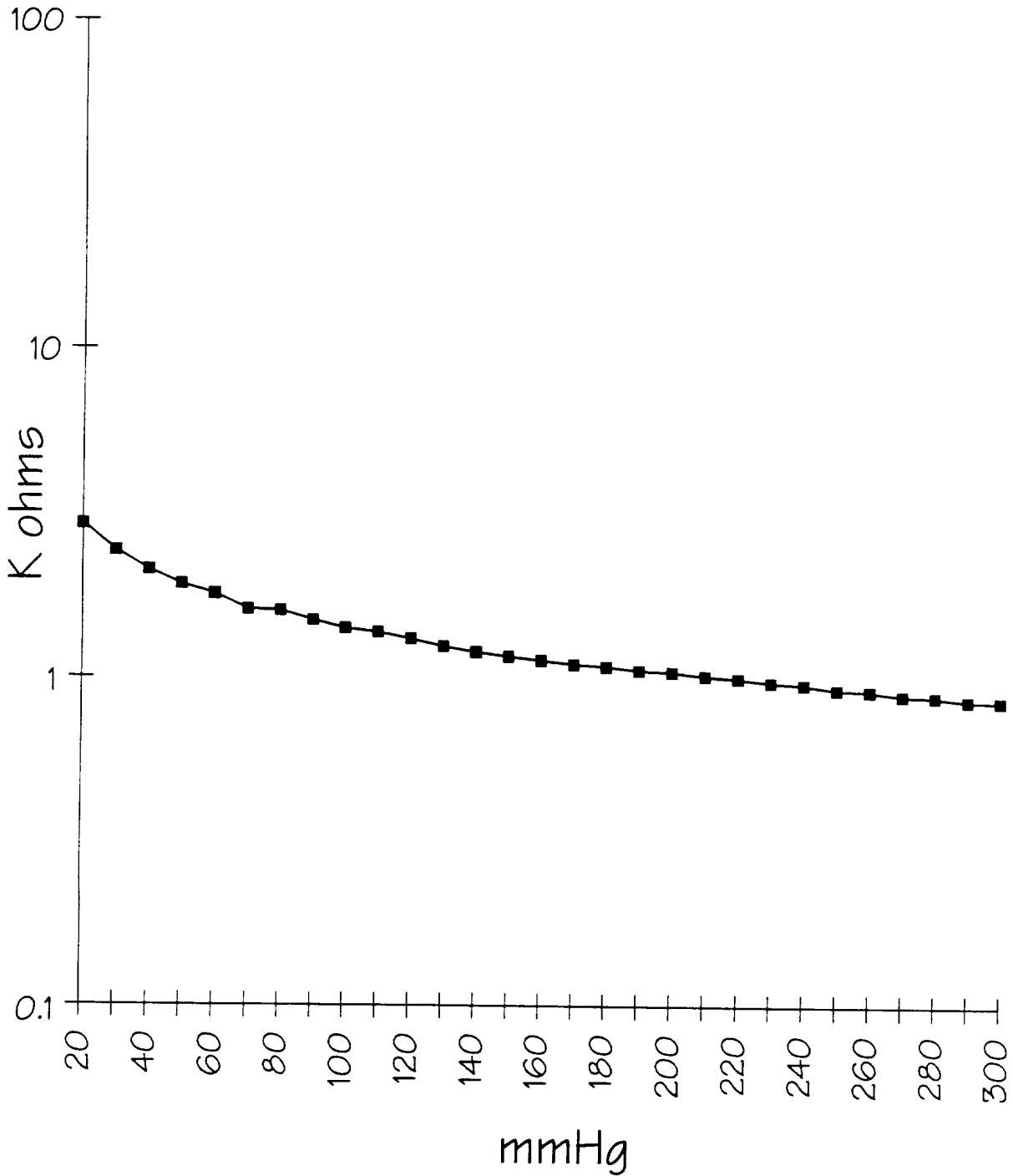


FIG. 3

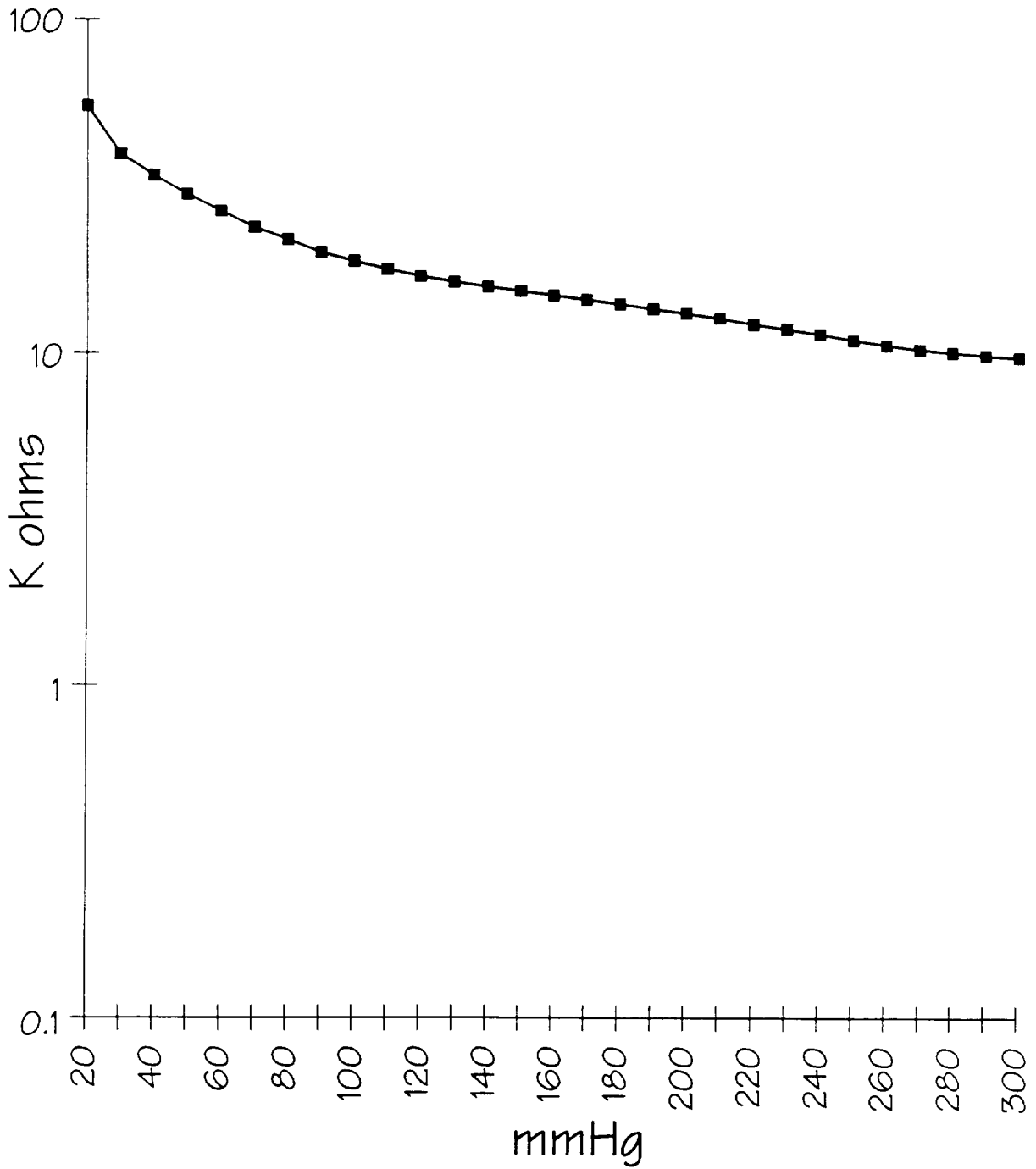
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FSR TEST - SHEAR SENSORS

FIG. 5A

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FSR TEST - NORMAL FORCE SENSORS

FIG. 5B

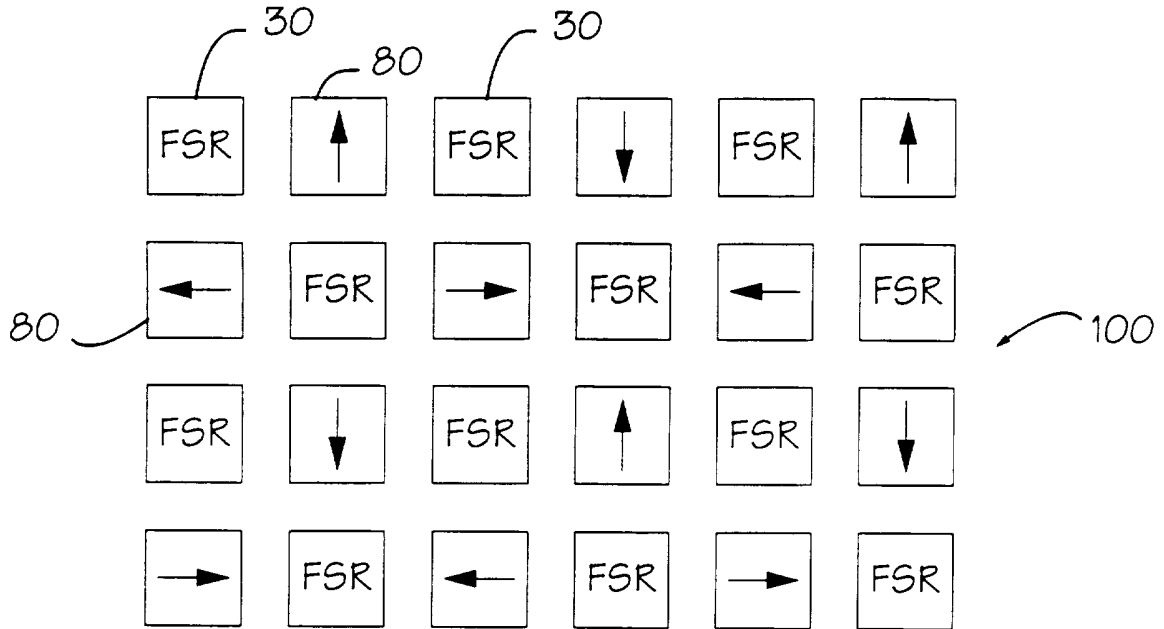


FIG. 20A

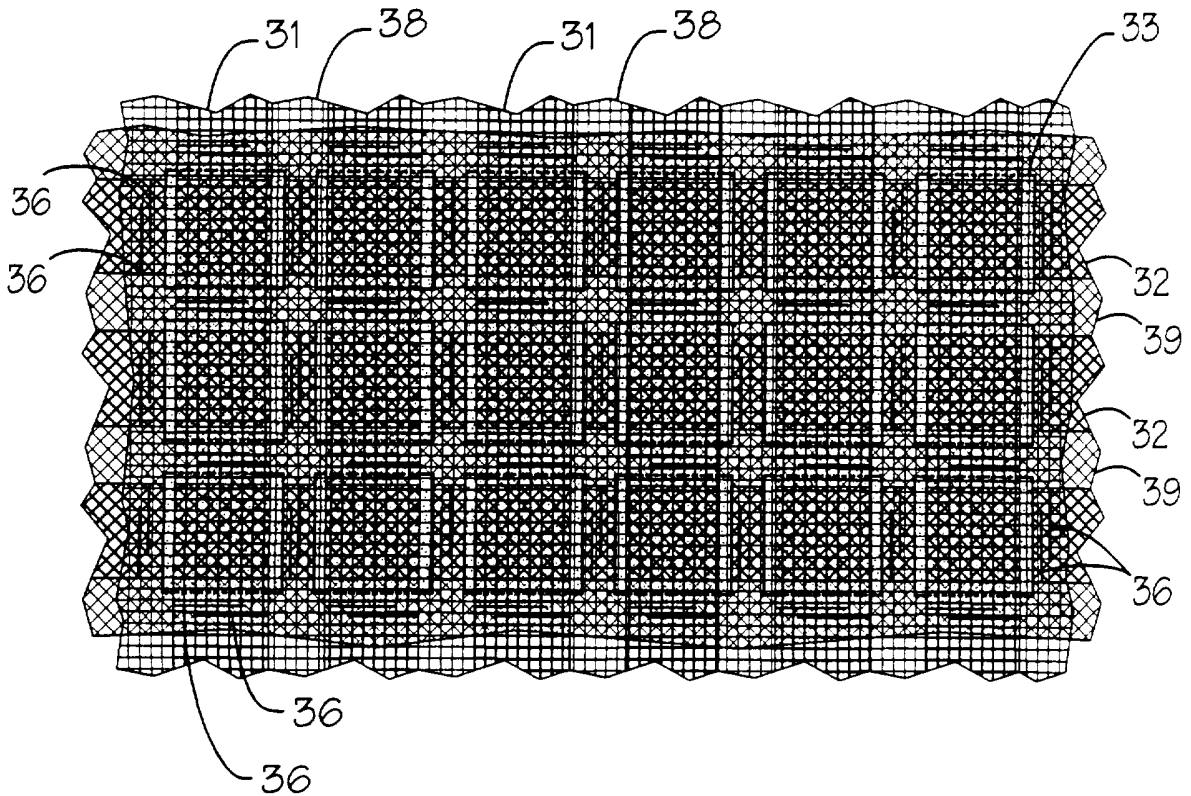
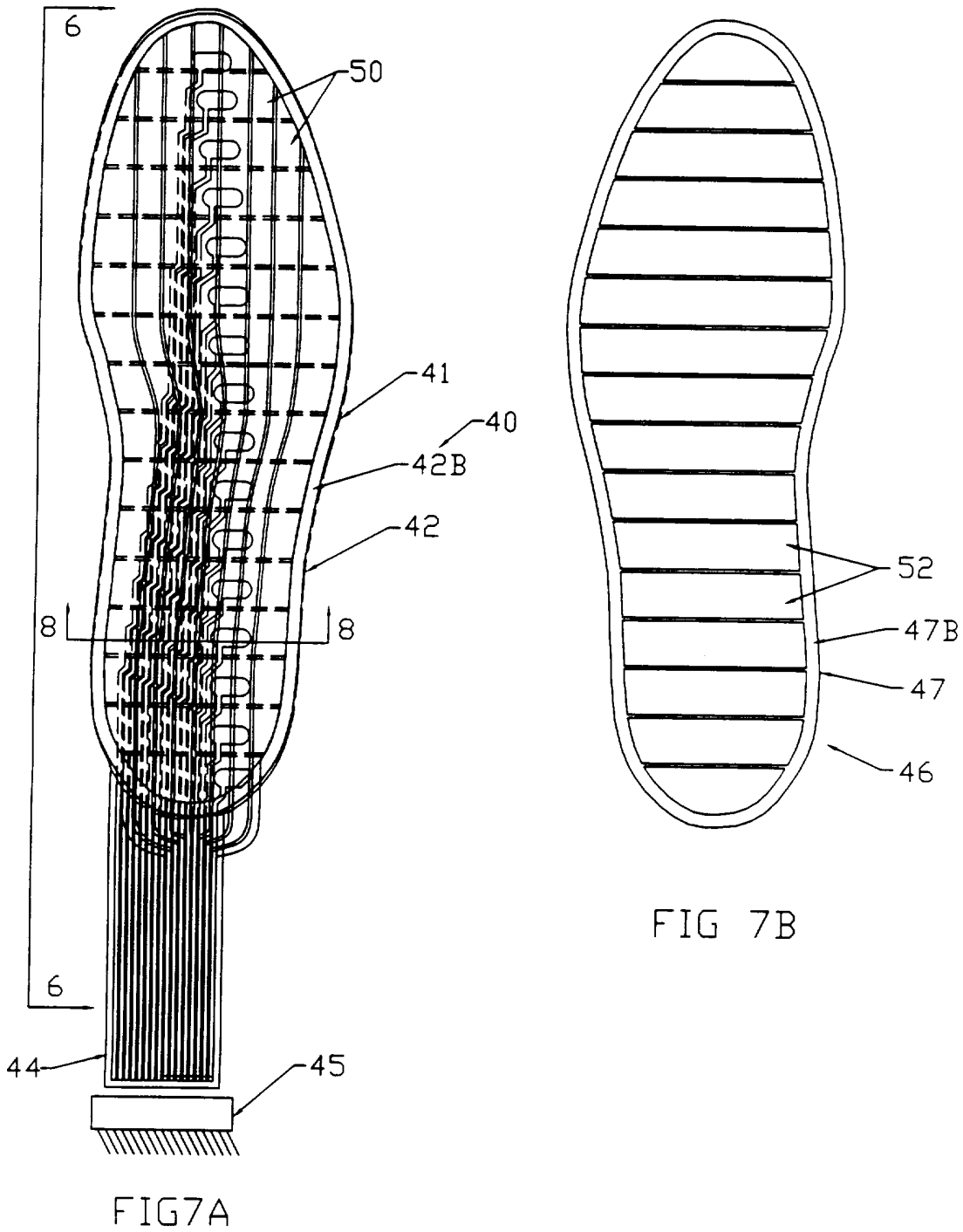


FIG. 6



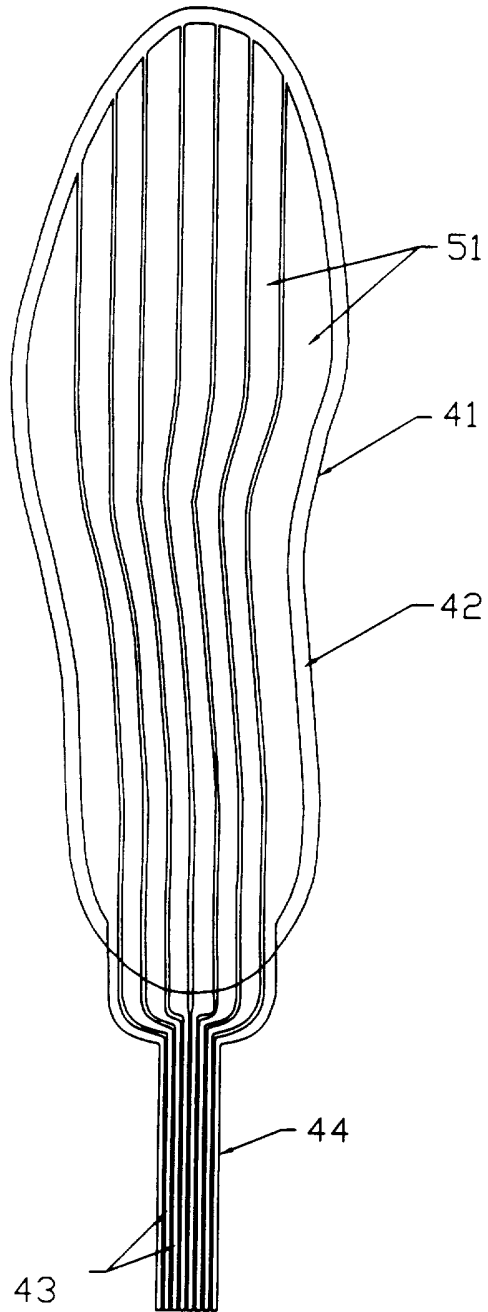


FIG 7C

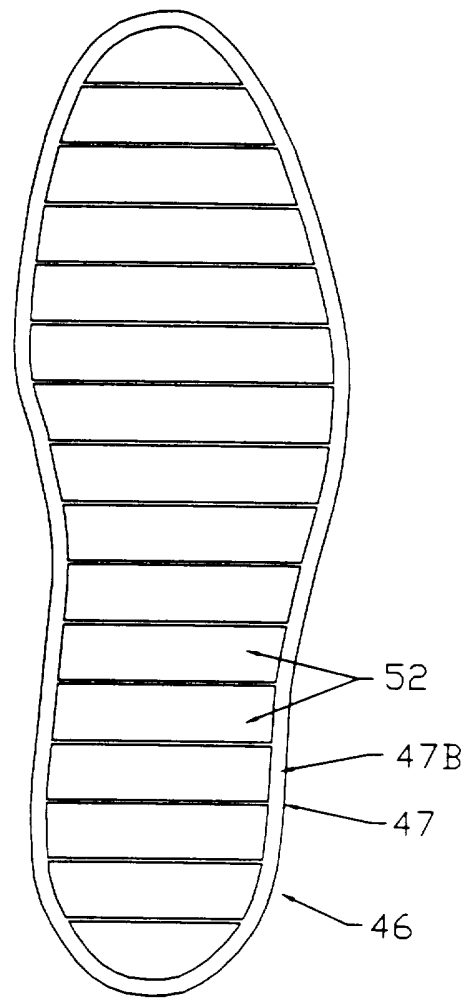
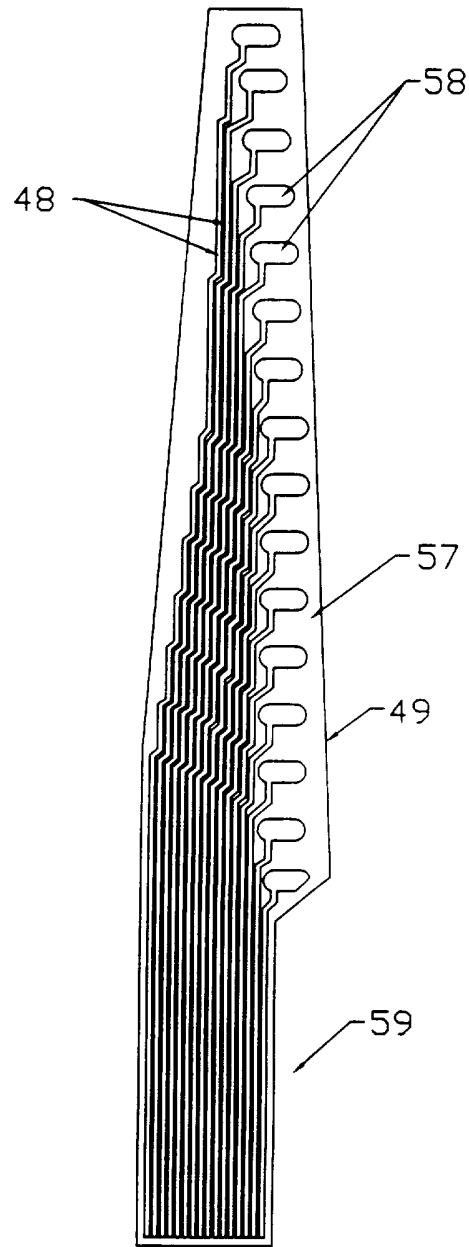
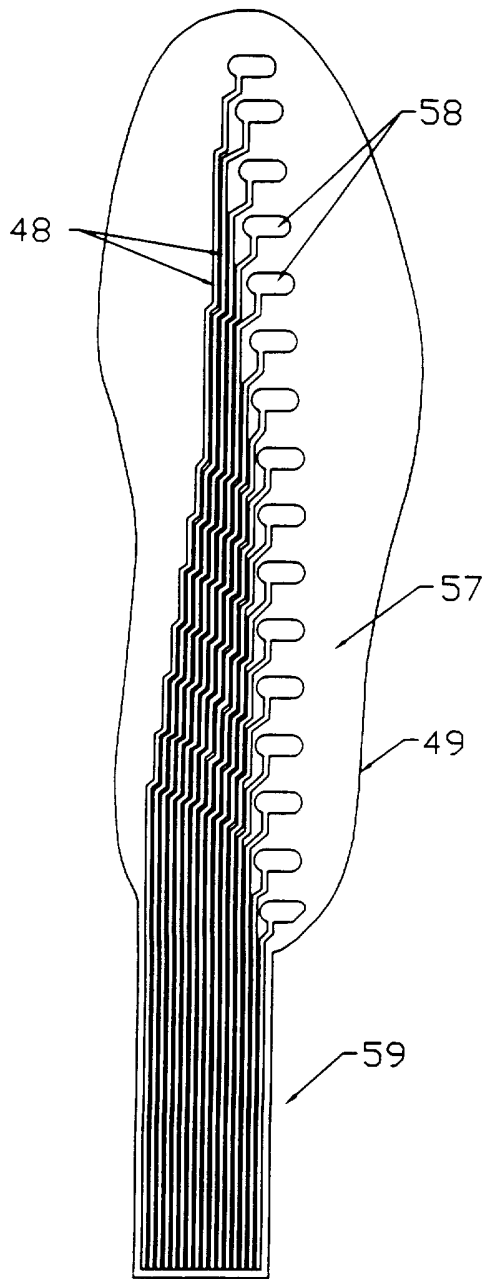


FIG 7D





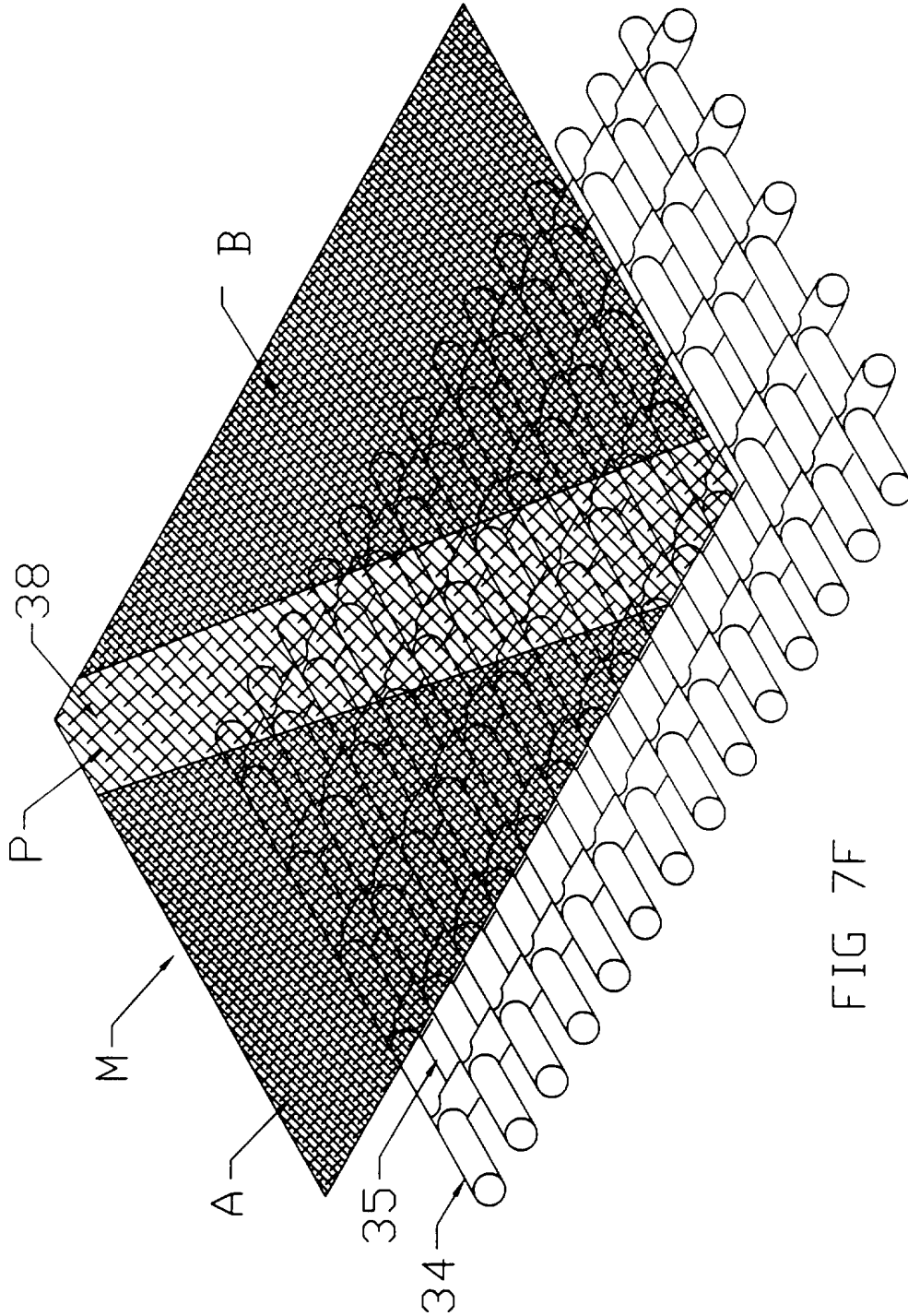
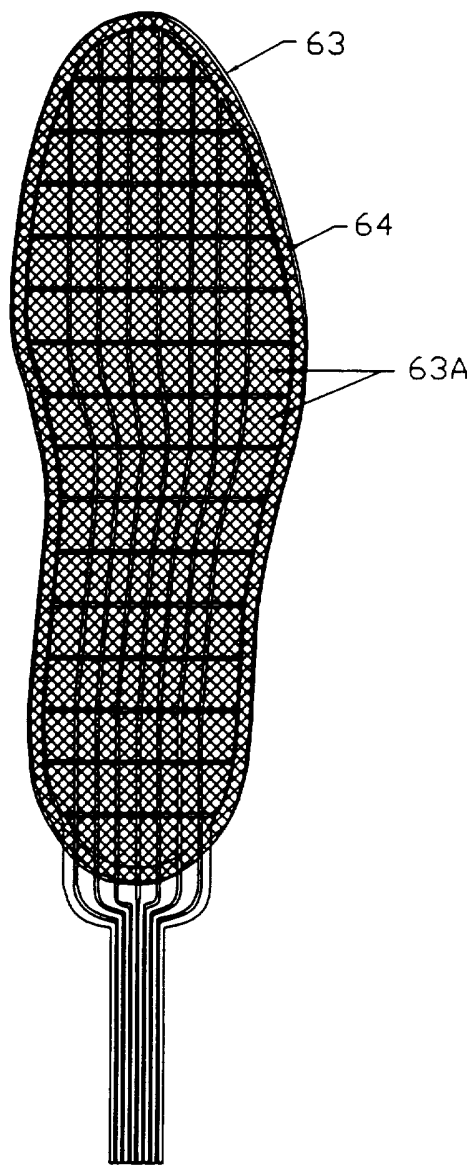
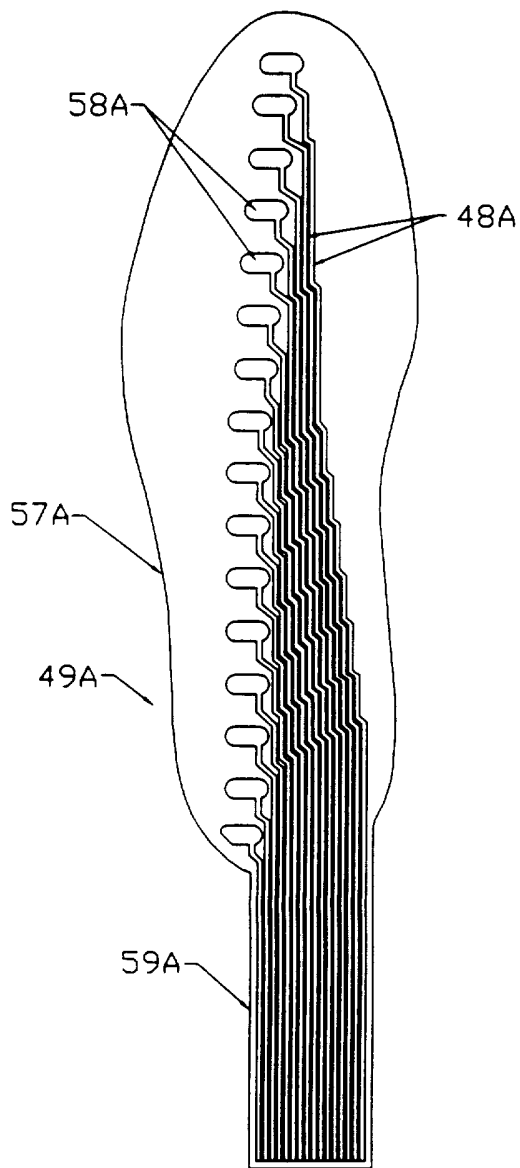


FIG 7F



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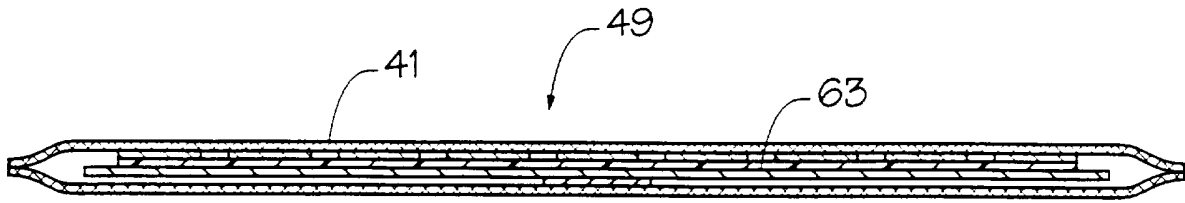


FIG. 8

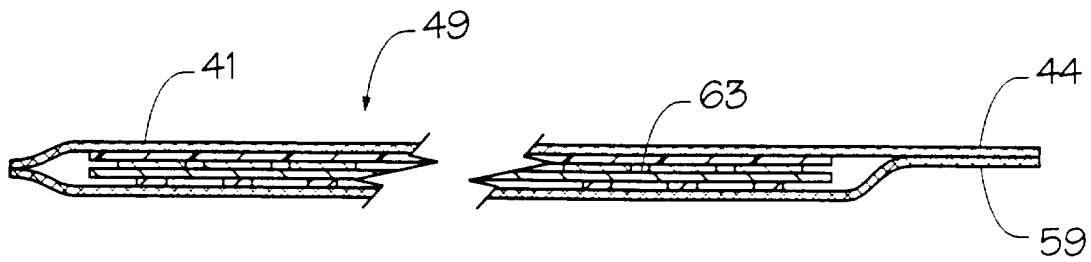


FIG. 9

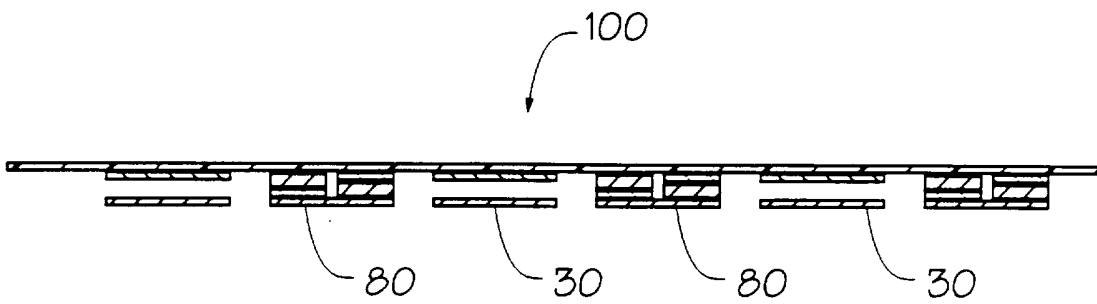


FIG. 20B

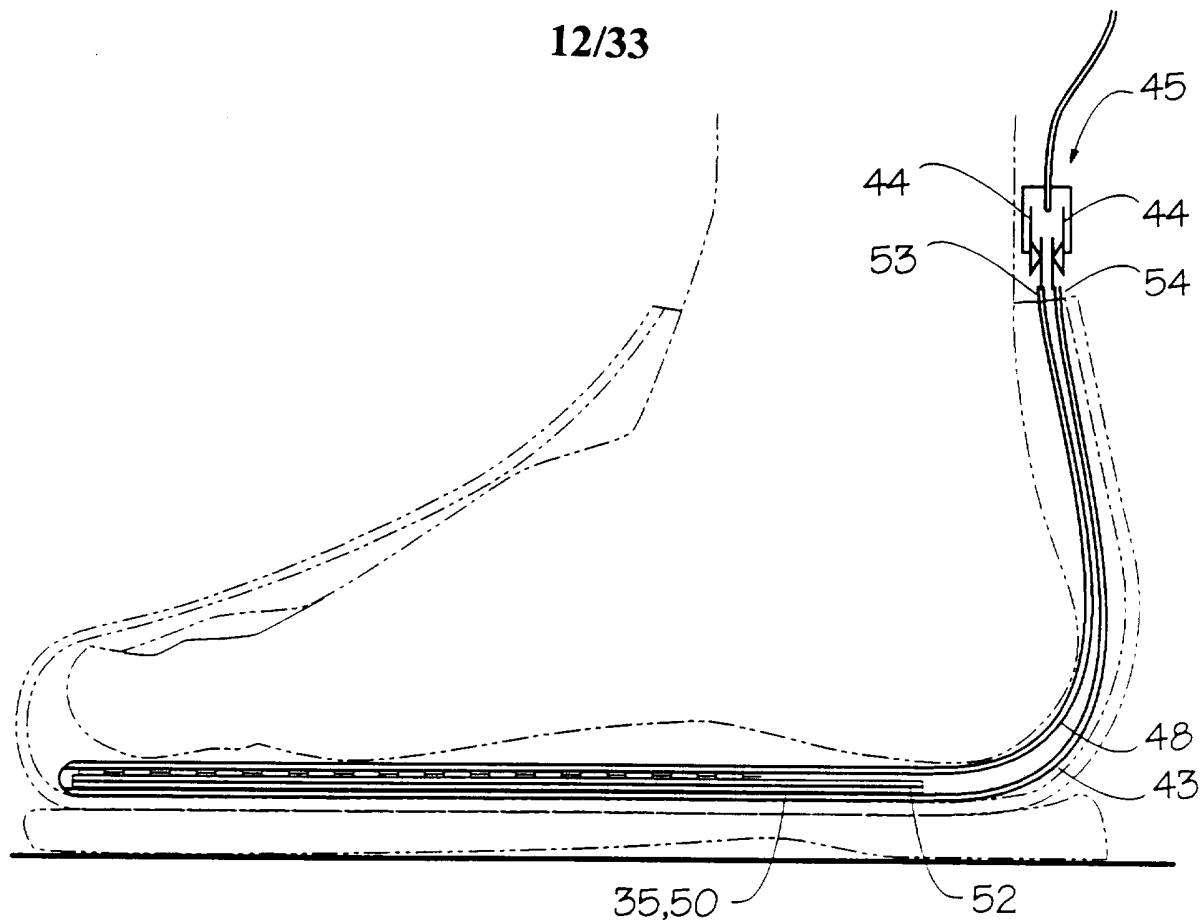


FIG. 10

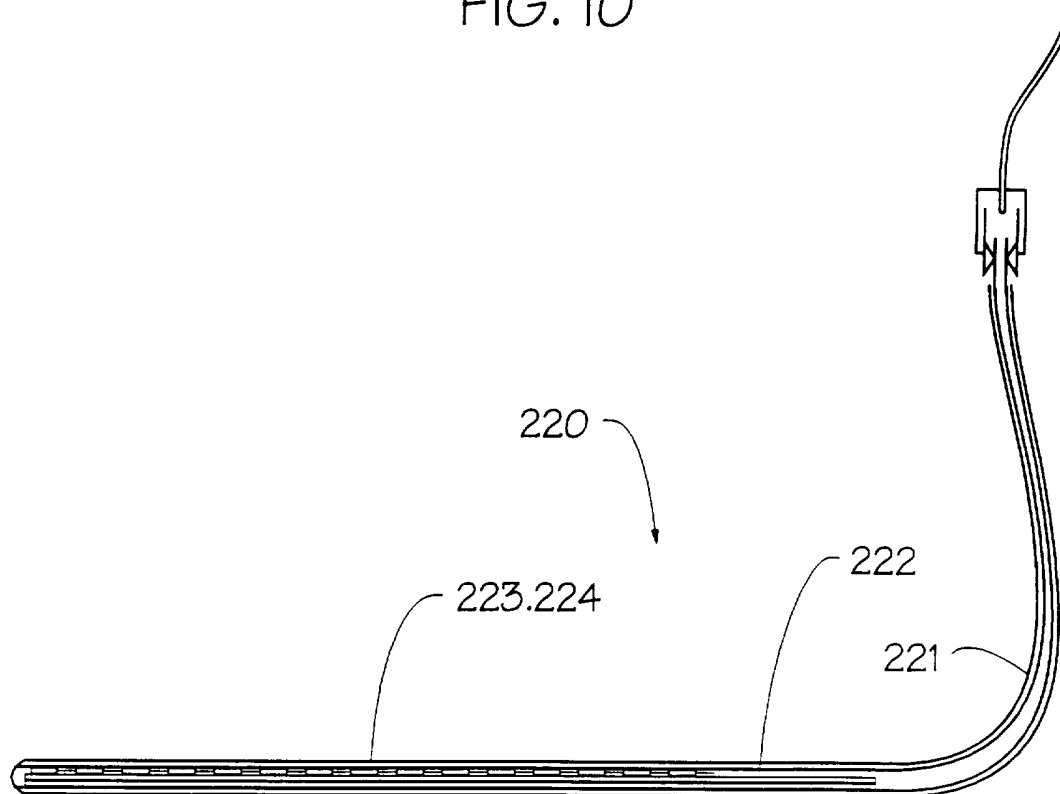


FIG. 30

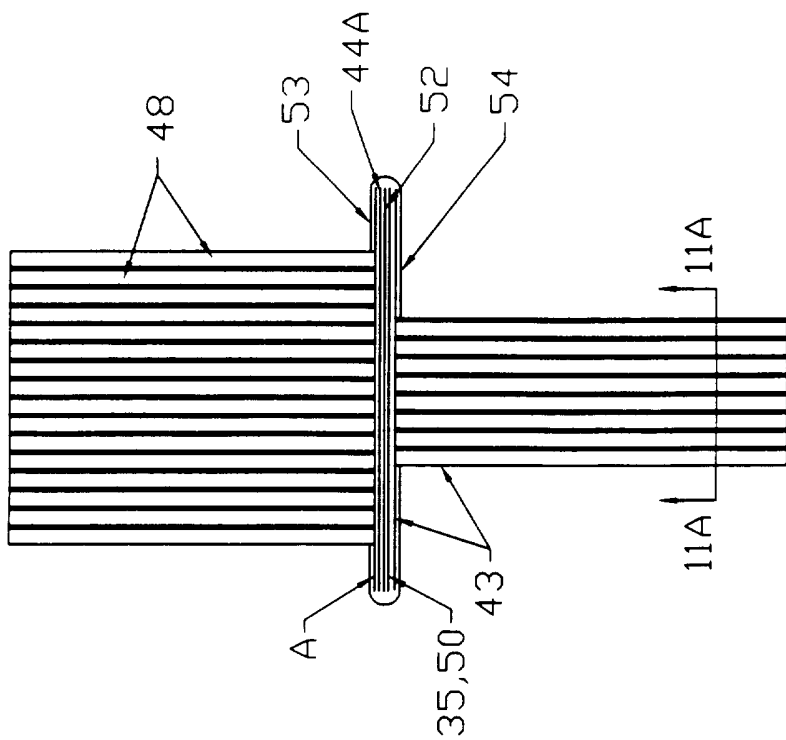


FIG 11

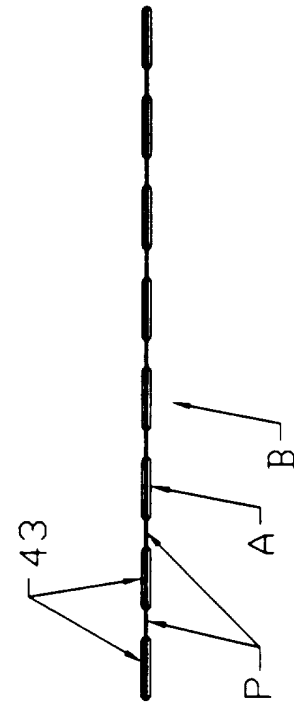
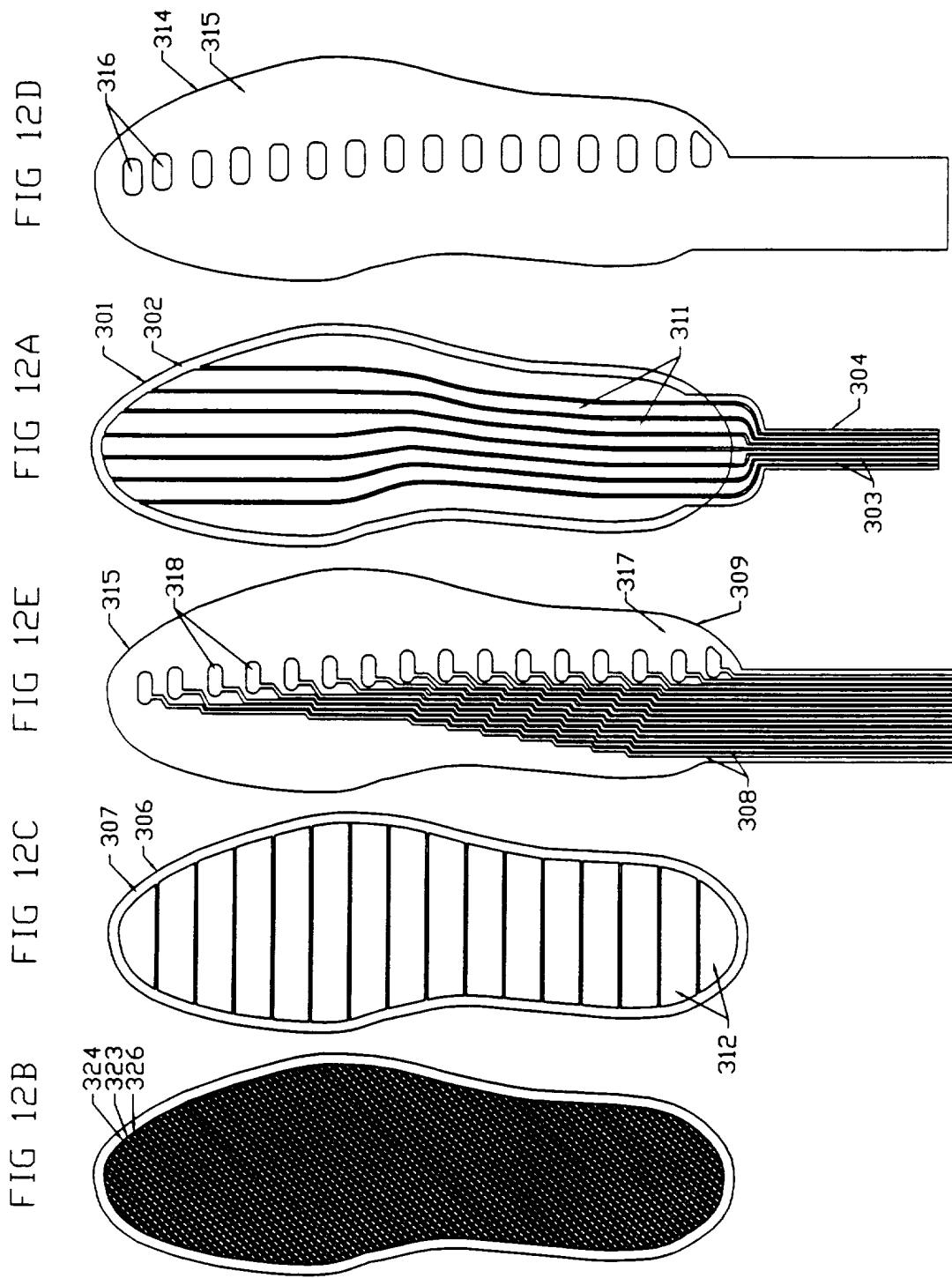
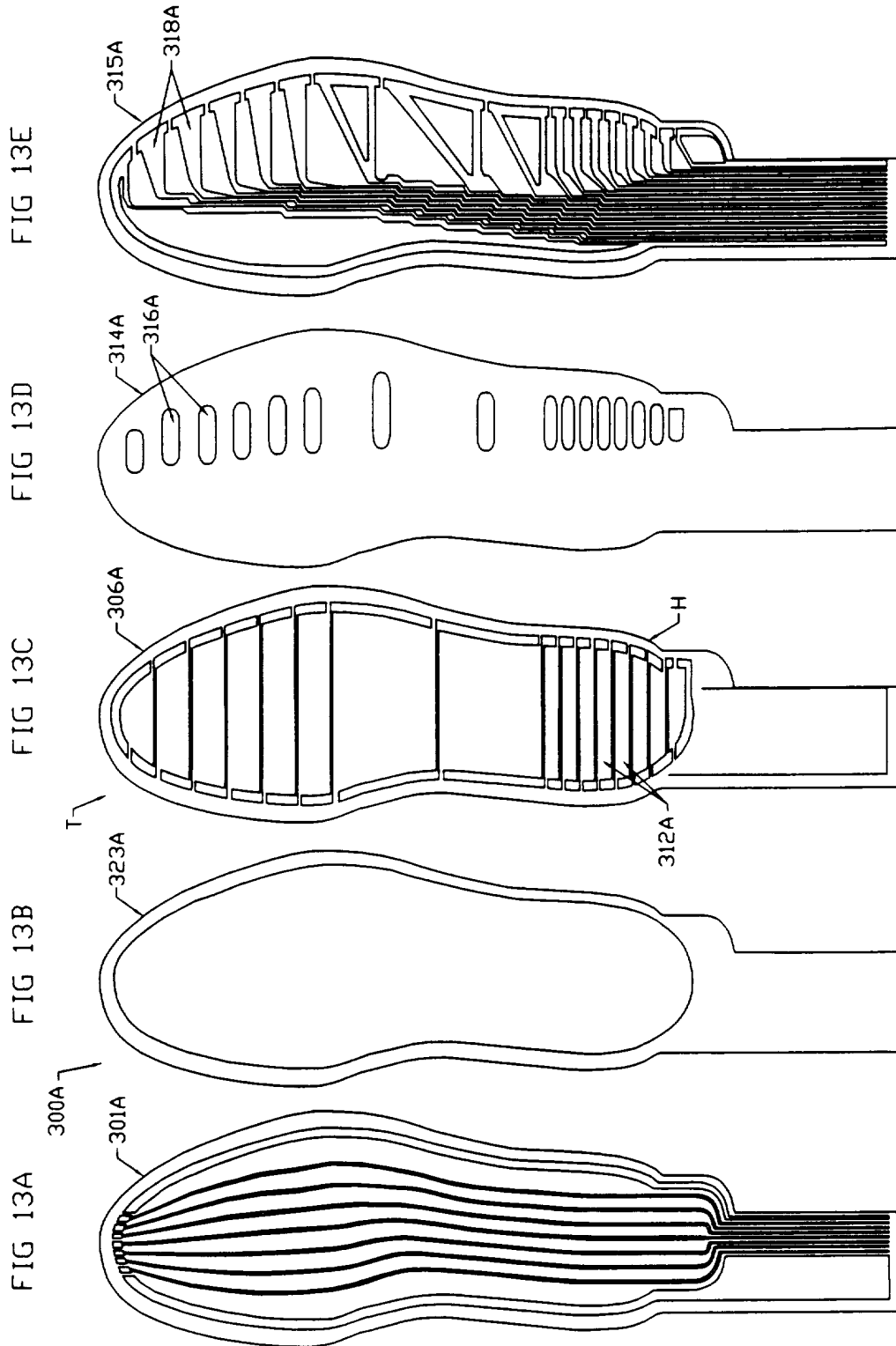


FIG 11A





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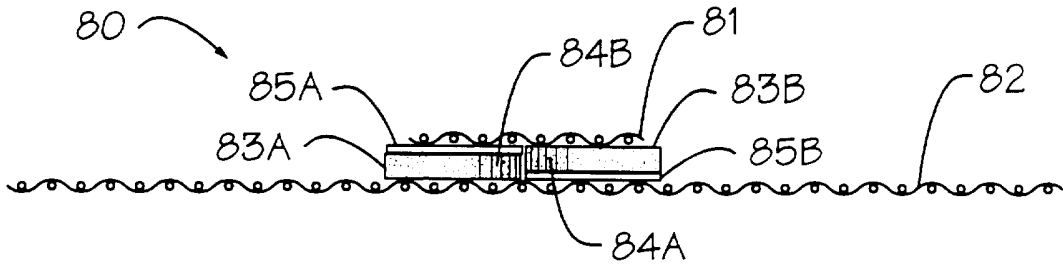


FIG. 16

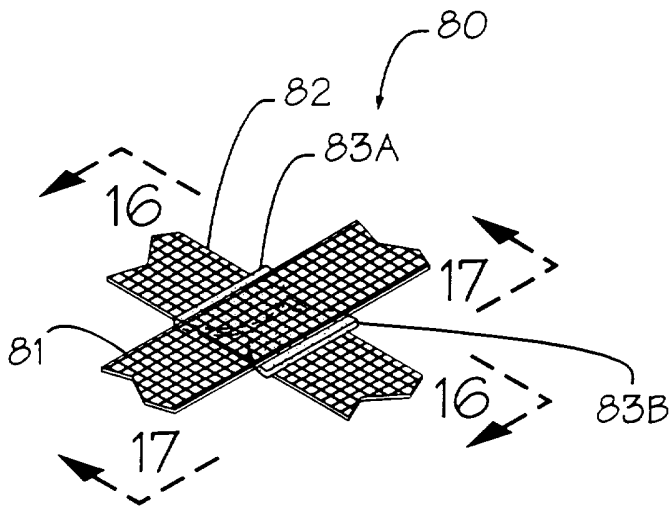


FIG. 15

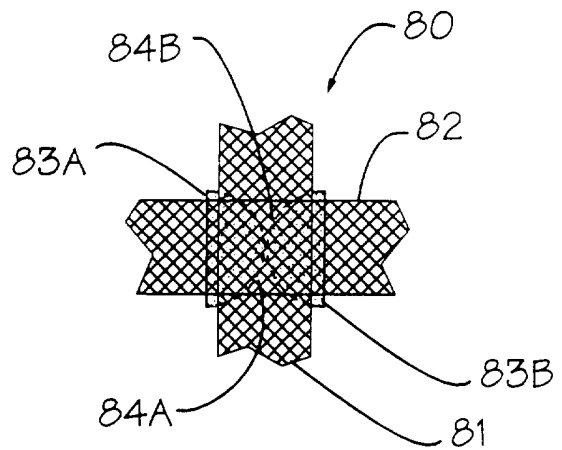


FIG. 18

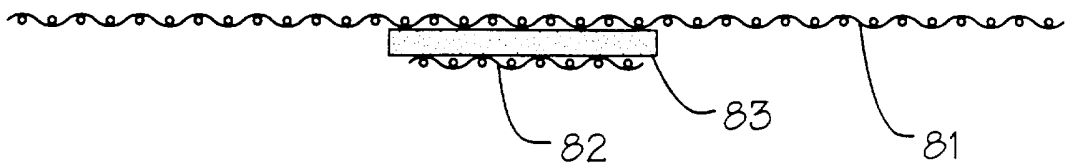


FIG. 17

SUBSTITUTE SHEET (RULE 26)



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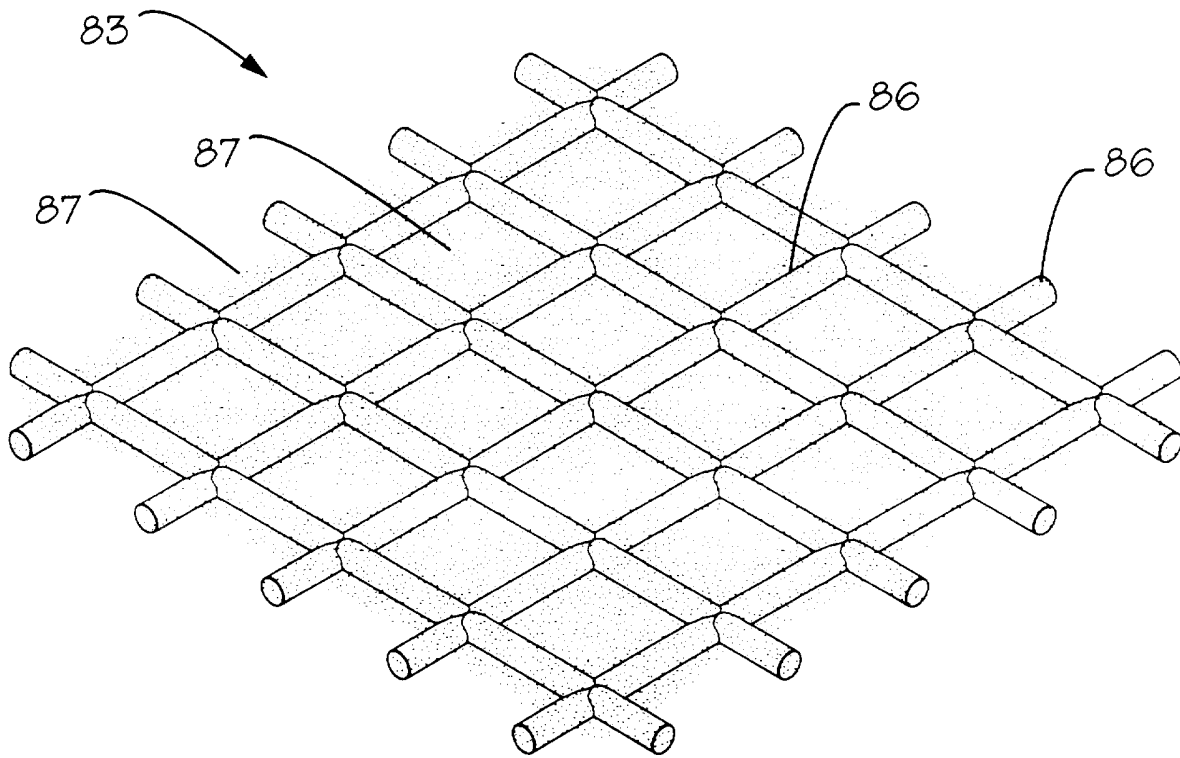


FIG. 18A

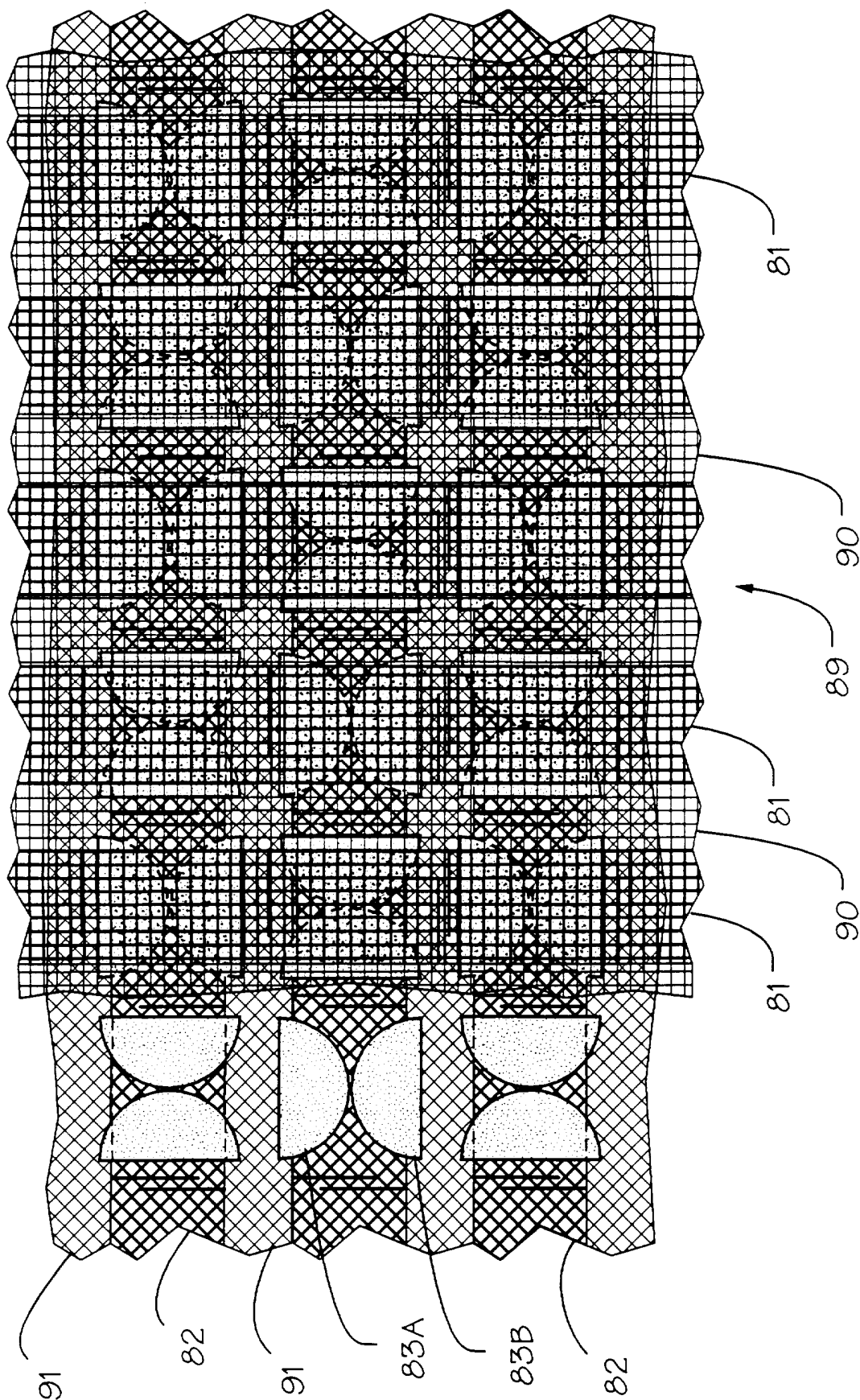


FIG. 18B

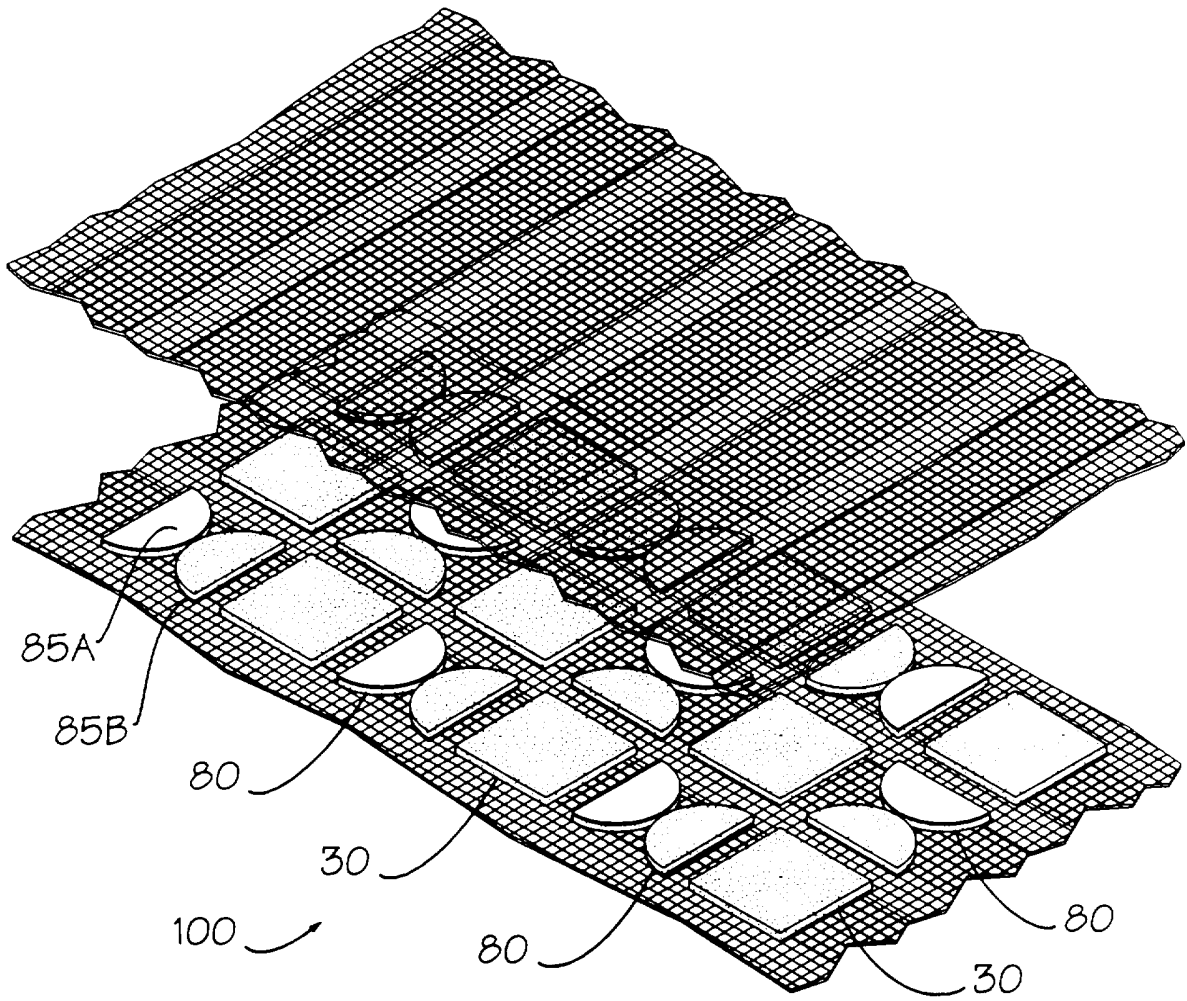


FIG. 19

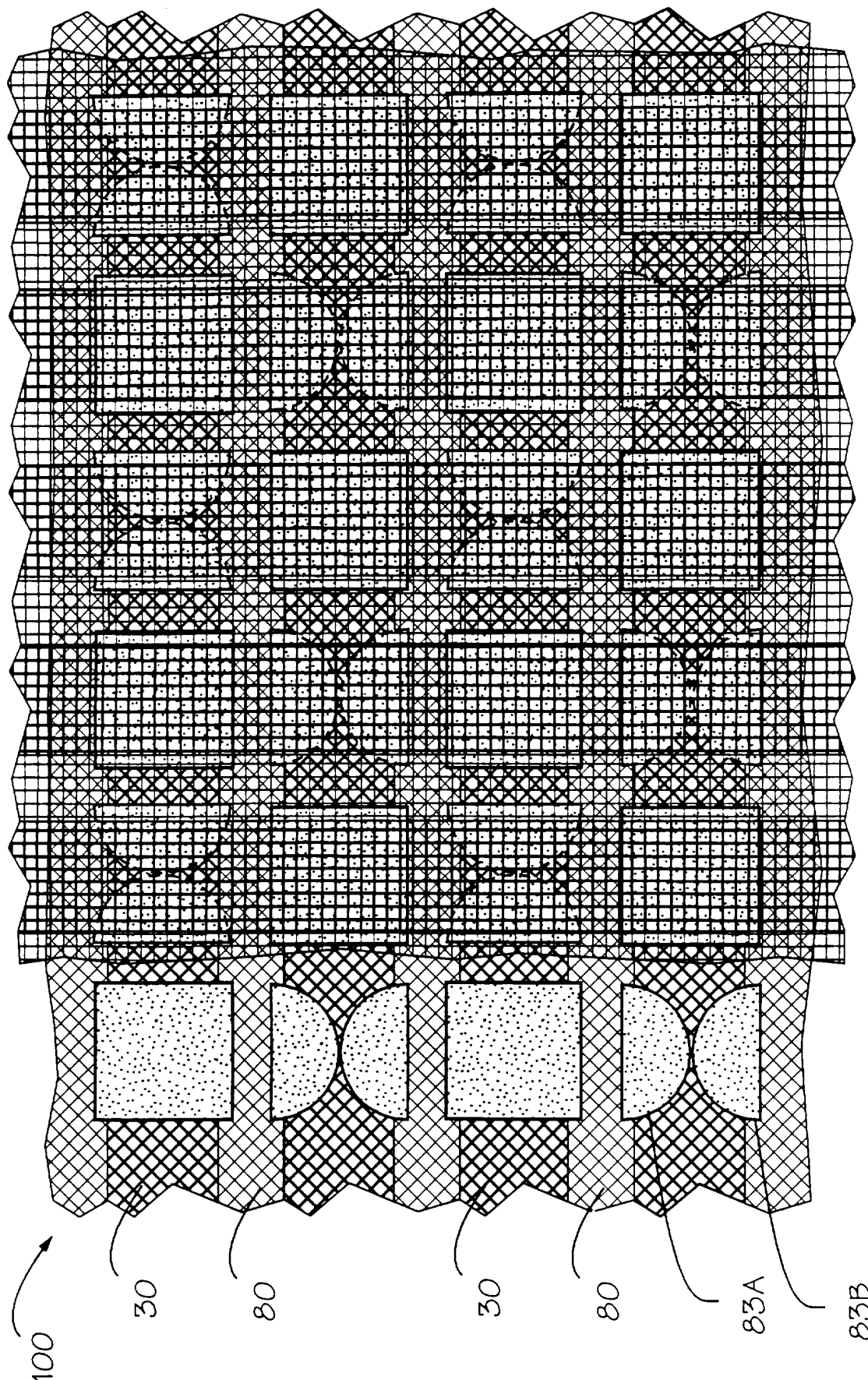


FIG. 20C

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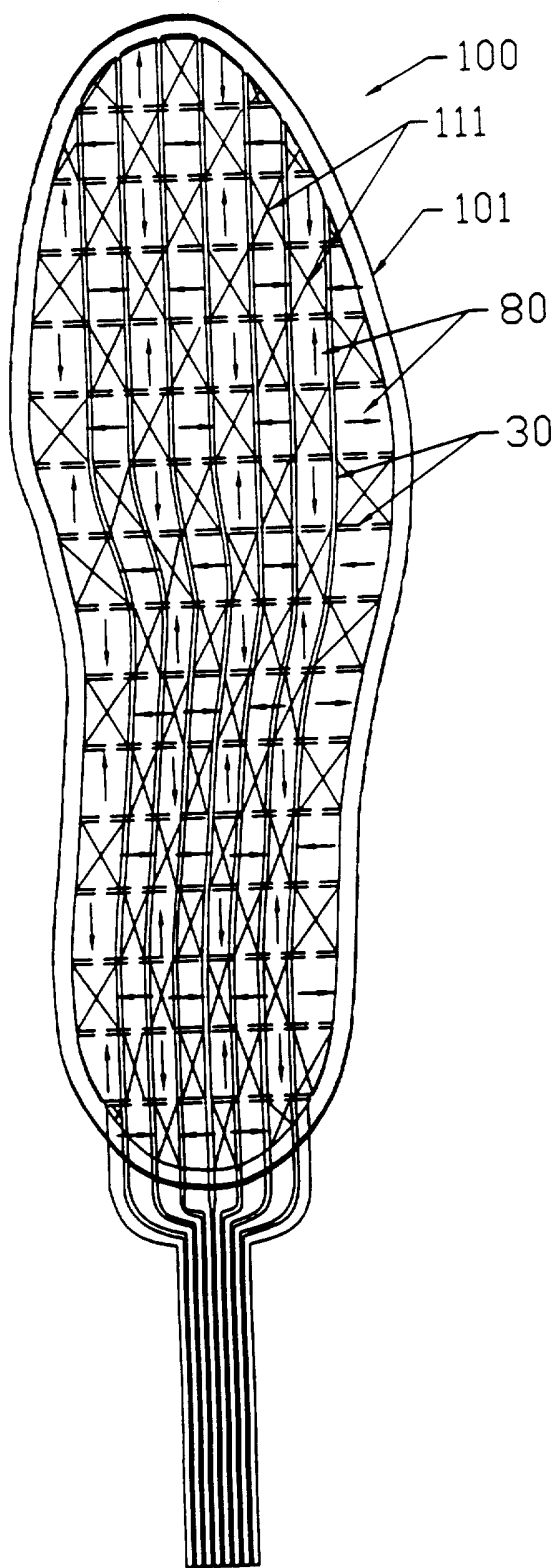


FIG 20D

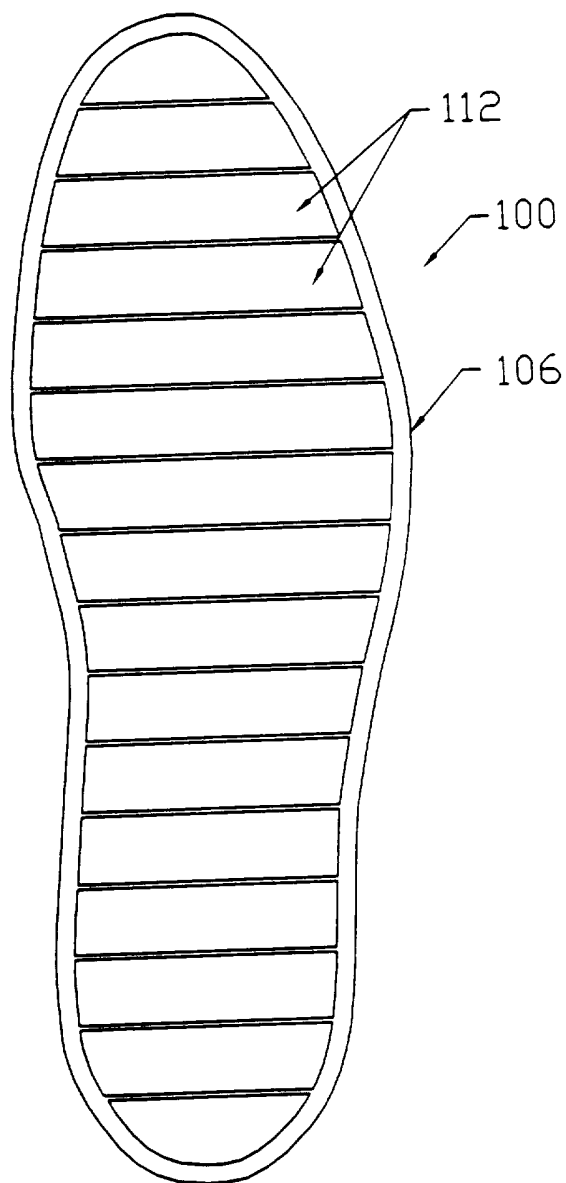
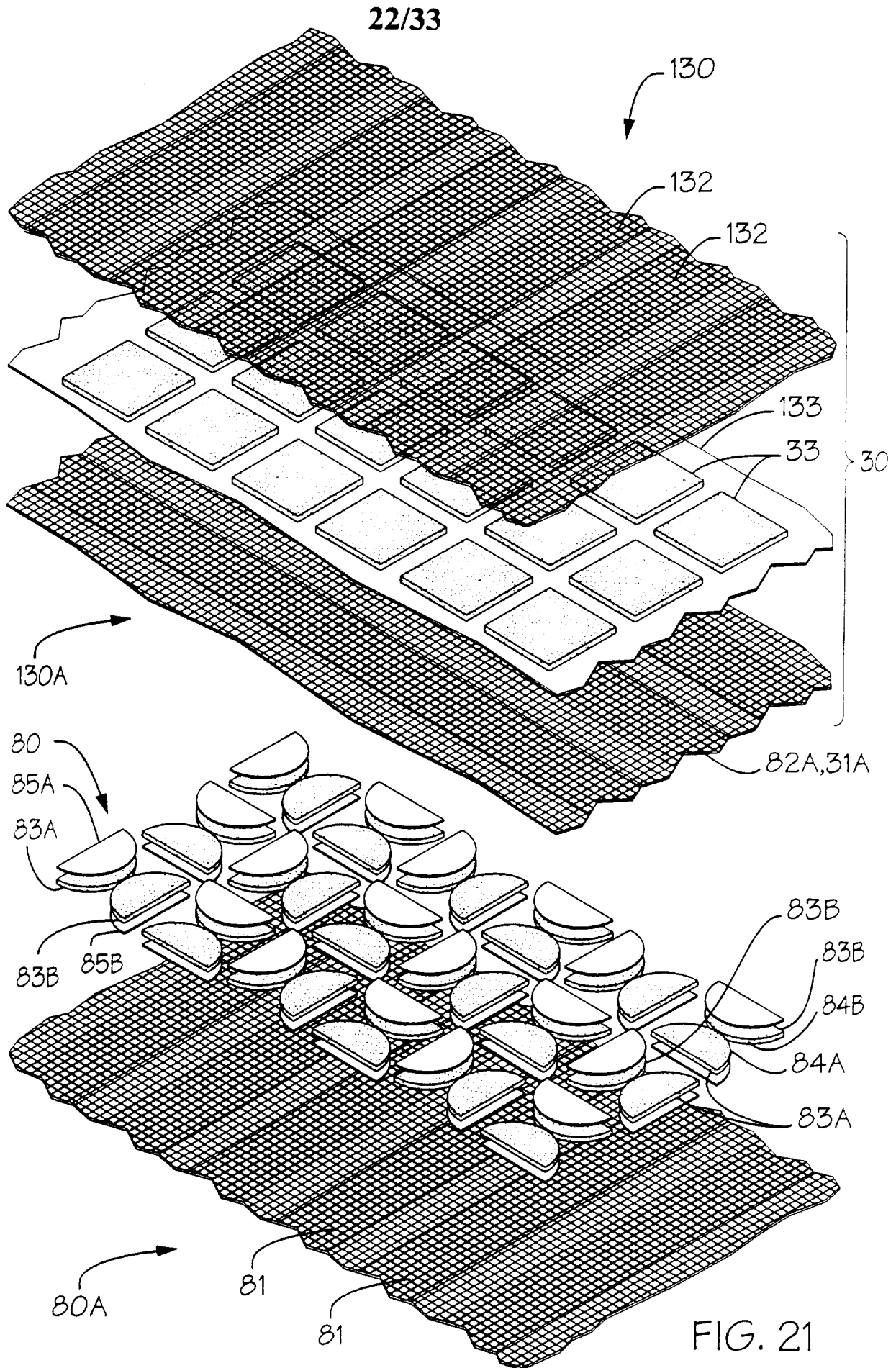


FIG 20E



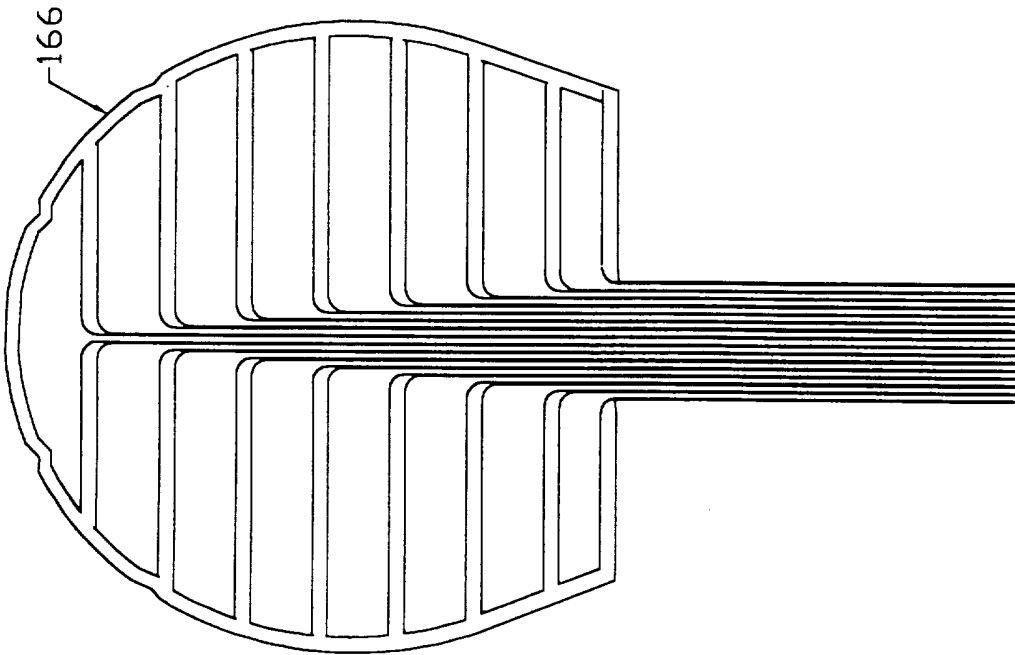


FIG 25B

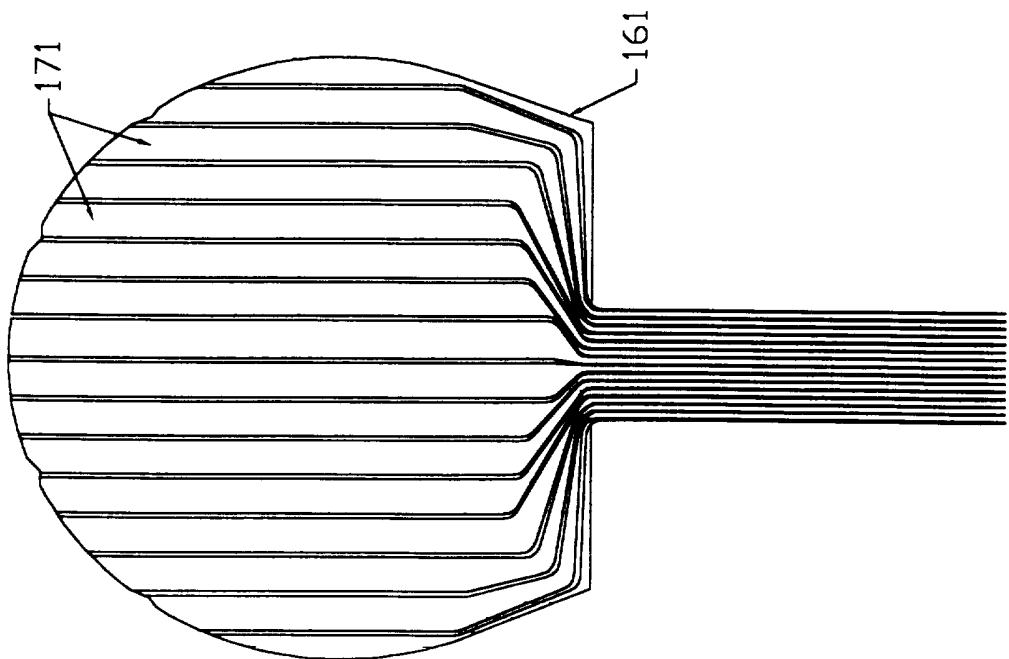


FIG 25A

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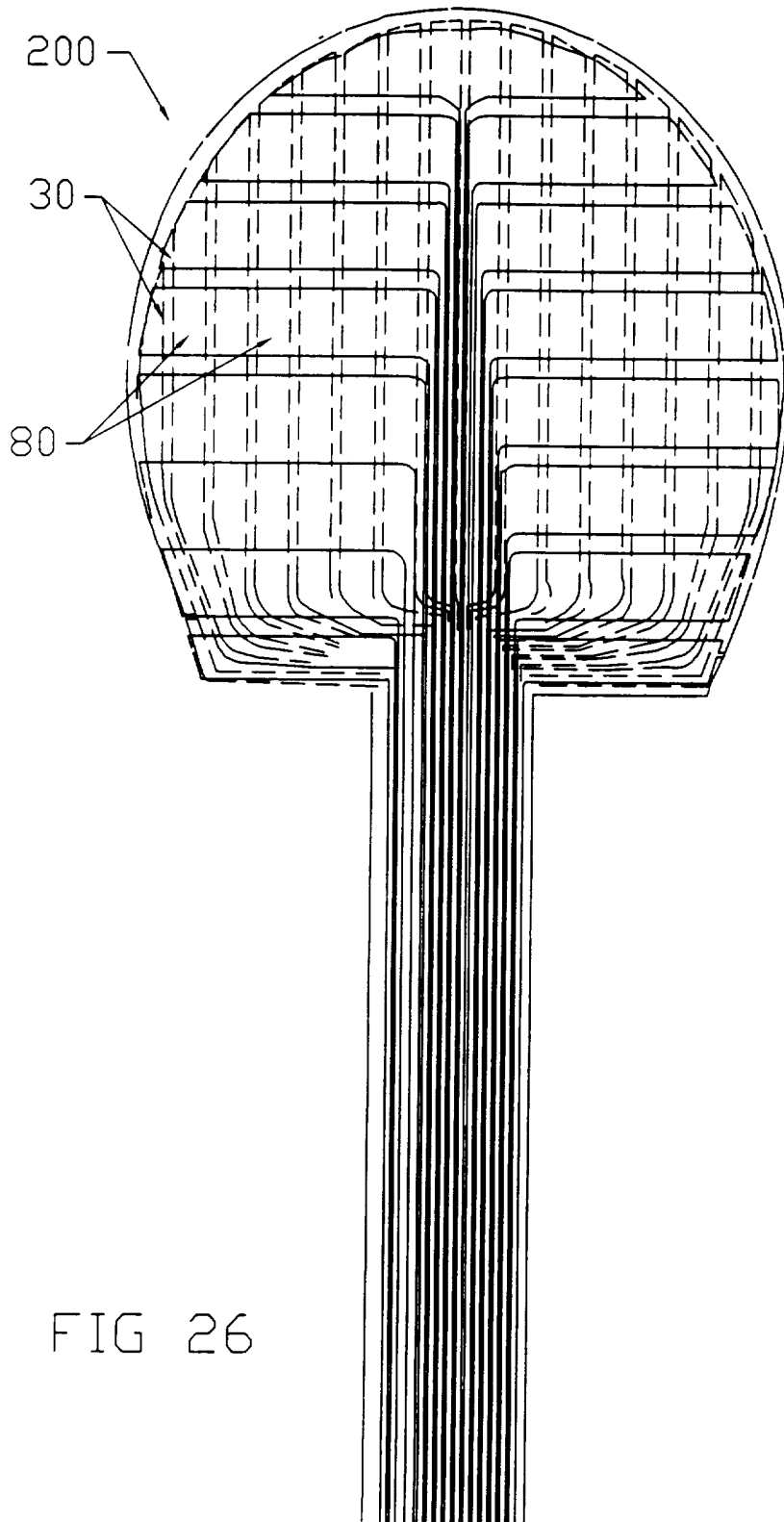


FIG 26



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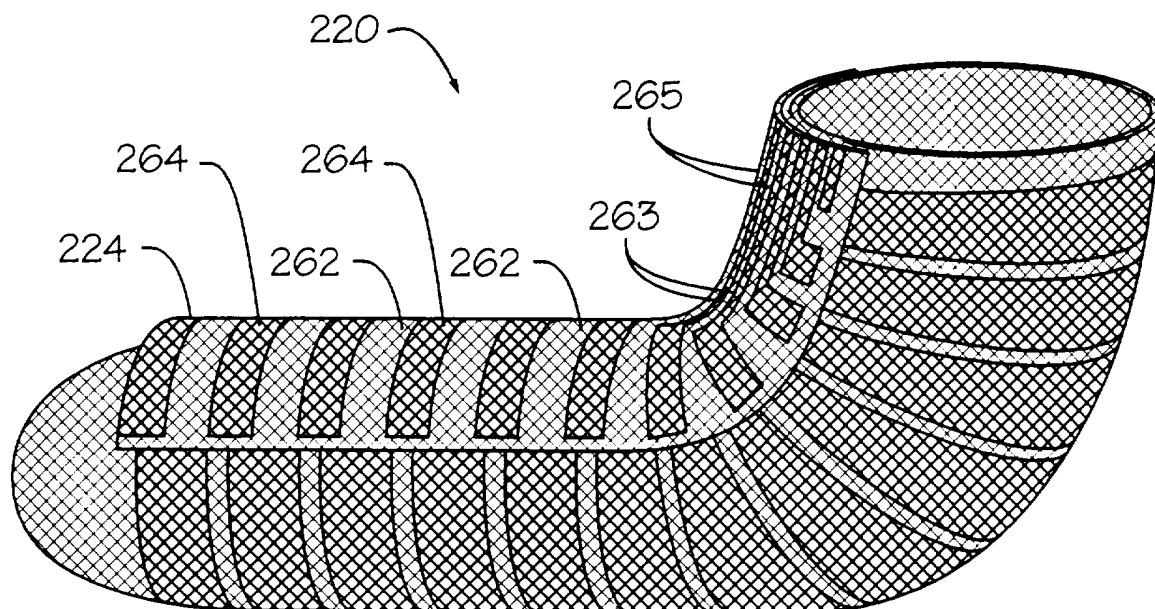


FIG. 27

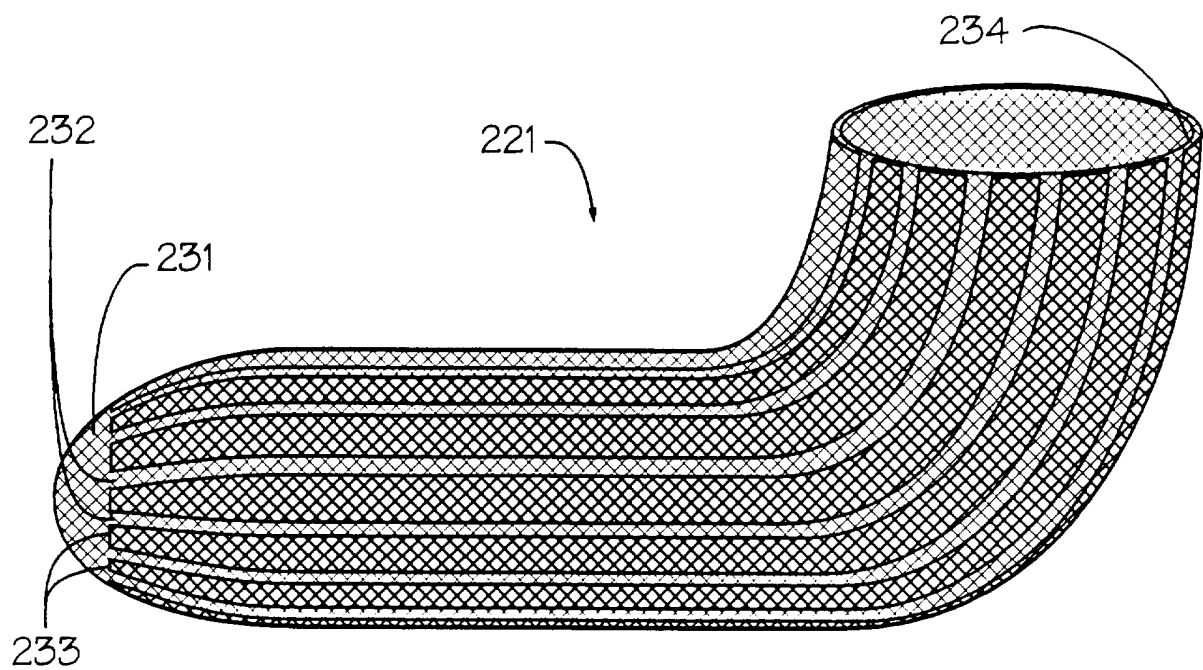


FIG. 28

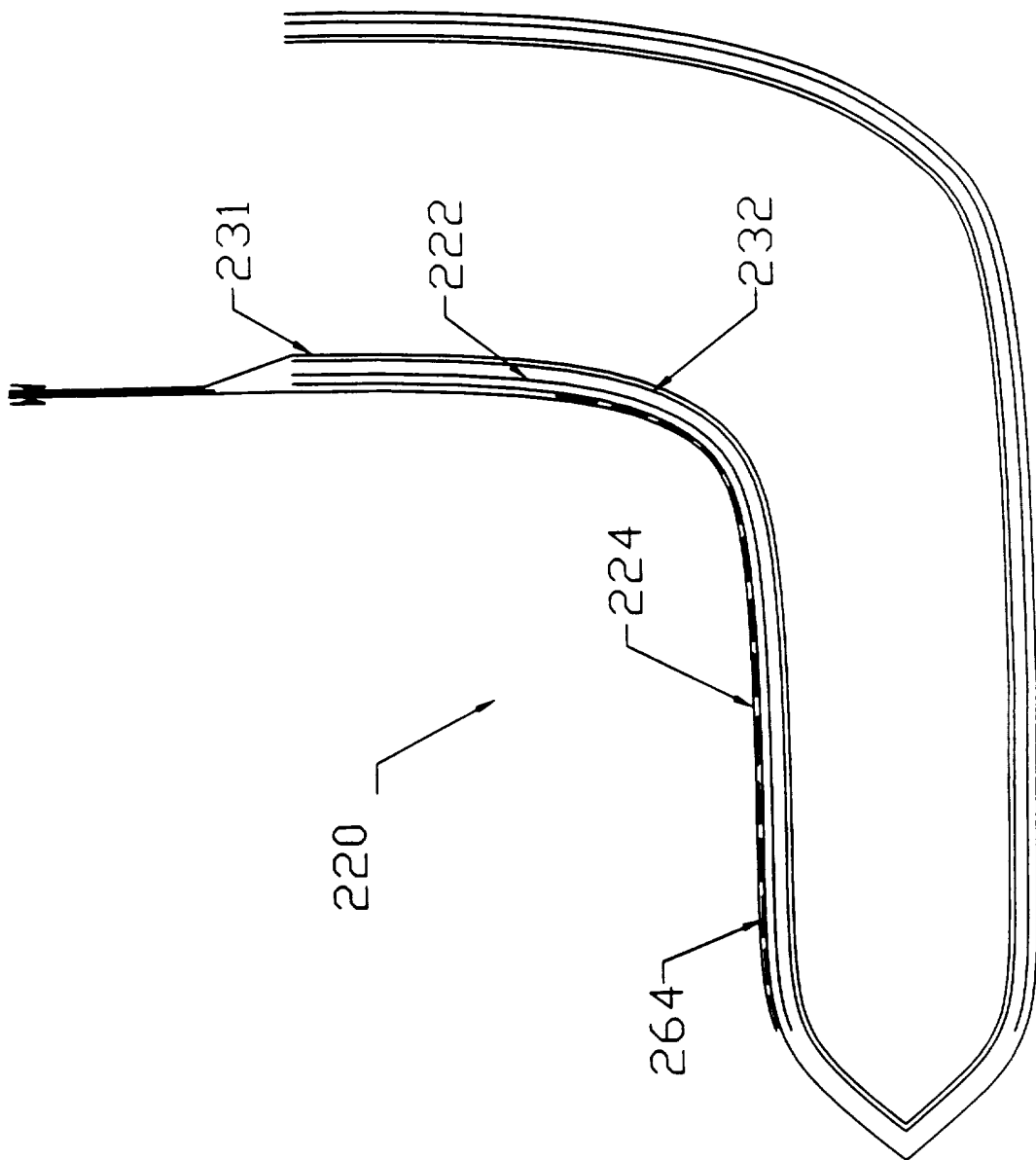


FIG 29

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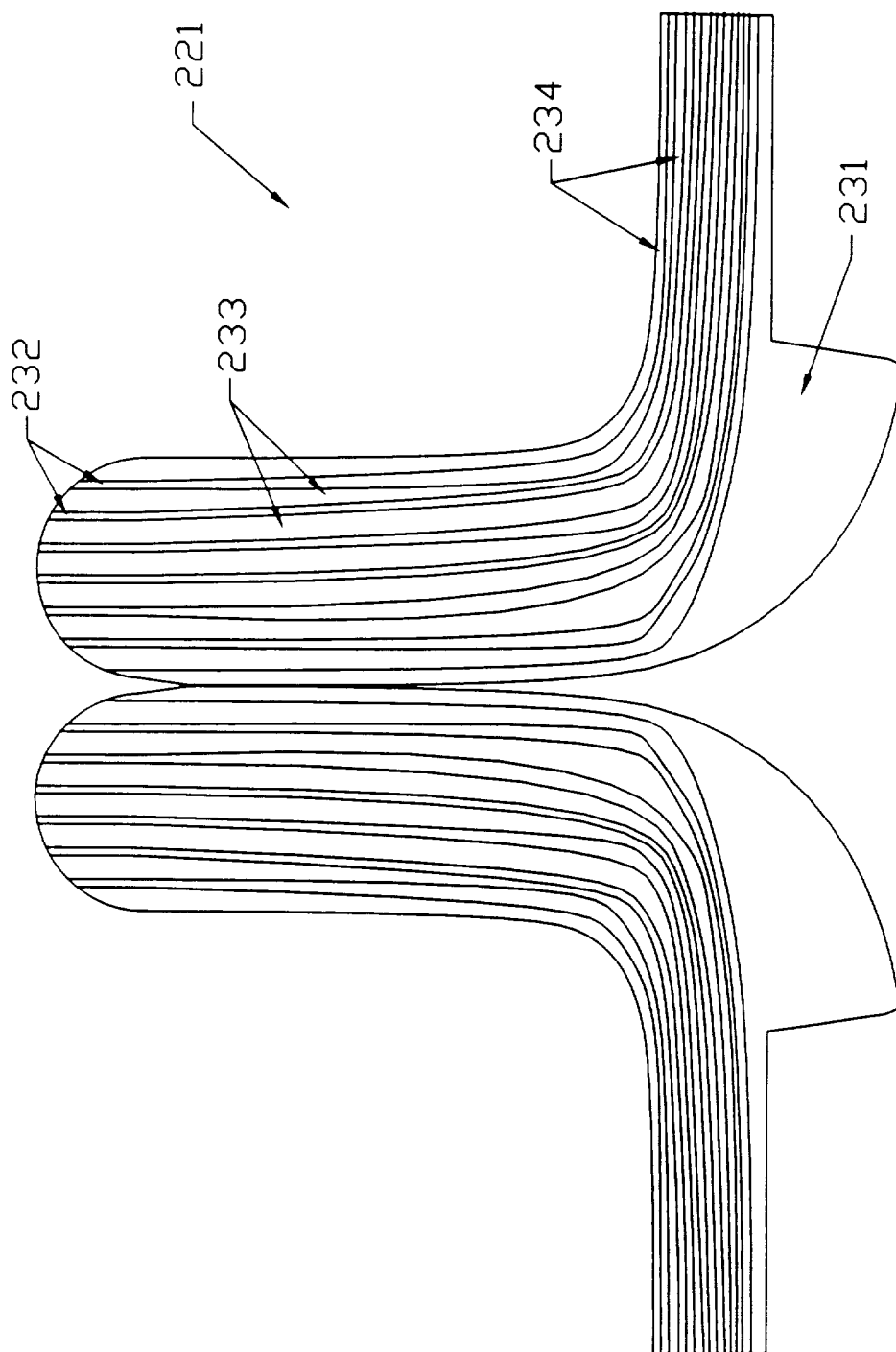


FIG 31

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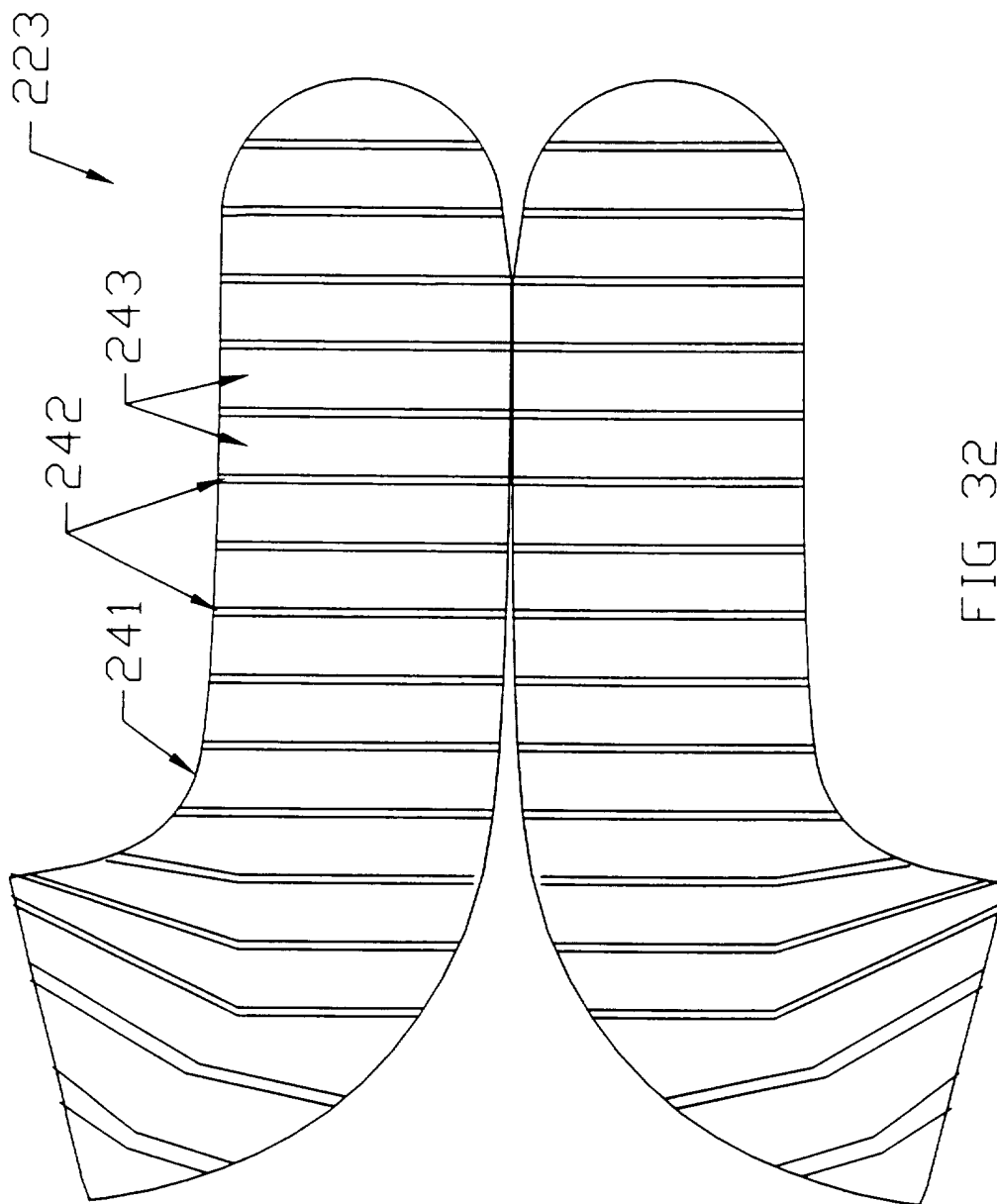


FIG 32

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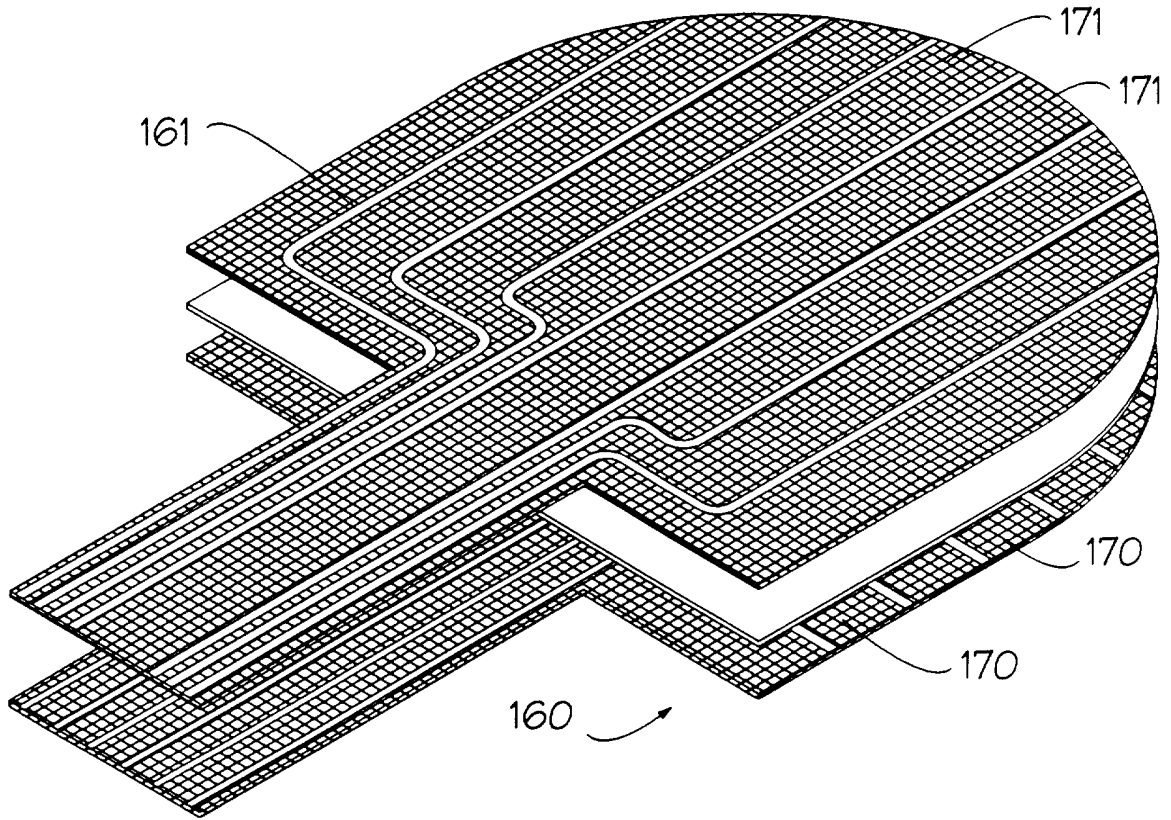


FIG. 24

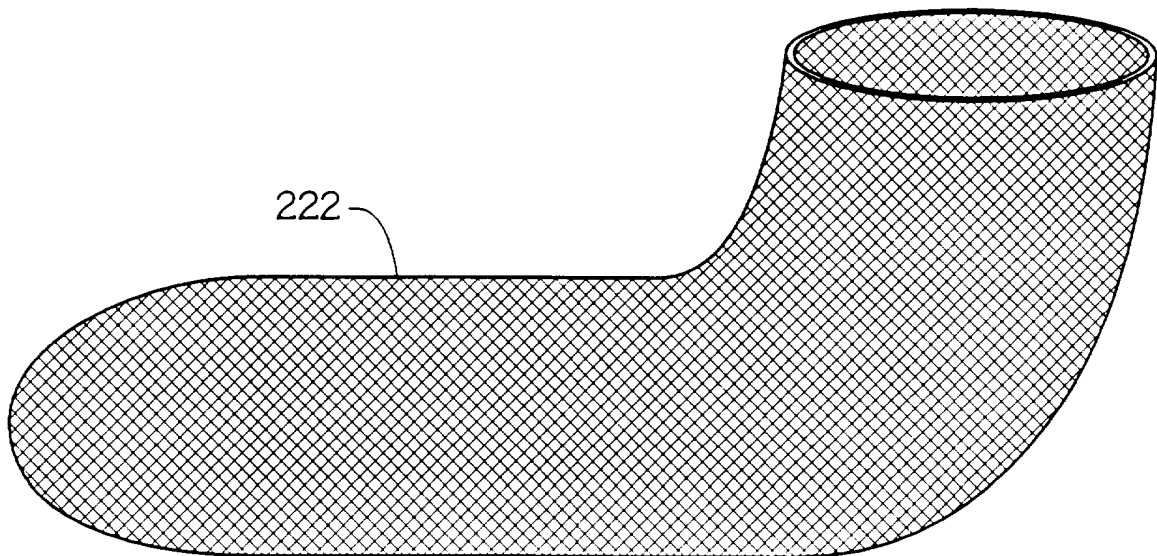


FIG. 33

SUBSTITUTE SHEET (RULE 26)

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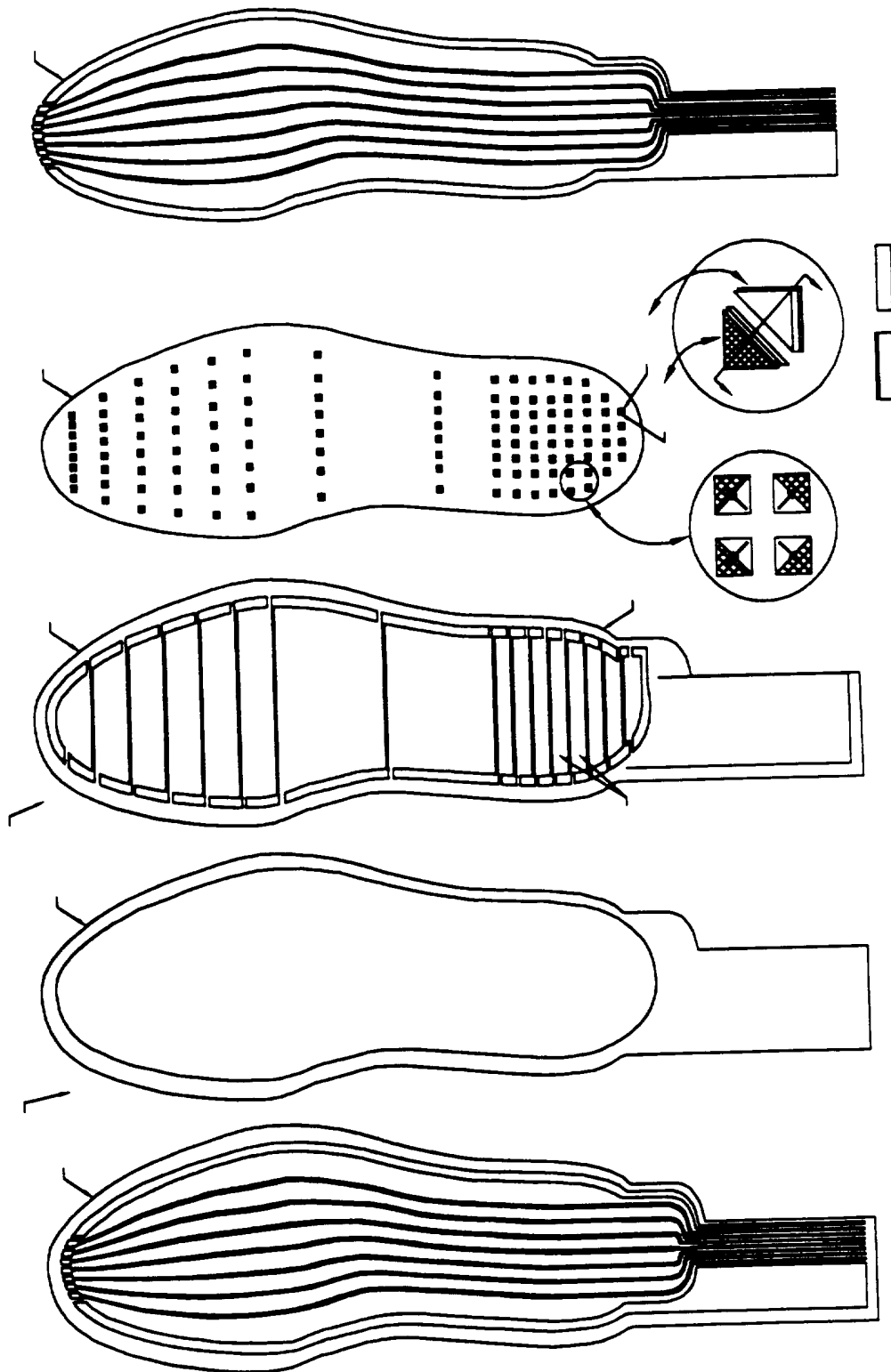
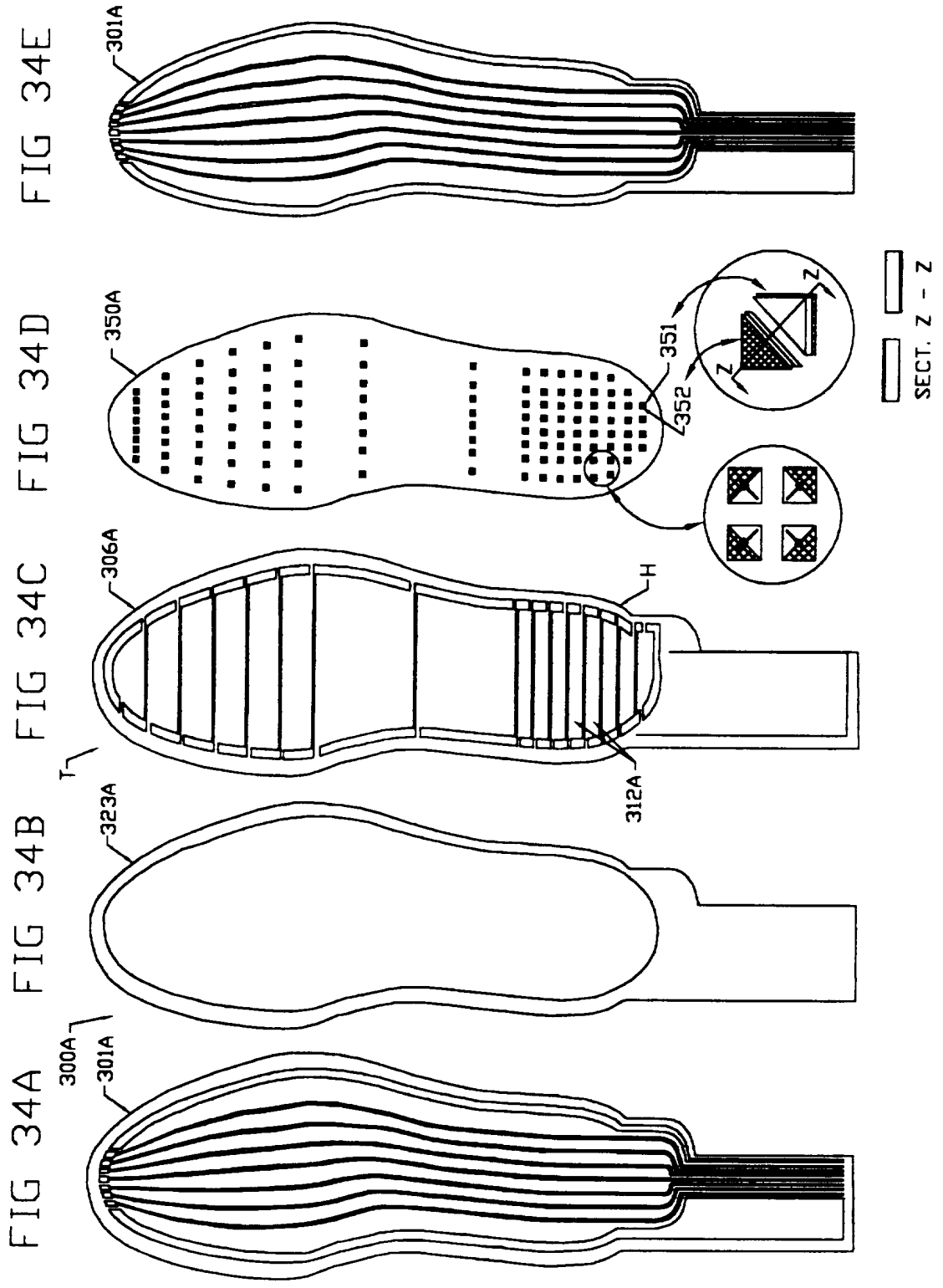


FIG 34



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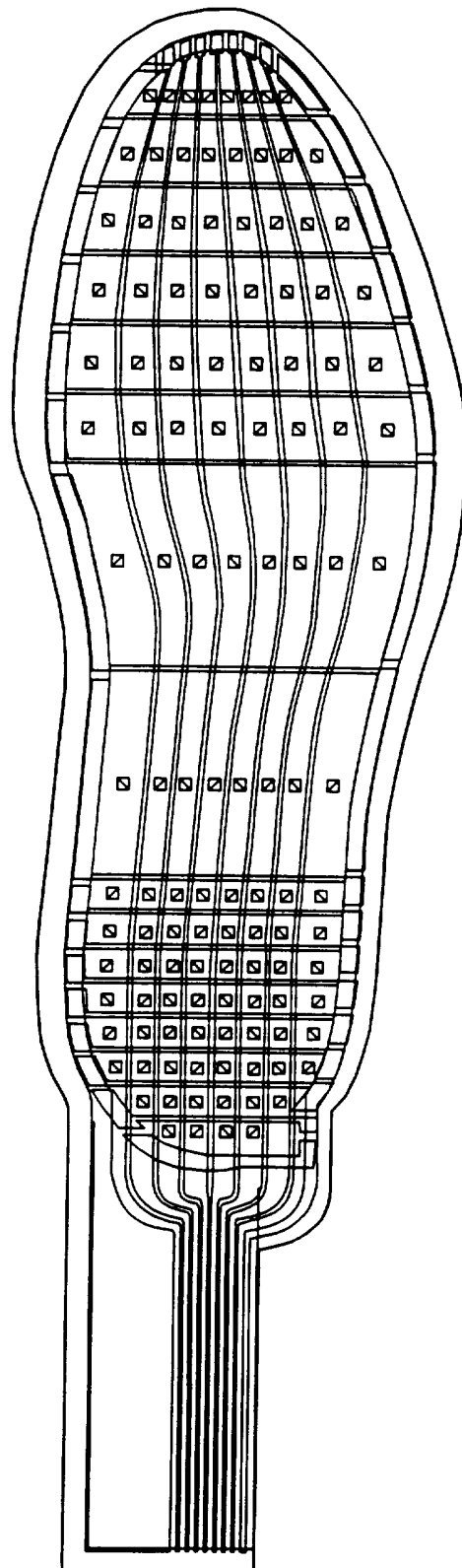


FIG 35



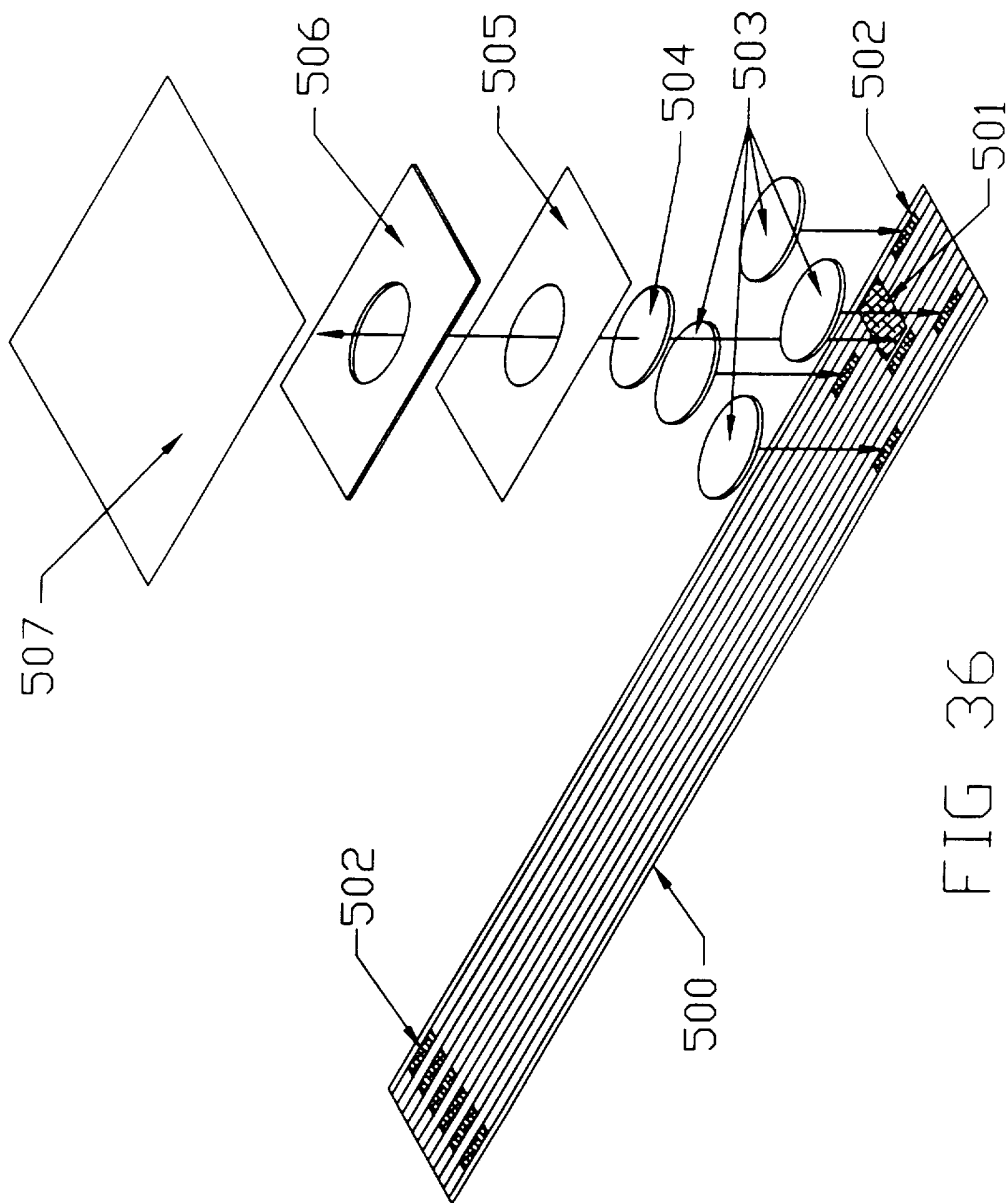


FIG 36

# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/IB 96/01467

<b>A. CLASSIFICATION OF SUBJECT MATTER</b> IPC 6 G01L1/20 A61B5/103		
According to International Patent Classification (IPC) or to both national classification and IPC		
<b>B. FIELDS SEARCHED</b>		
Minimum documentation searched (classification system followed by classification symbols) IPC 6 G01L A61B		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practical, search terms used)		
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 87 01574 A (INSTITUTO SUPERIORE DI SANITA) 26 March 1987 see claim 1; figure 1	1 2-6,8
Y	--- WO 92 10823 A (ASHER DAVID J) 25 June 1992 see page 16, line 24 - line 31; figure 10	2
Y	--- MEASUREMENT + CONTROL, vol. 18, no. 7, September 1985, LONDON , GB, pages 262-265, XP002028478 ROBERTSON ET AL.: "tactile sensor system for robotics" see the whole document	3-6,8
A	--- US 5 033 291 A (PODOLOFF ROBERT M ET AL) 23 July 1991 see the whole document ---	20,22
-/--		
<input checked="" type="checkbox"/> Further documents are listed in the continuation of box C.		
<input checked="" type="checkbox"/> Patent family members are listed in annex.		
* Special categories of cited documents :		
*A* document defining the general state of the art which is not considered to be of particular relevance *E* earlier document 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  27 March 1997	Date of mailing of the international search report  17. 04. 97	
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+ 31-70) 340-3016	Authorized officer  Zafiroopoulos, N	

# INTERNATIONAL SEARCH REPORT

International Application No

PCT/IB 96/01467

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 331 769 A (BRUNNER WOLFGANG ;ZECH LUDWIG VON (DE)) 13 September 1989 see abstract; figure 1 -----	11

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No  
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EP 0331769 A	13-09-89	NONE	