A Strengthened and Sensorised Custom Silicone Glove for use with an Intelligent Prosthetic Hand

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Abstract

External gloves for anthropomorphic prosthetic hands protect the mechanisms from damage and ingress of contaminants and can be used to create a pleasing, life-like appearance. The properties of the glove material are the result of a compromise between the resistance to damage and flexibility. Silicone gloves are easier to flex and keep clean, but also more easily damaged. This paper details the use of nanoclay fillers to enhance the properties of silicone, successfully increasing strength whilst maintaining flexibility. The performance of the enhanced silicone is as robust and resistant to tear and puncture as commercial gloves, while being more flexible.

This flexibility makes the incorporation of a piezo-electric pressure sensor based on the EEonyx conductive fabric, practical. A sandwich of the cloth and copper fabric creates the sensor, which decreases in resistance with increasing pressure. The sensors are characterised and production variability within the silicone are tested. Three sensors are incorporated into a glove made to fit around a Southampton Intelligent Hand. The hand adapts its grip shape and force depending on the object held. The technology is adaptable and it can be incorporated in a glove produced to fit any prosthetic hand.

Prosthetic Hand, Silicone glove, nano clay filler, sensorised prostheses, Southampton Hand

1 Introduction

An outer glove for prosthetic hands provides protection from damage and ingress of contaminants into the mechanism. It is also used to create a pleasing appearance. The physical properties of the glove can impact on the performance of the device [1]. To open, the hand must deform the glove, which requires energy. This impedes the action of the prosthesis. Since hand prostheses have to be light and practical, any part of the design that reduces the efficiency, reduces the performance of the device and so the user. Gloves, therefore, have to be flexible enough not to impair the action, while being robust enough to resist tearing or punctures. To create a glove with sufficient longevity, manufacturers opt for robustness over dynamic performance, resulting in thick and stiff gloves. Older designs of prostheses have a single degree of freedom with a limited flexion range, so the impact of the stiffer glove is reduced. For example: A Motion Control[1] hand (single degree of freedom) has 68mm between thumb and index finger and Ottobock[2] *SensorHand speed* is a similar design and a gape of 90mm. While the iLimb hand can open up to 130mm between tips. For the new generation of multifunction hands with multiple finger joints, the impaired function becomes more acute [2], (Figure 1 shows ranges of motion for single axis and multifunction hands).

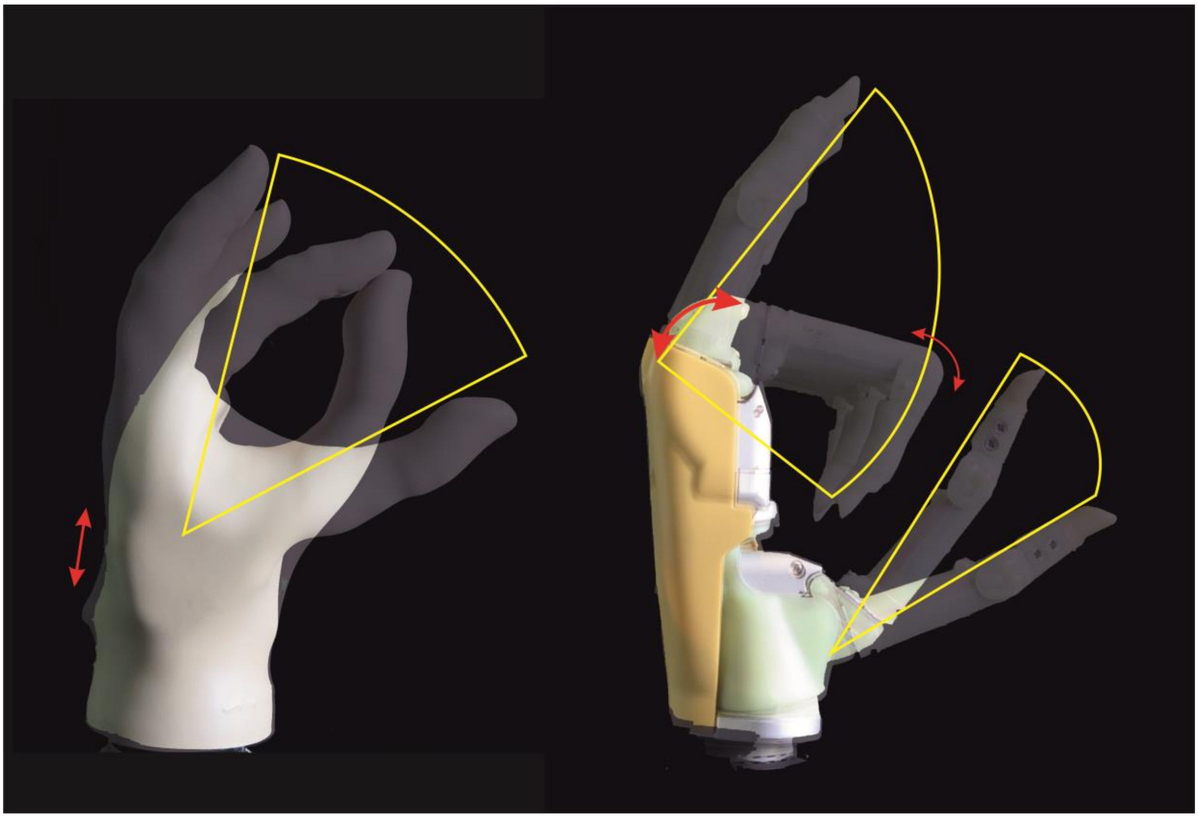

Figure 1: Range of motion of a typical single degree hand (yellow lines), and that of a multifunction hand (Motion Control and Touch Bionics). The multifunction hand has independent motion of thumb and finger, while the digits in the single axis hand are linked. The range of motion of the single degree of freedom is less than 50^0. The resulting motion causes the glove to become stretched as the hands close, the key points of stretch are indicated in red.

A second requirement for a glove is the growing interest sensing contact between the digits and the environment [3]. An existing method is to build sensors into the finger tips of the mechanism [4,5,6,7] but this limits its application to devices specifically made for the sensors, or modifications to the mechanism that prevents the original gloves from fitting. Many prosthetic hands only sense external contact through detecting the motor stalling when the digits contact the object [8]. This gives little information about the forces of the grasp. Therefore, a glove with sensors built into the fingers would enable existing prosthetic designs to become sensate.

Finally, the resulting prosthetic system has to be affordable by the user population.

[1] Motion Control, Inc. 115 N Wright Brothers Drive, Salt Lake City, UT, USA
[2] Otto Bock HealthCare GmbH, Postfach 1260, Max Näder-Straße, 37115 Duderstadt, Germany

This paper outlines a study addressing both of these requirements; robustness and sensation, by adding fillers to the silicone to increase strength and flexible sensors within the glove matrix. Only once a glove has greater endurance does the concept of adding sensors to the matrix of a glove become a practical consideration.

2 Background

2.1 Prosthetic Gloves

The most common material for gloves used with the single degree of freedom prosthetic hands is Polyvinyl Chloride (PVC). While PVC is robust (resistant to puncturing and tearing), it is hard to keep clean. PVC discolours easily when in contact with ink and dirt [9]. It is also stiff, so it interferes with the movement of the fingers. Conventional hands, are driven by a single electric motor, and have been available since the 1960s [8,10]. The fingers on these have a limited range of motion (less than 50^0), thus PVC can be used satisfactorily. Even so, the stiffness impedes the motion and the motors draw greater current. Similarly, in body powered mechanical hands, the operator's shoulder or arm pulls on a cable to actuate the hand, it requires significantly more effort from the user [11]. The result is a shorter battery life or much greater effort from the user [11].

The conventional solution is to use two separate layers; a very thick inner glove to protect the mechanism and a thinner outer glove to provide the anthropomorphic appearance and colour. One option to increase flexibility in the thicker inner glove is to add corrugations to allow for deformation. This cannot be used in the anthropomorphic external gloves, as it would compromise the appearance.

With the more recent developments of advanced multifunction hands with multiple joints in every finger (such as the TouchBionics and TASKA hands [12,13]), this problem has become more acute. Their smaller motors generate less torque and together draw more current, so they have trouble overcoming the resistance of PVC gloves. For example; when the fingers curl into the palm the ventral dimension of the finger increases from 92 mm to 136 mm in an iLimb hand[3]. The glove needs to deform to accommodate this, so the motors must overcome this resistance to flex the fingers. Compared with PVC, Silicone polymers have low toxicity, are chemically inert, water resistant, non-stick and thermally stable over a wide range of temperatures and hypoallergenic. Prosthetic gloves made from silicone are more less stiff and impede the motion of the joints less. While they are easily kept clean, they puncture and tear more readily. Silicone is available in a range of molecular weight distributions, curing types and cross-link densities, which allows the basic properties to be selected, but so far all silicone gloves for prosthetic hands have been less robust and more expensive than PVC gloves. Smit [11], studied the mechanical properties of commercial silicone and PVC gloves and showed the stiffness of the material is the dominant cause for the gloves properties. This stiffness requires greater force to operate a PVC glove and it has greater hysteresis, but PVC *is* more durable. It is the balance between durability and stiffness this study addresses.

[3] Dimension measured from the tip of the index finger to the top of the proximal joint shield in a series two iLimb hand.

It is an established technique to adjust the properties of silicone through the inclusion of other materials within the mix. The additives or `fillers' changes the physical structure of the rubber and alter its properties. Every mix is the result of compromises: Changing one set of properties to improve one feature while trying not to impact greatly on another, for example, increasing tear resistance makes rubber stiffer.

Conventional adulterants (fillers), like carbon black, tend to aggregate into relatively large particles, which, if not mixed thoroughly, form even larger agglomerations. These remain separate from the silicone leading to non-uniform properties across the resulting material. Silicone tends to fail at the boundaries of these particles, weakening the rubber. To have a useful change in the properties of the rubber, large concentrations of the fillers are needed, this creates a stiffer rubber. A sufficiently puncture resistant silicone may become too stiff to be usable in a glove.

Following the discovery of Buckminsterfullerene, [14], it became apparent that smaller structures of carbon had vastly different properties than carbon in bulk. Nanoclay emerged a commercial material, that can be used for numerous applications. It is a few layers of carbon sheet between 30 and 60 nm across. This creates a large aspect ratio, being very much larger *across* the sheet than through them. When added to silicone and mixed until the particles are distributed uniformly (larger carbon particles tend to clump which degrades the performance), nanoclays remain in much smaller particles and change the properties of silicone at a far smaller dimensions than soot. The percentage of filler can be considerably less for a useful change in properties. Thus the desirable properties of the silicone are maintained, while other properties are improved [15,16]. In this application, nanoclay in silicone changes the tear resistance without impacting on the flexibility. It is possible to start with a very extensible silicone formula, and adding very small amounts of the nanoclay improves tear resistance, creating a silicone glove with properties suitable for a prosthetic hand.

Bulk tests, such as frictional wear or tensile testing, reveals if a material performs adequately, but to understand the performance, results must relate to the interaction between individual nanofillers and the matrix [17,18,19,20,21,22].

2.2 Application of nanocomposites in prosthetic gloves

The of the study aim was to improve the strength properties of a prosthetic glove while using a far lower filler loading, compared to the conventional fillers.

Carbon nanotubes, nanoclay [23] and nanosilica, [24,25] and forms, such as Sylgard, were considered because it has moderate cross-link density and medium hardness, but it is harder to apply. Plastil Gel-10 is used for mould making, but has a high viscosity which makes its use in rotation casting difficult. Instead, TC-5101[4] was chosen as it has low cross-link density, low hardness, low modulus of elasticity, moderate strength properties and greater flexibility.

2.3 Prosthetic Sensors

The cost of a glove is important in determining how practical it is. A glove that does not last long or is expensive to produce is unlikely to be acceptable. Once a glove design has greater

[4] BJB Enterprises, 14791 Franklin Avenue, Tustin, California, 92780 USA

endurance does the concept of adding sensors to the matrix of a glove become a practical consideration.

It is widely accepted that prosthetic hands with sensors in the digits that feed the sense of touch to the wearer will be better used and better accepted [26,27,28,29,30]. This idea has only been demonstrated in the field, with implanted electrodes [31,32]. Surveys of prosthesis users show that it is a persistent wish among the user population [9,33,34]. It has been suggested that the lack of feeling is a factor in the rejection of existing prosthetic limbs. Laboratory based simulations can show if the sensory information is usable, but cannot reveal if it will be tolerated in the long term. Sensory feedback can only be clearly demonstrated when sensor systems are developed that can be routinely used by the wearing population.

Previously, gloves that have the sensors built into them have only been employed as data gloves or virtual reality interfaces, [35]. None have been recorded as used in gloves that fit around a prosthetic hand for use in the field. There are numerous sensory systems developed for robotic hands [36,37,38,39], and some that have been employed in commercial prosthetic devices [5,40], others in research systems [41,6,42].

The technology that has been used to detect force, include the use of Force Sensitive Resistors [43], strain gauges [7]. Object slip has been measured using microphones [44], Polyvinylidene fluoride (PVDF) [45] or accelerometers [46].

Many fewer sensorised prostheses have been used routinely in the field, most because they have to work outside the glove and any conventional glove would need to be cut, compromising the properties. One exception is the force and slip based sensors used in variants of the Southampton Hand [43,47,48,49]. These have been developed to work inside non-customised cosmetic gloves and have been used in the field for many years. They provide both force input as well as information on the sliding between the finger and the object [50]. A variation of this design of sensor is integral to the structure of the glove itself, but it has never been produced [47], the force and slip sensor used in the first microprocessor based prosthetic hand was a variant of this design [4]. Other sensors do not work *inside* gloves, being too large or the performance being impaired by the addition of a glove [51]. In contrast, this glove design can conceivably work with any conventional design of gloved prosthetic hand to extend its performance.

The sensor/glove system developed in this study was based around the SNAVE hand [43], variants of which have been used in the field since 1997. For this application the custom force and slip sensors were replaced with plain finger tips similar to those of a conventional prosthesis and the *same* electronics and program used to drive the resulting hand.

2.4 Transduction principles

The sensor used is based on two layers of cloth in contact with each other. As the load increases the resistance between them changes and this is interpreted as contact force. The change is based on variations of the surface contact area, it is more appropriately described as a *pressure sensor*, although pressure on a small contact patch approximates to force on the sensor sufficiently for this application.

The materials used have rough surfaces that deform under load, so the surface area of contact between opposing materials varies depending on the force acting upon them. Protrusions (asperities) exist regardless of how smooth the surface seems. The sensory properties are the result of the interaction of the highest asperities. Under load, the asperities deform increasing the area of contact [52]. Thus the area of contact is roughly proportional to the applied load [53]. As the pressure on the surfaces change, the asperities deform in a manner determined by their atomic, molecular and crystalline structures. The form of deformation controls the transducer's properties. The deformation will be more or less elastic, depending on the micro and nano-structure of the material.

Resistance at the contacting asperities is constriction resistance and is inversely proportional to the contact area. Conductivity is also inversely proportional to resistivity, so conductivity is directly proportional to the contact area and hence applied load [52].

2.5 Transducer material

The sensor described is based on the properties of Polypyrrole (PPy), a conductive polymer that is part of a class of polymeric conductors used in a wide range of applications. Eeonyx[5] has developed electrically conductive fabrics; EeonTex 1135 and 350 [54]. PPy's surface-morphology is described as having `cauliflower-like' nodes with a roughness that dependent on the conditions of its production, [55]. The result of these structures are that the surface contact occurs initially at the nano, followed by the micro, then finally at the macro scale. This means that as the contact force increases, substrates coated in PPy continue to increase their contact area with a result that a PPy based sensor will respond over a wide range of loads. For PPy there is a linear relationship between the distortion of the surface and the forces imposed, thus a linear relationship between force and changes in resistance. Additionally, if the change in resistance depends entirely on the surface phenomena it is more likely to have smaller hysteresis than if it depends on the bulk mechanical properties of the material.

2.5.1 Design of sensors

The EEonyx fabric was sandwiched between two layers of copper fabric. To connect the sensor to the external electronics a silver laden conductive thread[6] was stitched to the edges of the conductive pads. The thread thus made the connection to the sensors and created a flexible conductive track through the glove.

3 Methods

3.1 Glove - Materials testing

The silicone polymer PDMS-TC 5101 was chosen as the base as it has a blend of properties; flexible, without being too easily damaged. It was then mixed with a range of nano-fillers including nanosilica, nanoclay and carbon nanotubes (CNT) and cast into sheets from which tensile test-pieces and tear test-pieces were prepared using standard test-piece cutters. The

[5] Eeonyx - EeonTex conductive textiles are products of Eeonyx Corp. (Pinole, CA), made under license according to US Patents www.eeonyx.com or www.marktek-inc.com

[6] Madeira HC40 Conductive Thread, MADEIRA Garnfabrik, Rudolf Schmidt KG, Zinkmattenstrasse 38, D-79108 Freiburg, Germany

strength properties were measured according to ASTM 412 and ASTM 624 [56,57] standardised protocols for tensile strength and tear strength by using an Instron[7] Tensile testing machine (4465 Universal Testing System).

A range of different modifiers were added to the Base Polymer; 1% nanosilica, 1% nanoclay, 1% nanotubes, along with silicone from prosthetic gloves produced by two companies that manufacture prosthetic hands: Regal prosthetics[8] and Steeper prosthetics[9] the latter being a glove designed to be used with the multifunction bebionic hand.

Based on the success of the tests with the nanoclay, a second set of tests were conducted using different levels of loading of the nanoclays: 0%, 1%, 3% and 5%. These concentrated on the tensile properties and the tear strength.

3.1.1 Glove production

The base polymer TC 5101 was chosen with a combination of nanoclay and silica in order to achieve improved cut and punch resistance. The gloves were made by placing layers of silicone onto a mandrel and allowing it to cure while being rotated on a conventional rotation moulding device (rotacaster). The layers used two forms of the silicone with 1% and 2% by weight of the filler. This aimed to make the silicone more extensible. The densities were chosen to give the glove the same tear strength as the Steeper glove while keeping the other properties of the silicone.

3.2 Sensors - Performance Testing

The sensors made for the prosthetic application were 1cm square. Thus all the tests were conducted on sensors of this dimension.

3.2.1 Characteristic

The characteristic of the sensors was measured by using a Mecmesin[10] tensile testing machine (Mttr), to mechanically apply uniaxial loads to the samples. The characteristic was explored: The load was increased from 0 to 14mNm^{-2} in increments of 14mNm^{-2} and then from 0 to 69mNm^{-2}. Data for both runs are combined in the results. The conductance was measured using a voltage-divider circuit and read into a microprocessor. Measurements were sampled at 10Hz, and the average of 100 readings calculated internally. Results are given in conductance (W^{-1}).

3.2.2 Effect of silicone encapsulation on performance

The hysteresis of the sensors was measured by placing known masses onto the sensor pads and measuring the change in resistance of the sensor pad using a multimeter (Figure 2). The test was conducted first on an exposed sensor, it was then encapsulated within the silicone

[7] ITW Test and Measurement, Coronation Road, High Wycombe, Buckinghamshire, HP12 3SY, United Kingdom.
[8] Hong Kong Regal Prosthesis Limited, Room 3D, Tower F, Mai Luen Industrial Building, 23-31 Kung Yip Street, Kwai Chung, NT, Hong Kong.
[9] Steeper Group, Unit 3, Stourton Link, Intermezzo Drive, Leeds, LS10 1DF.
[10] Mecmesin Ltd, Newton House Spring Copse Business Park, Slinfold RH13 0SZ.

of the glove, and the trial repeated. Force was applied at 0, 18, 35, 53, 71, and 90N via the Mecmesin tensile testing machine. Foam inserts of fixed surface area ($1cm^2$) were placed between the machine head and the sensor pads in order to provide uniform force distribution across sensor. Measurements were made when loading up and then again when unloading. A fixed settling time of 10 seconds was allowed between measurements. Values presented are the mean of five sensor pad samples with errors calculated from the standard deviation.

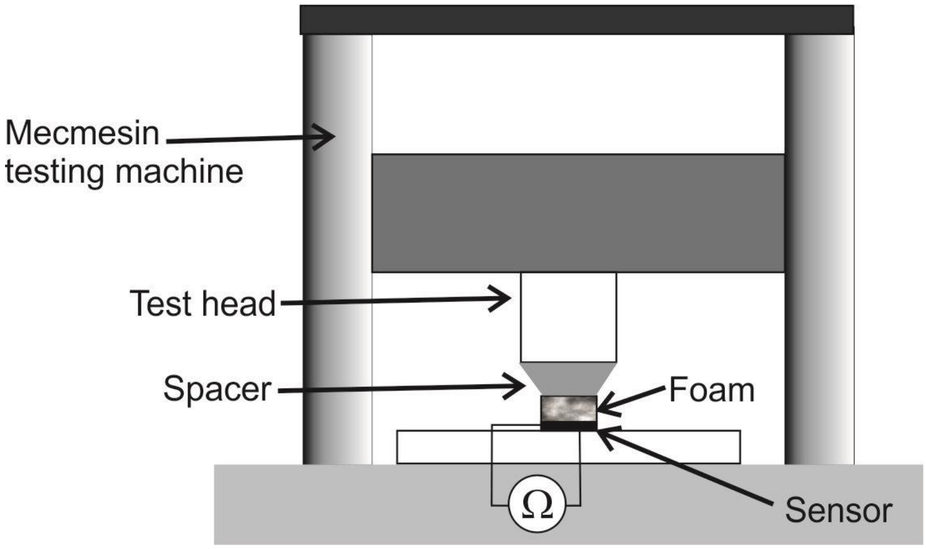

Figure 2: Experimental set up for testing the force sensors. A Mecmesin testing rig is used to load forces upon a sensor. It uses a foam insert to spread the load across the sensor. The resulting resistance of the sensor is then measured.

3.2.3 Production variability

Sensor consistency across a batch was assessed. The surface of the EEonyx cloth oxidises over time, this effect tends to plateau, thus to `age' the cloth it was washed in water for ten minutes[11]. Following this a batch of 17 sensors were constructed and each sensor was repeatedly subjected to a standardised load (4.4N). The average response of six repetitions was recorded. This reading was compared to the average and standard deviation of the entire sensor population. From this, reliable sensors were selected and embedded in the silicone gloves. Twelve out of the seventeen made (71%) could be used in the next stage were the variation between in-glove sensors was then investigated by again loading with the sensors to 4.4N.

3.2.4 Integration into gloves

Following characterisation of the form of the testing above, sensor pads were placed on the tips of the three driven digits, plus a larger pad in the palmar area of the hand. The thread ran between layers of the silicone glove to the electronics. Thread tracks ran a serpentine path across the joints and down the fingers to the connector at the wrist, so that as the fingers flex and force the glove to bend, the thread does not go taut. To connect to the sensors, thread was sewn into the cloth electrode and then crimped in a standard connector at the proximal end.

[11] Technique used by the company that supplied the EEonyx material.

The glove was made as a hybrid of two concentrations of the nanoclay. The first and last layers of silicone were 1% nanoclay and coat and the centre coat was 2% to give the glove greater tear resistance while not interfering noticeably with the flexibility. The sensors were placed between the second and third layer of the glove.

3.2.5 Prosthetic application

The prosthesis used in the tests was a SNAVE hand (Figure 3), the design of which has been used in field trails [43,58]. The custom force and slip sensors built into the finger tips, were replaced with plain tips and the same electronics and program was used to drive the hand. The controller program used was a Southampton Hand [59,60,61]. This control format uses the context of the hand to determine the grip form. So if the hand opens, and an object touches the palm first then the hand adopts a power grip, if it touches the tips first then a precision grip is used [43].

Figure 3: Silicone glove on the SNAVE hand. Sensors are on the digit tips and on the palm.

The control required a very limited number of changes to the program. The parameters associated with the thresholds of the digitised force values needed to match that of the new sensors. Once included, the controller program could work otherwise unaltered. Both object contact (touch) and object slip were derived from the sensors. The latter is based on changes in sensor values relative to values given by neighbouring sensors (an estimate of shear [50]).

The impact of the glove on current consumption of the motors was measured by recording the motor current and angle of flexion (from 0^0 at fully extended to greater than 60^0 when flexed). The SNAVE hand has potentiometers built into the mechanism and the resistance was measured. The angle of the base of the finger was calibrated against input voltage using a goniometer. The current was derived from the current sense from the motor driver (MC33926). The hand was flexed closed ten times with the current and angle recorded at 128Hz, without a glove and with the silicone glove. The mean of the ten runs was then recorded and the least squares best fit for the curve calculated (Excel, MS corporation[12]).

4 Results

4.1 Effect of filler materials

Table 1 shows the effect of the fillers on the silicone at 1% concentrations, compared with that of the base polymer and the commercial silicone gloves. All the fillers increase; the tensile strength, elongation properties, the force at breaking, and the energy needed to break the silicone, thus the tear strengths were also increased. Only the nanosilica and nanoclay increased the properties of the rubber to the same ranges as the commercial glove materials.

Sample	Tensile Strength (MPa)	Elongation (%)	Force at Break (N)	Energy at Break (J)	Tear Strength (N/mm)
Base Polymer	2.89	825	34.7	5.35	6.21
1% Nanosilica	3.02	794	36.5	5.64	18.91
1% Nanoclay	3.19	939	38.2	6.85	12.31
1% Nanotubes	3.09	880	36.9	6.39	6.26
Regal Prosthetics	1.91	189	32.9	1.09	14.09
Steeper Glove	7.51	918	60.3	8.24	12.95

Table 1: The effects filler on tensile and tear properties of silicone composites based on PDMS-TC 5101 base polymer - the Steeper prosthetic glove is significantly thicker than the other test samples, which are uniform in thickness.

Level of nano clay (%)	Tensile Properties					Tear Strength (N/mm)
	10% Modulus (MPa)	300% Modulus (MPa)	500% Modulus (MPa)	Tensile Strength (MPa)	Elongation at break (%)	
0%	0.005	0.20	0.42	2.64	1493	5.8
1%	0.003	0.24	0.51	2.88	1187	12.9
3%	0.000	0.25	0.61	3.01	1320	13.24
5%	0.0025	0.27	0.53	2.37	1154	10.18

Table 2: Effect of the nanoclay content on tensile and tear strength of PDMS-TC 5101 at different filler loadings

The addition of nanoclay to the silicone in any concentration had no clear impact on the resistance to stretching, or the elongation at breaking (Table 2). However, the tear strength

[12] Microsoft Corporation, Redmond, Washington, United States.

increased with concentration to 3%, where it dropped below that for 1% concentration at 5% loading.

The properties of the composite are dependent on the nanofiller dispersion and its distribution in the silicone matrix, filler volume, and particle size are in Table 3.

Nano filler	Tensile Properties 10% Modulus (MPa)	300% Modulus (MPa)	500% Modulus (MPa)	Tensile Strength (MPa)	Elongation at break (%)	Tear Strength (N/mm)
1% Cloisite 30 B (Nano Clay)	0.003	0.24	0.51	2.88	1187	12.9
1% Cabosil M-5 (Nano silica)	0.00	0.33	0.69	1.98	964	5.75
1% Cabosil EH-5 (Nano silica)	0.00	0.32	0.67	3.25	1317	15.9
1% CNT (Bay Tube 70 p)**	0.00	0.29	0.50	1.18	737	5.80
1% CNT- 4 Hours Ball milled	0.00	0.36	0.80	3.00	1196	5.36

Table 3: Effect of the types of nano fillers on tensile and tear strength of PDMS-TC 5101 at different filler loadings

4.2 Sensors - Testing

4.2.1 Characteristic

Figure 4 shows the response of the sensor was a monotonic quadratic curve:
$y = 308x^2 + 4.25x + 0.0001$, $R^2 = 0.99$, least squares fit,[13].

4.2.2 Effect of silicone encapsulation on performance

Placing the sensors within the silicone reduced the sensitivity, but the relationship between load and resistance remained similar (Figure 5). The data uses separate scales, the scale for sensors tested outside silicone is ten times greater. Hysteresis is observed in each case. A greater degree of variance is observed of sensors encapsulated within silicone.

4.2.3 Production variability

Thirteen out of the seventeen sensor pads fabricated were within one standard deviation of the population mean (Figure 6). From this test, five sensors that demonstrated good reproducibility were selected to be embedded within a silicon glove. The resistance response of these five sensors before and after encapsulation within a Silicon glove are shown in Figure 7. It is apparent that overall conductance of the sensing pads is lowered when inserted into the silicone impacting the sensitivity, but the variance is also substantially lowered, meaning reproducibility is improved.

[13] Excel, (MS corporation)

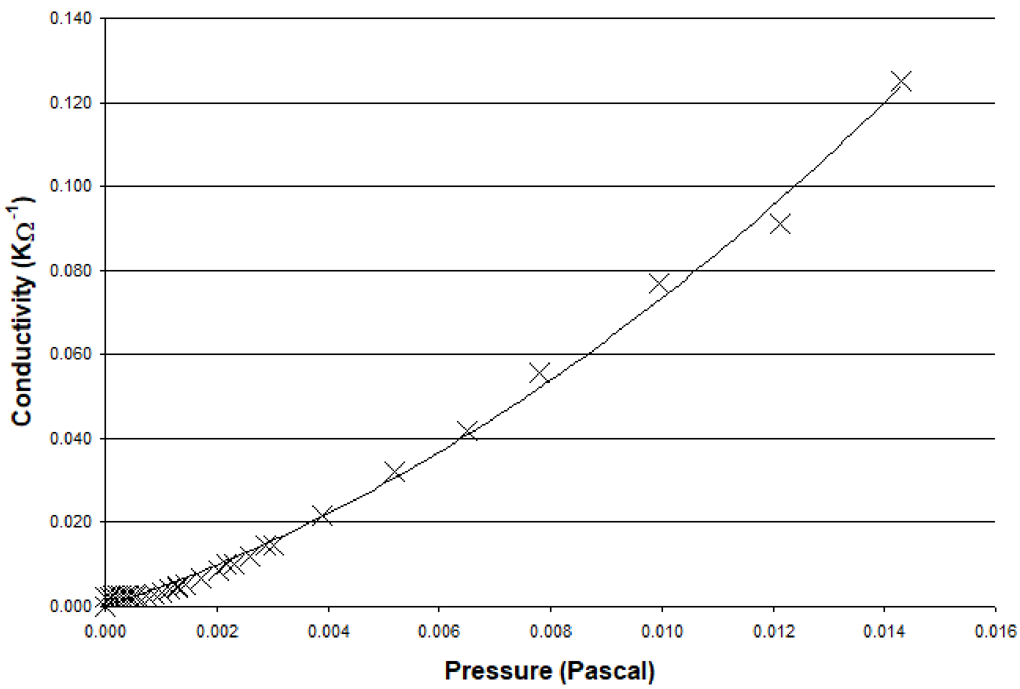

Figure 4: Characteristic of a single sensor. Increasing pressure is placed on the sensor using a Mecmesin tensile testing machine. The increasing conductivity is the result of increasing contact area between the cloth and the conductive layer. This is supported by the observed quadratic relationship between the conductivity and the pressure imposed.

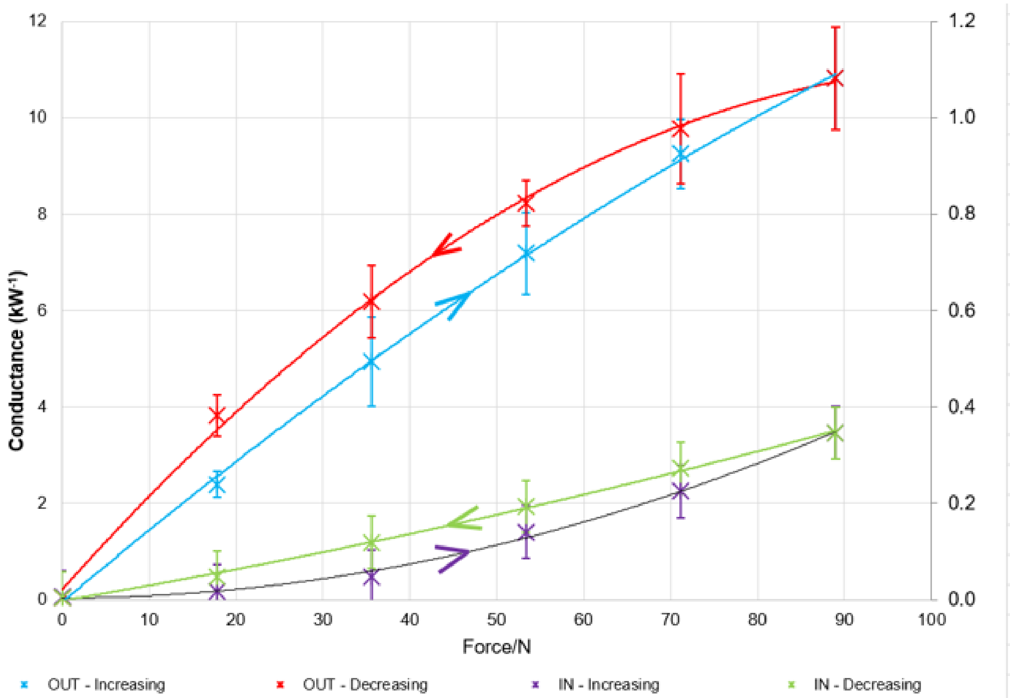

Figure 5: Characteristic of a single sensor with increasing (blue and mauve) and decreasing (red and green) loads. First outside (OUT) then after embedding in (IN) a silicone composite used to make the prosthetic gloves. Measurements are the conductance, recorded five times after the reading had settled for 10 seconds. **Note: The OUT glove readings use a scale ten times the In glove readings.**

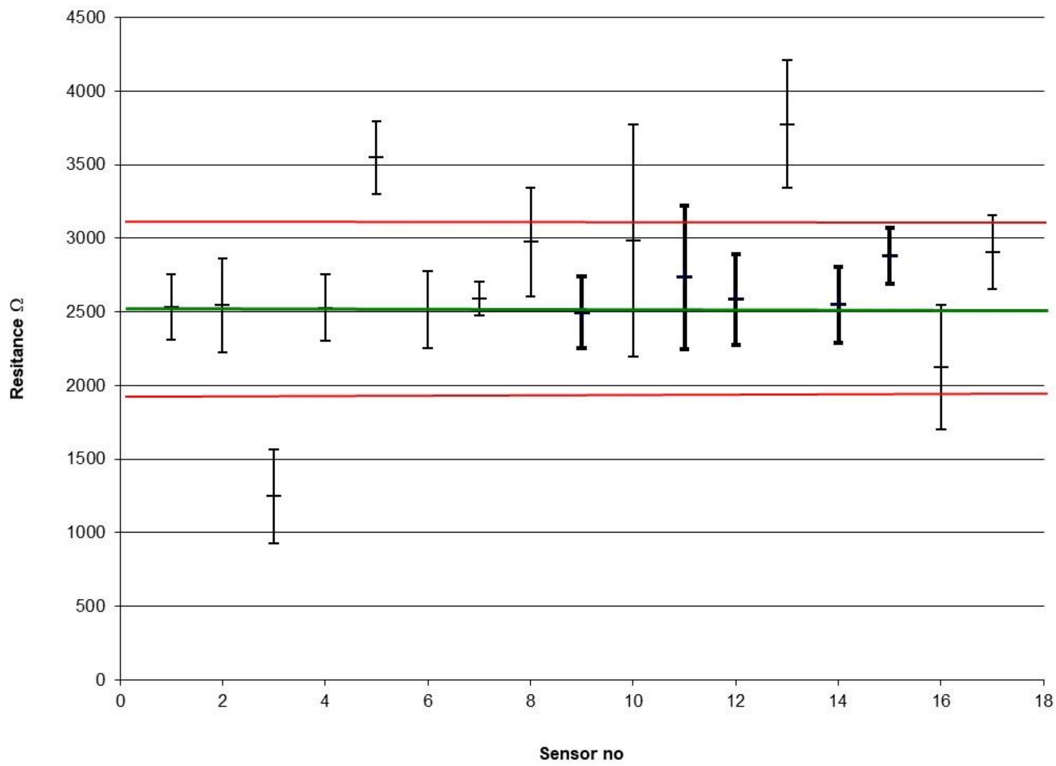

*Figure 6: Performance of a batch of the sensors. Each value is the response of the sensor to a 4.4N load made over six measurements (error bars). Sensors used in the next stage (encapsulation) are in **bold**. Order left to right the same as in Figure 7. The green line is the population mean and the red lines is the standard deviation from the mean*

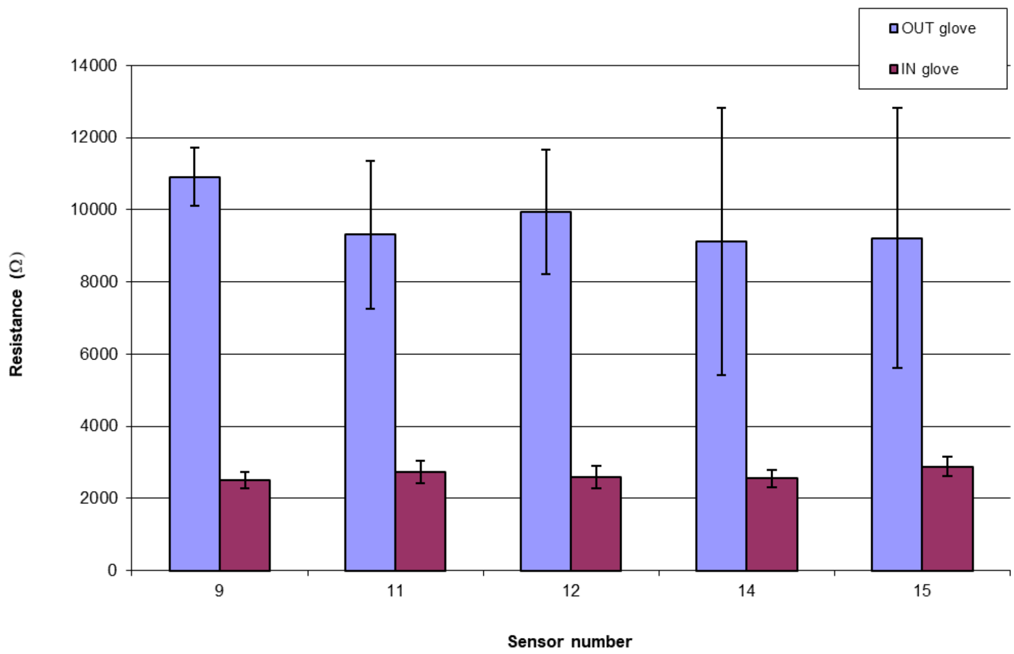

Figure 7: Resistance response to a 4.4N load of sensors in their normal state outside of a silicon glove (OUT glove) and encapsulated within a silicone glove (IN glove). Overall sensor conductance is lower when inserted into a silicone glove, but variance is also substantially lowered

4.2.4 Prosthetic application

Figure 3 shows the glove mounted on the prosthesis. The prosthesis operated in a similar manner with the glove based sensors as with the standard sensors, it could sense first contact and switch between precision and power gasp and it detected objects slipping in the grasp. There was no measurable resistance to closure with the ungloved hand. To close the hand with a glove the current required to close the hand increased monotonically:

$i = 8x10^{-5} q^2 \ (R^2 = 0.9),$

where *i* is the current in amperes and the angle, q (in degrees) from zero at fully flexed.

5 Discussion

The addition of the fillers changed the properties of the silicone and this allowed for selection of the fillers to achieve improved properties. The Steeper glove, designed for the bebionic multifunction hand, is considerably thicker (4mm overall), which gives it greater tear resistance, but at the expense of increased weight[14]. The greater bulk also impedes the curling action of the fingers.

5.1 Effect of different filler materials

All three nanofillers improve the tensile strength of the silicone, but not to the same levels as the commercial gloves. The nanoclay and nanotubes improved elongation over the base polymer, the nanoclay brought the performance up to the same level as the Steeper glove. The force required to break the silicone was the same for all materials, except the Steeper glove. This pattern was similar for the energy at breaking (with the Regal glove being far lower). The impact of the fillers on the tear strength was the most significant. While the nanotubes had no effect on the properties, the silica raised the strength to above that of both the Steeper glove and the silicone with nanoclay added. The Steeper glove was significantly thicker, and therefore resisted flexing, which would impact on the day-to-day performance of the prosthesis. Additionally, this glove adds considerably to the mass of the entire prosthesis, (a PVC has a mass of 338g [11], while the Steeper glove is 670g, [62]). As the mass is distal to the arm and it bares on the skin of the distal aspect of the residuum, this increase is unlikely to be welcome.

While the silica has the greatest increase on the tear strength, it does not extend under load as much as the nanoclay fillers do. Hence for the rest of the tests, the nanoclay was chosen.

5.2 Effect of different concentrations of fillers

Increasing the amount of nanoclay filler had a measurable effect on the tensile properties of the silicone. A small amount (1%) increases the tear strength (5.8 to 12.9N/mm). Trebling the amount only increases by a further 10% (up to 13.2N/mm). Greater concentrations

[14] Steeper produced the bebionic hand and gloves to fit it. While Steeper no longer produces this hand, the glove represents a conventional commercial silicone glove that is designed to be used with a multifunction hand and so still represents a valid comparison.

tended to reduce the performance of the silicone (down to 10.2N/mm). At this point its presence becomes similar to the impact of the macroscale fillers on silicone. Hence the optimal loading is below 3%. This led to the choice to use a three layer combination of 1% and 2% silicones to fabricate the prosthetic gloves. The silicones were layered with the first and last layers being 1% nanoclay silicone and the coat in the centre was 2% nanoclay silicone. This aimed to give the glove greater tear resistance, while not interfering with the flexibility. It is a conventional technique to build up a rubber item from layers of y rubbers of different properties to obtain the desired result.

5.3 Sensors - Testing

5.3.1 Characteristic

The characteristic is of a quadratic form support the principle that the transduction effect is based on contact area between the conductor and the deformation of the transduction material.

5.3.2 Effect of silicone encapsulation on performance

The silicone reduced the sensitivity of the sensors by a factor 50, while the variability measured remained larger (suggesting the variability is dependant on other factors). Hysteresis has the effect of obscuring the difference between loading and unloading, (a desirable effect in this application). The hysteresis observed shows the sensor cannot be used in applications where it is necessary to repeatedly measure grip forces. However, the program used to control the prosthesis is not predicated on the precise properties of the sensor, it employs the *relative* change of the input signal. It is necessary to create a prosthetic device that will work in the field without frequent servicing, over a range of unknowable conditions with compact electronics. Precision is not required, but sensitivity to relative changes and repeatability will suffice, the prosthesis has operated in the field with this algorithm for many years, thus the performance with this prosthesis with the glove sensors was found to be acceptable.

5.3.3 Production variability

For any item produced in bulk, consistency is important. The variation within the batch of 17 sensors shows that it is reasonable to exclude some that prove to be less reliable. Earlier tests of the encapsulation produced sensors with greater variability (for example 34kW, 63kW and 74kW for sensors 2, 4 and 5), when the sensors were allowed to age before encapsulation and the control over proportions of the the silicone mixture was poorer than later production runs. This shows that all aspects of the manufacture process are critical to the performance of the sensors. A deviation in sensor conductivity, if stable once incorporated into the glove, is of lesser concern. The differences can be incorporated into the program within the target hand using set up parameters. Naturally, increased consistency eases application of the technology but programming can circumvent many aspects of the design, if the device is affordable.

5.3.4 Prosthetic application

One aim of the design was to increase the reliability and reduce the cost of producing a glove. The glove is the part of the system that becomes dirty and discoloured and so needs replacing more often. Silicone is harder to discolour, but can rip within weeks, while PVC stains but can last over a year. The goal of the work is to reduce the cost to the consumer *and* increase the lifetime of the glove. The current cost of PVC gloves in the UK is less than one hundred pounds, while silicone gloves cost multiple hundred pounds. Halving the cost or doubling the lifetime could have an impact on the accessibility of the gloves.

The aim of the tests was to show that the glove had no impact on the performance of the hand and the sensors worked with the existing program. The glove was able to interface directly to an existing advanced hand controller [43], with only minimal changes in software. The sensors detected the contact forces on each of the finger tips and the palm and determined the appropriate grip form. If the object slipped within the grasp the hand increased the grip force automatically [43,48].

5.3.5 Further developments

The next step for this technology is to integrate the sensors into third party multifunction hand systems using the sensors to switch the hand into different grip forms without the user needing to use some other means to trigger the grip change. While there are now many different external switching systems for the different multifunction hands, they rely on complex arrangements such as code switching of their command channel, using a smart phone to make the switches. Other methods include RFiD tags so that the user either waves the hand over tags mounted on their body or place many tags in their environment [63], or accelerometers that allow the hand to be `bumped' into a new mode [12]. The Southampton controller simply needs the user to touch the appropriate part of the hand to trigger the appropriate grip.

For this demonstration simple single sensors were produced for each finger. The advantage of textile sensors is that they are easily modified and techniques for changing form and shape are well developed. For example; it is possible to use a single ground plane and multiple contact patches on the upper surface of the sensor [59]. This creates multiple sensors to give greater resolution. Using conductive and non-conductive threads the sensors could be woven together in a single patch with a concave surface that matches the profile of the finger tip. It is possible to build electronic processing into the glove structure to reduce the number of contacts leaving the glove, the drawback would be to increase complexity and cost of manufacture of the glove.

6 Conclusion

A prosthetic glove material with improved cut/punch resistance properties with superior texture and extensibility has been produced by use of nanoclay fillers to silicone. A pressure sensor using EeonTexT can be incorporated into a silicone glove and operates satisfactorily with an intelligent prosthetic hand controller. Force feedback to the electronic controller and the patient are seen as desirable goals for improved prosthetic function. This form of sensorisation can be added to existing hands as well as custom designs.

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