TACTIP - Tactile Fingertip Device, Challenges in reduction of size to ready for robot hand integration

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***Abstract*—Previous work on the TACTIP project has demonstrated a prototype tactile fingertip device, at a little over twice the diameter(40mm) of a human fingertip (16-20mm). Unlike most other developed MEMS sensors, the TACTIP device is appropriate for all tasks for which humans use their fingertips; examples include object manipulation, contact sensing, pressure sensing and shear force detection. This is achieved whilst maintaining a very high level of robustness. Further work with this concept has reduced the size of the device to that closely matching the range of a human fingertip (20mm). Previous development of the TACTIP device has in isolation, proven the potential for these applications, but not provided a benchmark specification of its technical performance. This paper presents benchmarking results from testing pressure and shear force readings using both versions of the TACTIP designs with comparisons that highlight the compromises encountered when reducing the physical build size of the device. The results show that a reduced size device offers greater sensitivity under lower forces, but cannot be subjected to the greater forces that the larger device can.**

I. Introduction

The TACTIP device is a biologically-inspired sensing and object manipulation device, based upon the deformation of the epidermal layers of the human skin. Deformation from device-object interaction is measured optically by tracking the movement of internal papillae pins on the inside of the device skin. These papillae pins are representative of the intermediate epidermal ridges of the skin, whose static and dynamic displacement are normally detected through the skins mechanoreceptors, see Fig.1.

[1], [2] , [3] and [4] have presented the TACTIP device as a 40mm diameter probe, with the mechanics inspired by the human fingertip but at more than twice the size. This paper presents the latest work in reducing the size of the TACTIP design closer to the size of a human fingertip with the eventual intention to integrate it with a robotic hand. Both the old and new TACTIP designs have undergone benchmark testing for comparison in performance of sensing basic force interaction. The reduction in size of the initial prototype TACTIP device has presented some interesting challenges and changes in design, presenting design variables

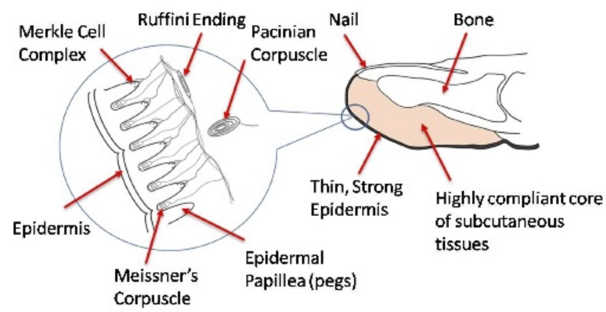

Fig. 1. Cross section of human finger

for consideration in future development and application.

II. Device Description

[1] presents the TACTIP device as a biologically-inspired sensing device, based around the deformation of the epidermal layers of the human skin. Similar approaches to replication of a natural fingertip sensor can be seen in [5] and a comparison between soft and rigid sensors for sensitive manipulation can be seen in [6]. As a deformable contact device, the TACTIP shares characteristics with the human fingertip that make it not only a sensing device but also a gripping device. With greater applied pressure, the contact surface area naturally increases, providing a varying level of friction, aiding in gripping. This separates the TACTIP device from rigid sensing devices. Furthermore the physical separation between the passive tactile sensing region of the papillae, very close to the contacted object and the camera observing the internal environment, removes any physical contact with delicate electronics. This restricts potentially damaging forces, which are absorbed by the flesh like polymer structure. The device works by visual observation of the pin movement in relation to object interaction and deformation of the device skin. The nature of the device provides an enclosed and constrained image processing task that can identify a range of contextual data, including pressure force,

shear force, edge detection and shape detection.

Fig.2 demonstrates the several components that make up the TACTIP device; there is a silicone outer skin with inward facing papillae pins, a compliant optically clear gelatinous polymer inner membrane, a lens, and light source and camera. The camera looks through the lens to optically monitor the skin deformation. This optical based approach has been presented before by [7] and [8] where both monitor two dimensional patterns printed on to the skin surface. The novelty of the TACTIP resides in the raised three dimensional papillae(pins), see Fig.2 and optical tracking of their free movement. These raised papillae are a mechanical representation of the biological epidermal papillae presented in Fig.1. Fig.3 shows the original large TACTIP device next to the new small TACTIP device, along side their associated moulds. The moulds show the difference in pin arrangement and pin density.

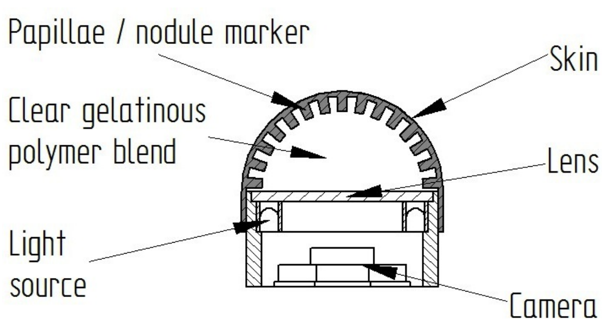

Fig. 2. Cross section of device design

[1] shows the potential of the TACTIP device in measuring force interaction through pin displacement and also characterising contact shape. For example, edge detection is possible using a simple image processing approach for blob detection [2] , [3] . The edge detection algorithm works using adaptive thresholding, dilation, erosion and then blob detection. The aim of this sequence is to first extract the pins from the back ground. Secondly, the erosion expands the white circles created by the pins, to the point that, with no device contact, all black regions are removed. When contact with the device is made, at the point of contact, the adjacent pins are moved such that the pins separate in relation to the skin deformation, revealing a greater area of the black background. Using erosion, this area is expanded, and smoothed out to join any potentially separated regions due to pin positioning. The overall picture now shows a black region, or blob, that represents the position and shape of the contacting surface. Using a blob detection algorithm, the shape and size can be abstracted, and simple line characterisation is then used on the blob to determine the line shape and angle.

Further work with this device has been made by [4] who has applied the TACTIP device to a haptic tactile feedback system where the TACTIP assumes the role of a remote tactile sensor in the context of a surgery robot. The image presented by the TACTIP device's internal camera is divided into a 4x4 matrix, where each matrix cell is weighted by the average light value of the pixels encapsulated with that cell region. This value is then translated to linear movement of one of sixteen linear actuators that make up a haptic feedback device attached to the user's fingertip.

Current work on the device presented in this paper focuses on integration with a robot hand. The device design reported on by [1] is unsuitable for use on a humanoid robot hand due to its large size (40mm diameter, see Fig.3). In order to reduce the device down to a practical size of a human finger-tip (16-20mm [9]), several challenges had to be overcome. The two most prominent of these were embedding a camera very close to a view with a relatively large depth of field, and manufacturing a high enough density of papillae (pins) to produce a sufficient environment for image processing to take place. In order to understand any differences in performance between the original large device and new small device, benchmark statistics are required for fair comparison. The chosen characteristics for comparison are pressure force sensing and shear force sensing.

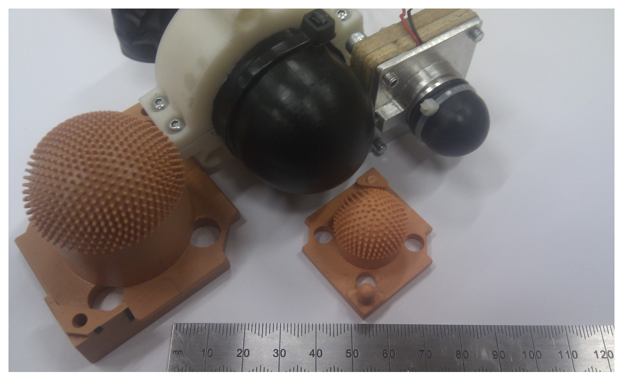

Fig. 3. Photograph of the large 40mm and small 20mm TACTIP devices next to their corresponding casting moulds

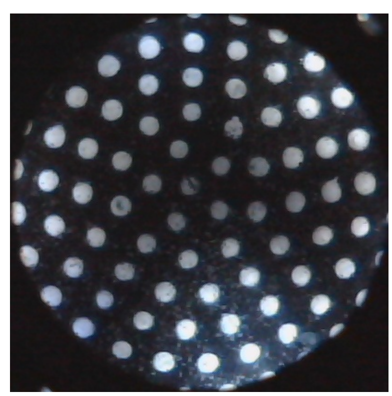

Fig. 4. Example raw image from the 20mm TACTIP device, no object contact

Both sizes of TACTIP use a basic VGA web camera with manual focus. For fair comparison between the two designs, images taken from the camera are cropped to the region of interest and scaled to 100 pixel by 100 pixels. This maintains a consistent benchmark comparison between pin displacement when subjected to object interaction. For these presented experiments, the image processing task is a simple method of counting pixel change from a control position in which the device is not in contact with any object.

Fig.4 presents a raw image from the smaller 20mm device. The image is captured in a colour format, so it is firstly converted to grayscale to ease with image processing later on. Secondly, the image is subjected to thresholding. This creates the image to the left in Fig.5. A region of interest is then extracted around the linear path of a chosen pin. This is shown to the right of Fig.5 where the lower pin is highlighted as moving along a linear path up and down. A counting process from the base of the region of interest up, looks for the white pixels of the monitored pin. The distance of pixel movement is a translation of applied force.

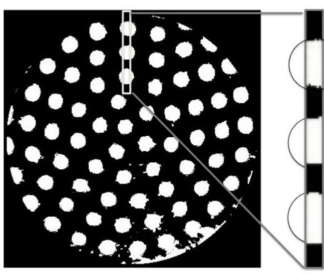

Fig. 5. Demonstration of an extracted region of interest, to allow counting of the pixels from the base up to the first white pixel, determining the pin displacement and relative applied force

A. Alterations For Smaller Design

III. Build Process

The original TACTIP device described by [1] comprises of a camera looking through a plastic tube to the silicone skin mould with pins that simulate the fingertip papillae. The overall size of the device is 40mm in diameter, a little over twice the diameter of a human fingertip, which is approximately 16-20mm diameter. The skin, hosting approximately 526 pins, each 1.5mm in height and 0.75mm in diameter at the base, was made using a vacuum casting process. Using 3D printed moulds, a soft silicone negative mould is prepared that will form the pins. The material used is a silicone RTV 240, Shore A 20 hardness. This mould shapes an inverted skin, for ease of casting, so that the pins face outwards. A soft mould is used because it allows safe and easy removal of the final silicone skin without tearing or loss of pins. The skin is 0.5mm thick so it presents no problems being inverted. The silicone skin, Vytaflex Shore A 60 silicone rubber, is a two part 1:1 ratio mix with a small amount of black pigment that is susceptible to bubbles unless correctly de-gassed in a vacuum chamber. The de-gassing process also aids in pulling the silicone in to the mould cavities increasing the chance of a successful mould. Fig.6 presents 3D printed moulds used in the manufacture of the devices rubber skin. A second 3D printed part is then placed on top of the silicone mould to form the outer wall of the skin. Curing takes around 10 hours. Once set, the silicone skin is cut out, the tips of the pins are painted white to contrast with the black pigmented silicone, aiding the image processing task. The gelatinous polymer is poured in to the skin and held in place with a clear acrylic lens. Fig.6 shows the arrangement of the 3D printed moulds that make the soft silicone negative mould.

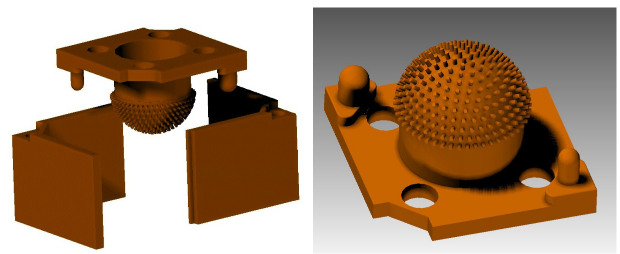

Fig. 6. 3D printed mould assembly, locating points ensure wall thickness. Note that to aid in successful casting of the skin, the mould is inverted and the skin is later reversed so that the papillae pins face inwards.

The new smaller TACTIP device comprises of scaled versions of the larger device's components and design. A smaller camera, is again pointed towards a silicone rubber skin through a gelatinous polymer. The overall size of the skin is 20mm diameter, but the number and size of pins have been explored to achieve a comparable working system.

1) Material Differences: The original approach to downscaling the larger device was to reduce everything by 50 percent in size. This presented difficulties in the casting process whereby a smaller wall thickness of 0.25mm would not successfully form, leaving broken sections, large holes and half built pins. The first solution to this was to maintain the 0.5mm wall thickness, but this produces a much stiffer structure that does not flow with pressure contact, but offers a greater initial resistance that then pops in to an indented form. To reduce this new stiff property, a softer lower Shore valued material was used, Pro Flex Shore A 30. With this new material, casting was successful and the physical response of the skin was similar to the original larger device. Later a slightly harder material, Pro Flex Shore A 40 silicone rubber, was also experimented with. This offered a better configuration for the TACTIP device with more resistance than the Shore A 30 skin but less stiffness than the Shore A 60 skin.

2) Pin Count: In order to maintain a fully formed pin, the size of the pin had to increase closer to the size of the pins in the original device. This reduces the amount of available free surface space on the skin to place the pins, so in turn the pitch of the pins needed to be reduced. A compromise of 75 percent pin size and 50 percent pin density was first made, providing a total of 181 pins. Casting success was achieved, however the the lower number of pins provided sensitivity issues with the image processing. So, whilst maintaining the size of the pins, the density was increased to 75 percent of the original, providing 276 pins. This change increased the sensitivity of the device to a working level again.

IV. Pin Arrangement

Fig.7 demonstrates the method of pin arrangement of the original device in comparison to the new smaller design. Pins are arranged in a geodesic dome representation, where each pin occupies a midpoint or junction of the edges of the triangular faces. The intention of this was to attempt a relatively uniform arrangement of the pins. The design and scalability of this method is problematic due to the lack of approapriate design tools in available CAD packages, and so the gain and necessity was brought into question. A different approach to pin arrangement is to produce horizontal rings at regular intervals down the length of the device, increasing the pins that follow that ring by 5 at each new stage. This maintains the same number of pins as the geodesic dome approach but provides a more scalable model, to ease in mould development. Whilst pin density remains relatively uniform in the centre of view of the camera, the trade off occurs mostly at the outer rings where pin density noticeably increases. However, object contact does not typically occur in this region, so the practical use of the device is not hindered.

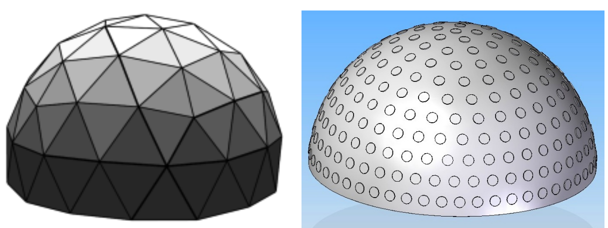

Fig. 7. Difference between geodesic dome and circular array pin arrangment

V. Experiment Description

Two experiments were constructed to detect pressure and shear force. The intention of these tests was to compare the physical properties and responsiveness to simple force interaction with both the larger 40mm and smaller 20mm device. The test environment consisted of a cartesian positioning table, load cell and TACTIP device. Three configurations of the TACTIP device were experimented with, the 40mm Shore A 60 skin, 20mm Shore A 30 skin and 20mm Shore A 40 skin. This explores the effects of reducing the mechanical size of the device, along with some adjustment in characteristic to identify an effective working range.

3) Pressure Detection: Fig.8 demonstrates the pressure test set up and the direction of force applied. To measure pressure, the device is pushed down on to the load cell such that the central axis of the device is perpendicular to the plane of the load cell. The TACTIP device measures applied pressure through observation of pin movement along a linear path that occurs as the skin surface deforms in relation to various forces. The greatest pin movement is noticed around the outer rings of the skin whilst the central pins exhibit the least amount of movement. Monitoring these outer pins provides a better resolution of pressure detection. The algorithm used, tracks the linear movement of one pin, measuring the number of displaced pixels that the pin moves through, during the extent of pressures applied. At first a control reference is taken whilst no contact is made with the device. The current position of the pin during the control reference, is noted as a zero reference point. As the device is pushed down onto the load cell, this pin will move in a linear fashion outwards in relation to the pressure applied.

During the execution of the pressure detection tests, it was observed that the 20mm Shore A 30 device deformation was relatively much greater than that of the 40mm Shore A 60 device. To explore the original decision to use a Shore A 30 silicone to compensate for the relative increased wall thickness and structural 'popping', a new skin was cast using a Pro Flex Shore A 40 silicone. This would allow opportunity to identify the affect of varying the stiffness of the device and potentially provide a solution for the greater deformation of the new smaller 20mm device. A similar approach has been explored by [10], where a MEMS sensor is embedded in a flexible polymer for tactile sensing. The stiffness of the polymer is varied showing that the sensor is capable of reading a new range of forces.

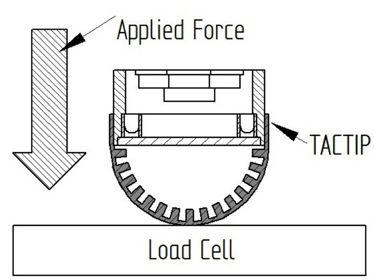

Fig. 8. Description of experiment arrangement alongside monitored pin movement

Different versions of the device can be subjected to a different range of forces, as the results later demonstrate. The larger device has been subjected to forces in excess of 30N and has not yet been broken. The smaller 20mm version is not as robust, having been tested to a maximum of 11N and beginning to show signs of considerable wear. During the experiment, pressure on the device is increased by 0.1225N steps from 0N through to the point that the device appears to have reached its limit. A limit is determined by visual observation of the device being subjected to extreme deformation, where the skin becomes thin through stretching and the mechanical clamp holding the skin begins to deform and move. Applied force ranges for each device version are shown in Table.I. To put this into perspective of a human fingertip, [11] explores shear force measurement of a human fingertip up to 4N, [12] describes individual finger forces of up to 10N during a full hand pinch grip of a 2Kg weight, and [13] explores index finger and thumb pinch grip up to 20N.

TACTIP Version	Min Force (N)	Max Force (N)
40mm Shore A 60	0	30N
20mm Shore A 30	0	7.35N
20mm Shore A 40	0	11.27N

TABLE I
RANGE OF FORCES APPLIED TO EACH DEVICE DURING PRESSURE TESTING.

4) Shear Detection: The test for shear force detection involved placing the TACTIP on a load cell with consistent applied downward force, pushing against the loads with a lateral force, as shown in Fig.9. Similar to the pressure detection, measured shear force is directly relational to pin movement along a linear path, but in this case it is the central pin that provides the greatest amount of pin movement in relation to shear force. Each device has been subjected to three stages of down force loads, 0.49N, 1.96 and 4.9N and then an increasing level of shear force applied. Shear force was applied until a visual limit of extreme deformation was noticed.

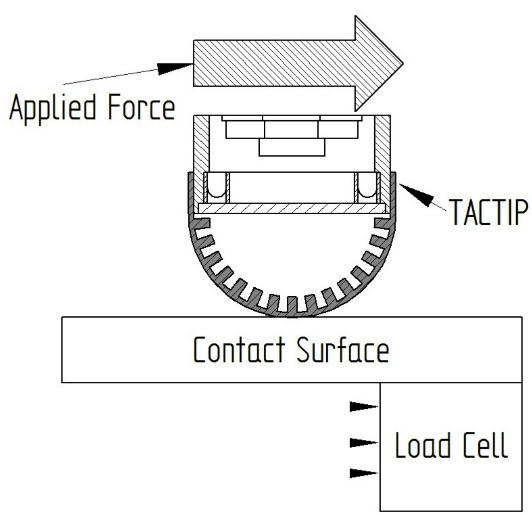

Fig. 9. Arrangement of load cell for shear force tracking

VI. Results of Experiment

5) Pressure Detection: Fig.10 demonstrates the performance of the three configurations of TACTIP tested against load pressure. The first notable result is the greater range of sensing of the larger 40mm Shore A 60 version in comparison with the two 20mm versions. A drop of just over 18N in sensing range has occurred between the larger and smaller devices. In all three cases, the lower applied pressure forces show increased resolution compared to higher applied pressure forces, where the pixel displacement begins to plateau.

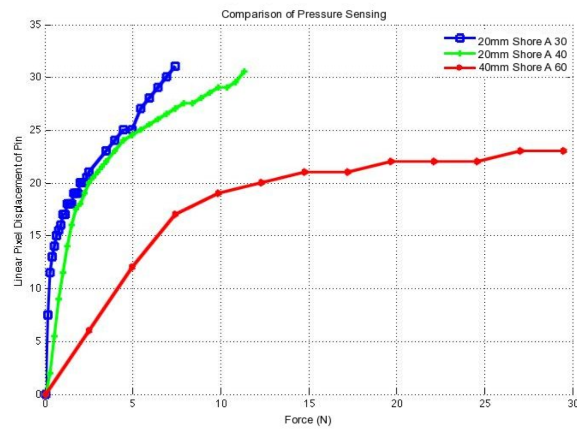

Fig. 10. Pin movement along a linear path verses applied pressure, for both 20mm dia. & 40mm dia. versions

In the two 20mm versions this early stage sensitivity is much more prominent, and shows promise for a more sensitive and accurate fingertip device. Focusing on the differences between the 20mm Shore A 30 and 20mm Shore A 40 versions, the harder skin material has successfully increased the load bearing capability of the device, with only a small decrease in sensitivity. This opens up opportunity for task specific devices with a focused balance between load or sensitivity. In comparison to other tactile sensor development, the working range of the TACTIP can be considered high. [10] present a POSFET sensor with a sensitivity of 0.01N and working range of 0 to 3N, whilst [14] present a similar optical tactile sensor which has been tested between 0N and 10N, with a sensitivity of 0.3N, and [15] presents a capacitive tactile sensor with a working range 0 to 10mN.

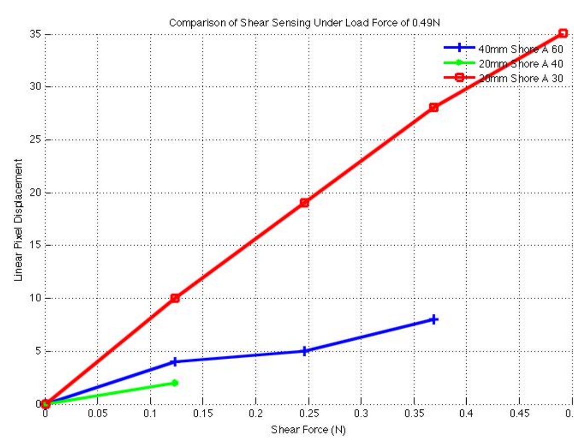

Fig. 11. Pin movement along a linear path verses applied shear force under 0.49N pressure, for both 20mm dia. & 40mm dia. versions

6) Shear Detection: The results of shear detection tests are split in to three separate graphs, Fig.11, 12, 13, each applying to the three stages of applied down force. Fig.11

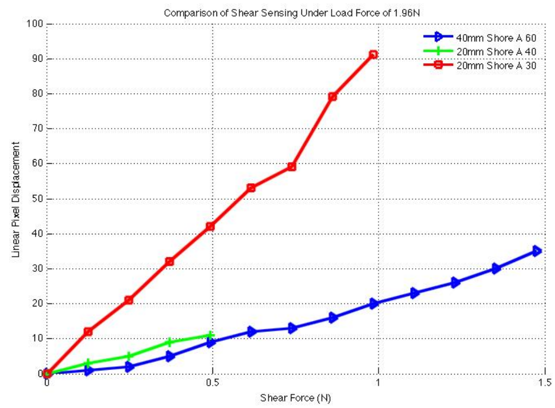

Fig. 12. Pin movement along a linear path verses applied shear force under 1.96N pressure, for both 20mm dia. & 40mm dia. versions

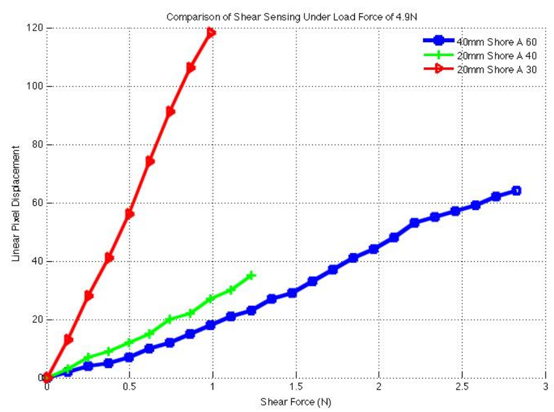

Fig. 13. Pin movement along a linear path verses applied shear force under 4.9N pressure, for both 20mm dia. & 40mm dia. versions

shows results of the device subjected to 0.49N downward force, Fig.12 shows results of the device subjected to 1.96N downward force and Fig.13 shows results of the device subjected to 4.9N downward force. The graphs show a trade off between surface area of contact verses the flexibility of the device skin. Under very little applied down force of 0.49N the softest device with shore A 30 skin, presents the greatest range of shear sensing before the device would slip along the contact surface with more shear force applied. As the applied down force increases, the smaller softer device continues to offer the most pixel displacement, however it reaches the point of reaching its deformation limit much quicker than the other two devices. The shore A 40 skin shows less sensitivity than the shore A 30 skin, but greater sensitivity than the shore 60 skin, however it continues to slip on the contact surface until a much greater downforce is applied. The shore 60 skin can be subjected to much greater shear force but offers greatly reduced sensitivity. Fig.14 summarises the most effective device with regard to range of shear sensing in relation to applied down force. This further emphasises that

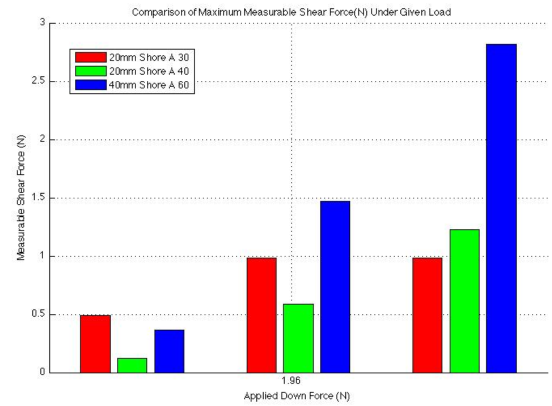

Fig. 14. TACTIP output verses applied pressure, for both 20mm dia. & 40mm dia. versions

a softer TACTIP device can detect greater shear at lower downward forces. However as the downward force increases, a harder TACTIP device becomes more effective.

VII. Conclusion

Here we have presented a comparison in performance between the original TACTIP 40mm device developed by [1] and the newly developed 20mm TACTIP device. We have discussed the mechanical challenges in reducing the size of the device, and the solutions we have identified with implementation and testing. The TACTIP device has proven to be a novel and competent tactile sensing device (see [1], [4]) but, until this point, it had been missing clear bench mark testing of basic force detection for fair comparison against alternative tactile sensing solutions. Our experiments have presented detailed pressure and shear testing results based upon linear pin displacement. These experiments present approaches to independent sensing of basic forces. At this stage of development, without contextual awareness, pressure force is indistinguishable from shear force with these basic algorithms. Further work would fuse these algorithms to present one approach to sensing multiple forces simultaneously.

Detection of basic forces such as pressure and shear, provide crucial information for many robotic tasks that involve gripping and manipulation of objects. There is growing interest in placing robots in the workplace along side humans in a human-centric environment. Such environment are well suited to humans because of their inherent ability for diverse sensing and capability to manipulate a diverse range of objects. For robots to function effectively in this environment, they need to be able to perform these complex functions of sensing and manipulation that traditional sensors and grippers do not allow [16]. TACTIP is a robust device with a large working range in relation to hand manipulation tasks. Typical robotic hand gripping activities require compliant contact surfaces, the fingertip and palm, coupled with good force sensing capabilities. The TACTIP offers both of these attributes in one device. These results have proven a good working range of forces similar to those required in typical hand object manipulation tasks, where both shape characterisation, [2] , [3] , and force sensing are necessary to both manipulate the object.

Future work will further develop the small device to remove the large camera and introduce an embedded camera with on board image processing. This will allow the TACTIP device to be mounted onto a robotic hand to further explore gripping and manipulating tasks, in the the scale and context of industrial or humanoid applications.

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