Interfacial pressure and shear sensor system for fingertip contact applications

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This Letter presents a capacitive-based sensor system for fingertip contact applications. It is capable of simultaneously measuring normal (pressure) and tangential (shear) stresses at the interface between a fingertip and external objects. This could be potentially exploitable for applications in the fields of upper limb prosthetics, robotics, hand rehabilitation and so on. The system was calibrated and its performance was tested using a test machine. To do so, specific test protocols reproducing typical stress profiles in fingertip contact interactions were designed. Results show the system's capability to measure the applied pressure and stresses, respectively, with high linearity between the measured and applied stresses. Subsequently, as a case study, a 'press-drag-lift' based fingertip contact test was conducted by using a finger of a healthy subject. This was to provide an initial evaluation for real-life applications. The case study results indicate that both interface pressure and shear were indeed measured simultaneously, which aligns well with the designed finger test protocols. The potential applications for the sensor system and corresponding future works are also discussed.

1. Introduction: Finger contact sensing [1] has attracted significant research interest in recently years due to its wide potential healthcare applications [2], such as in upper limb prosthetics, robotics, assistive devices and rehabilitation [3].

Tactile dexterity requires the precise and real-time identification of the mechanical contact information between the finger(s) and the object in both normal (pressure) and tangential (shear) directions [4]. In particular, the determination of shear stresses is essential to detect object slipping and corresponding manipulations [5–7]. Moreover, contact shear stresses have arisen as key indicators of hand functionality, providing valuable information on hand function during rehabilitation [8].

For most of the reported systems capable of detecting pressure and shear stresses, typical drawbacks include high complexity [6, 7], low accuracy [9], reliance on indirect assessments, e.g. optical [7], high levels of noise and slow response, all of which prevent their use within a closed-loop control system [1]. Furthermore, most of these reported sensors are rigid structures, while finger contact pressure sensors are also flexible to comply with non-planar finger–object interfaces.

This Letter presents a capacitive-based sensor system capable of simultaneously measuring pressure and shear stresses at the fingertip contact interface. Its advantages include a simple design and decoupled measurement of pressure and shear stresses. Additionally, it features a flexible sensor frame to potentially accommodate bespoke surface shapes [10]. Its application at the interface of residual limb and socket interface for lower limb amputees was reported [11].

In this Letter, to assess its potential application at fingertip and external surface interface, the system was calibrated using a lab-based test machine. Initial test protocols, reflecting typical finger contact activities, were carried out to assess the sensor system's performance. Subsequently, initial results from a case study of 'press-drag-lift' using a single finger of a real subject are presented to verify the sensor's suitability for fingertip contact applications.

2. Developed sensor system: Fig. 1 shows a schematic diagram illustrating the key components of the developed sensor system, which is capable of measuring pressure and shear stresses. The system comprises of a set of sensory units for the transduction of the mechanical stresses to measurable electrical signal as well as a data acquisition system.

The capacitive sensor unit ($20 \times 20 \times 1$ mm) is flexible, and translates the pressure and shear stresses into capacitive signals [10]. Compared with other types of sensor, capacitive-based ones benefit from low drift and high sensitivity [12]. The analogue output signals from the capacitive sensors are sampled at 100 Hz and digitised by capacitance-to-digital-converter peripherals. This data is received by the data acquisition system and subsequently sent to a personal computer (PC) wirelessly via Bluetooth™. Custom software was developed and installed on the PC for the collection, storage and translation of the data to pressure and shear values.

3. Sensor system evaluation: A mechanical test machine (ElectroPuls E1000, Instron Ltd., High Wycombe, UK) was used to calibrate and test the sensor system's performance. Due to the uniaxial nature of the machine, purpose-made platens were designed to perform the pressure and shear tests, respectively (Fig. 2). The input pressure and shear values (kPa) were calculated by using the respective uniaxial loads (N) divided by the device area of 20×20 mm. It is also worth noting that, due to intrinsic constrains of the evaluation setup, a constant time delay (~0.15 s) was identified between the Instron test machine and our sensor system.

3.1. Sensor system validation: Figs. 3*a* and *b* show the measured versus applied stresses for pressure and shear (*Y*) channels, respectively. Since shear in both *X*- and *Y*-directions perform symmetrically, shear in the *X*-direction is not presented here. Peak values of 100 and ±20 kPa of pressure and shear, respectively, were chosen as they correspond to peak values reported for typical fingertip applications [13–15]. For both pressure and shear measurements, linear fit lines with slopes equal to one in Figs. 3*a* and *b* show a high linearity ($R^2 = 0.990$ and 0.995), as well as a good match between applied and measured values.

This linear characteristic is advantageous for both the calibration of the system as well as system's design simplicity as nonlinear behaviour usually requires complex circuitry and signal processing.

3.2. Test protocols for typical fingertip contact applications: Specific test protocols using the Electro-Puls test machine were designed to evaluate the system's performance under typical

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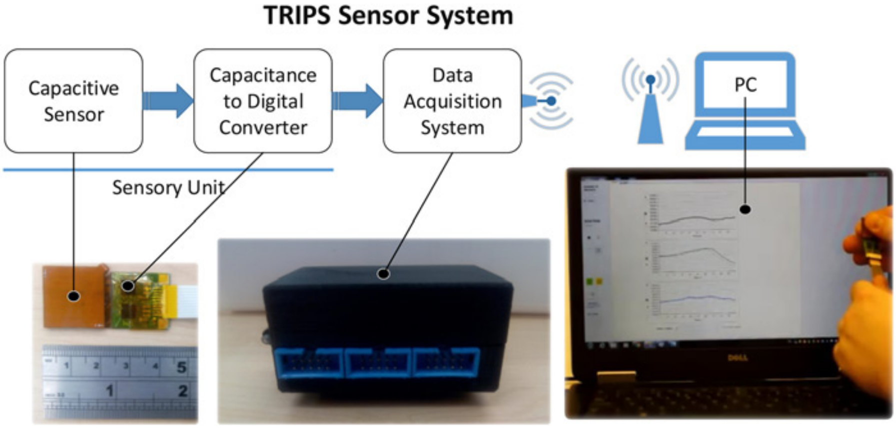

Fig. 1 *Designed sensor system. Its key components include a sensory unit and a data acquisition system*

stress profiles associated to fingertip contact interactions. This was done by comparing the measured output values against the known inputs.

To comply with the uniaxial nature of the test machine, the protocols were to test pressure in one procedure and the shear channels in another. Each fingertip contact interaction results in a three-dimensional stress vector which can be decomposed into one normal (pressure, *Z*-direction) and two tangential components (shear *X*-and *Y*-directions).

3.2.1. Test protocols to evaluate the sensor system's pressure channels

- *Test protocol mimicking pressure induced from a fingertip 'press' activity:* We define pressing as exerting a compressive stress (pushing) on a surface or an object continuously with the fingertip. Example gestures include ringing a bell, pressing a button and so on. An example of the pressure generated in 'press' activity is shown in Fig. 4*a* (dotted line). This stress profile exhibits a trapezoidal-like shape, in which we can differentiate three main phases: (i) the ramp-up phase, where the pressure increases to a certain peak value, (ii) the hold phase, in which the stress stabilises and (iii) the ramp-down phase, where the stress decreases until its initial value. The press-and-hold stress profile in Fig. 4*a* is defined by 100 kPa/s ramping-up and ramping-down velocities, 50 kPa peak pressure value and 5 s hold time. The sensor system response to this stress profile is also shown (solid line). The slightly delayed system response (~0.15 s) as in comparison with Instron sinusoidal input was due to the intrinsic delay in the evaluation setup as mentioned earlier. As it can be seen, the sensor system shows both a fast response and a stable hold time. In fact, there is little signal deterioration during the hold phase.
- *Test protocol mimicking vibration sensing:* The ability to sense vibrations using fingers and hands from, e.g. a power tool provides us with feedback from our environment. This often includes sinusoidal-type stress profiles. Fig. 4*b* shows a sinusoidal stress pattern with 100 kPa peak-to-peak and a 1 Hz frequency (dashed line). As shown, the sensor system exhibited a stable dynamic response (solid line).

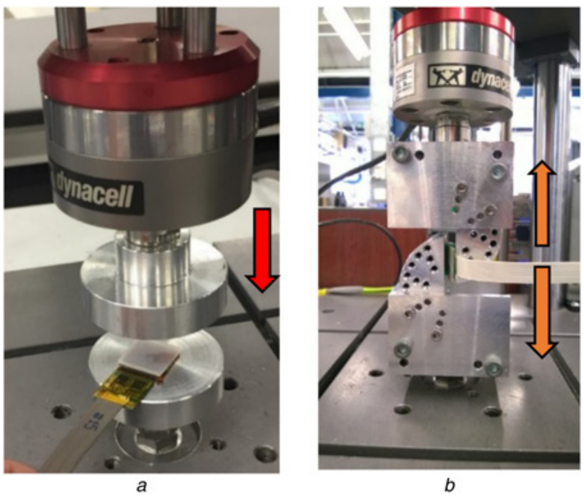

Fig. 2 *Experimental setup for*
a Pressure test
b Shear test

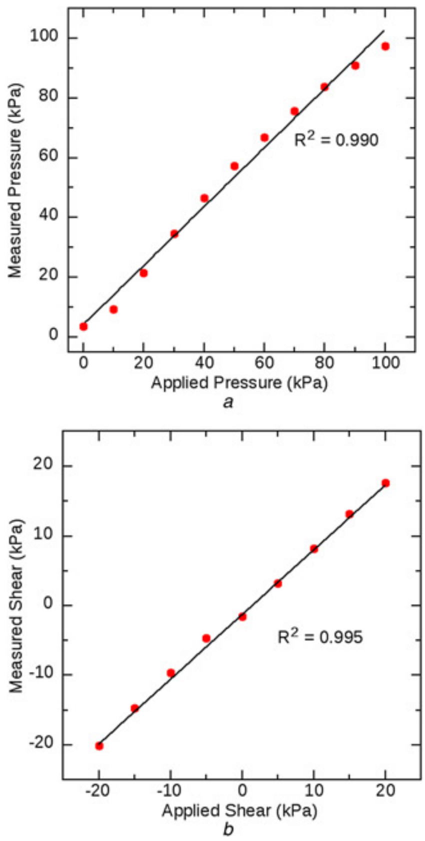

Fig. 3 *Measured against applied stresses*
a Normal (pressure) stress
b Tangential (shear) stress. Lines are linear fittings with slope = 1

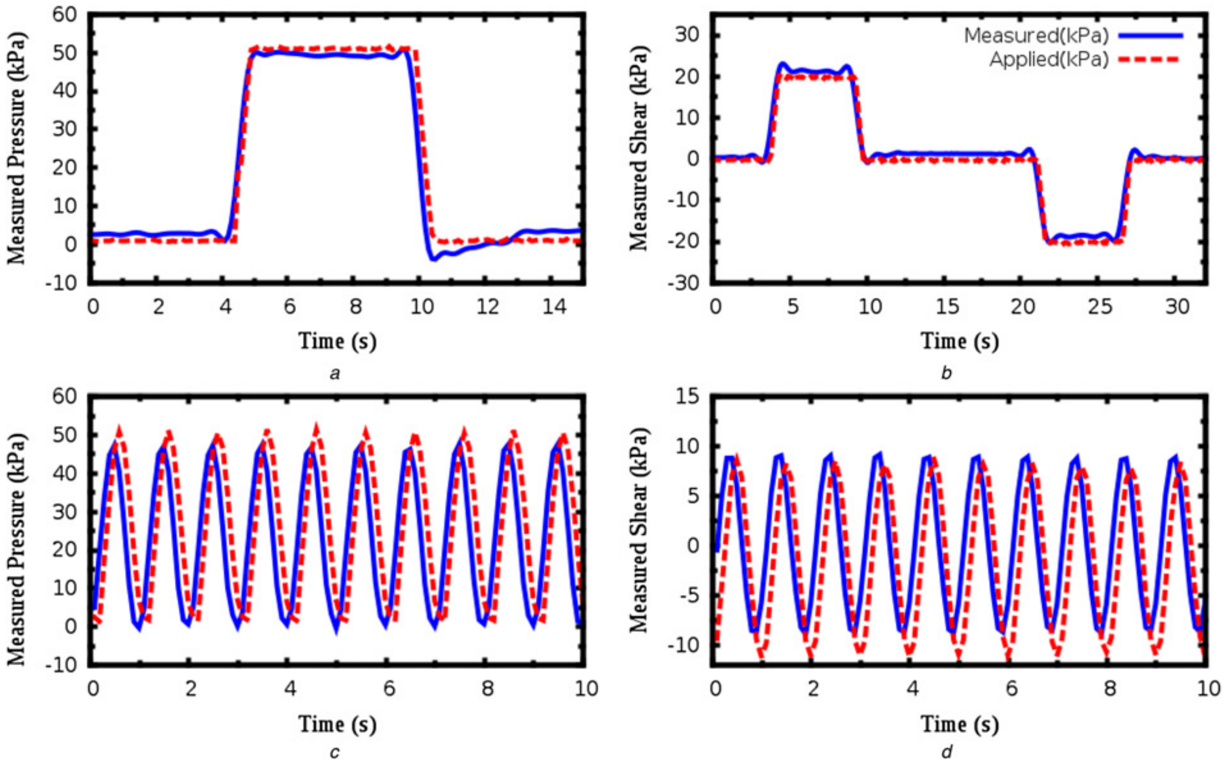

Fig. 4 *Comparison of measured (solid lines) with applied stresses (dotted lines) as a function of time*
a Test protocol mimicking pressure induced from a fingertip 'press' activity
b Test protocol mimicking vibration sensing
c Test protocol mimicking shear stresses induced from a fingertip 'drag' activity
d Test protocol mimicking shear stresses induced from a fingertip 'rub' activity

3.2.2. Test protocols to evaluate the sensor system's shear channels

- *Test protocol mimicking shear stresses induced from a fingertip 'drag' activity:* We define dragging as sliding the fingertip along an object/surface, keeping a continuous contact. Scrolling the laptop touchpad or when playing an instrument, like the guitar, fall into this category. Fig. 4*c* shows a shear stress profile example (dotted line). Similar to the one in Fig. 4*a*, this stress profile exhibits a trapezoidal-like shape, in which we can differentiate three main phases: (i) the ramp-up phase, where the shear stress increases to a certain peak value, (ii) the hold phase, in which the stress stabilises and (iii), the ramp-down phase, where the stress decreases until it reaches the initial value. Note that these can have positive or negative sign, depending on the direction of the applied stress along the axis. The stress profile in Fig. 4*c* has ramping-up and ramp-down values of 100 kPa/s, ±20 kPa peak values and a 5 s hold time. As it can be seen, the system response exhibits a symmetrical and stable response in both positive and negative directions.
- *Test protocol mimicking shear stresses induced from a fingertip 'rub' activity:* We define rubbing as sliding the fingertip over a surface or an object using a repeated back and forth motion. This can be used to perceive texture, as the textured surface exerts varying shear stresses as the digit passes over it. This typical stress profile can be characterised by a sinusoidal, shear stress pattern. The example stress profile in Fig. 4*d* comprises of a 1 Hz sinusoid, with a peak-to-peak amplitude of ~20 kPa. As it can be seen, the sensor system response (solid line) to vibratory stimuli comprising shear stresses exhibits no drift and a stable measured frequency. Similar to Fig. 4*b*, the delayed system response as in comparison with the sinusoidal input was due to the intrinsic delay in the evaluation test setup.

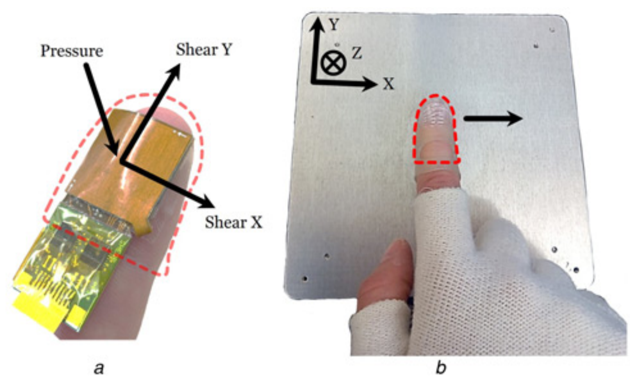

Fig. 5 *Functionality of the sensor system for real fingertip contact applications was tested by fitting it into a custom instrumented glove*
a Location of the sensor on the fingertip
b Picture of the digits' position in a 'press-drag-lift' finger tactile activity, consisting of sliding the distal phalanx of the index finger on a smooth, hard surface while exerting a compressive stress over it

4. Case study: The functionality of the sensor system for real fingertip contact applications was evaluated by attaching a sensor unit to the index finger of a human subject (Fig. 5*a*). The subject was then asked to push and drag the index finger over a smooth surface in the *X*-direction (Fig. 5*b*) and finally lift the finger. The subject was asked to perform this task at the pace they would perform the activity on a daily basis activity, namely, when sliding over the screen of a smart phone. This study was approved by University of Southampton Ethics and Research Governance Committee (ID: 20847).

The simultaneously measured pressure and shear stresses are shown in Fig. 6. As it can be seen, shear *Y* was negligible, thus indicating that the movement was confined to the *X*–*Z* plane. In Fig. 6, we can distinguish three stages as follows.

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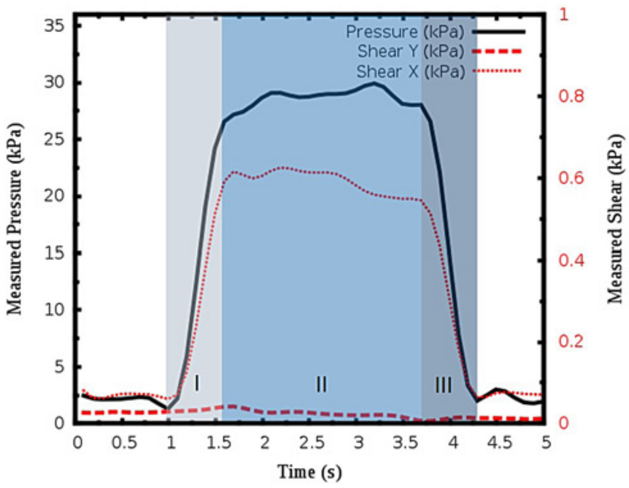

Fig. 6 *Measured pressure and shear stresses in the press-drag-lift activity described in Fig. 5. Three phases can be distinguished: (I) contact phase, (II) press-drag phase and (III) lift phase*

4.1. Contact phase: Around $t = 1$ s, the contact was established. Both pressure and shear X stresses increased up to a maximum. As shown, in this case there was a good level of synchronisation between the normal and tangential displacements, with almost matching ramp-up durations around 0.5–0.6 s. As it can be seen, an increasing shear stress was applied in order to overcome the static frictional force opposing to the start of movement.

4.2. Press-drag phase: This phase approximately comprises data in the time range 1.6–3.7 s. The measured pressure and shear X stress peak values were approximately up to 32 and 0.6 kPa, respectively. It can be seen, except for small variations, stress values have stabilised. This is what we would expect from a healthy subject. The appearance of irregularities like sudden spikes and so on would hint a potentially compromised hand functionality – namely tremors and so on.

There is, however, a slight decay in the shear values. We interpret this as a possible adaptation of the shear forces applied, i.e. once the threshold of motion is exceeded, the necessary shear stress to sustain the movement is less than the value required to initiate the movement. This is down to the fact that the kinetic friction coefficient is typically less than the coefficient of static friction during such movements.

4.3. Lift phase: At approximately $t = 3.7$ s, the movement started to cease. Both pressure and shear X stresses steadily decreased until they reached similar values to those in the pre-load phase. It is worth noting the symmetry exhibited, with respect to the ramp-up phase, with an almost matching duration (0.5–0.6 s).

5. Conclusions: A capacitive sensor system, designed to measure both pressure and shear stresses at the interface between the fingertips and external objects, was studied. In particular, a mechanical test machine was used to calibrate and validate the sensor systems' performance. To do so, specific test protocols reproducing typical stress profiles in fingertip contact interactions were designed. Initial results show a strong degree of linearity between the applied and measured values. Furthermore, the sensor system exhibited a fast and a stable response over time, with little signal deterioration while stresses are sustained over time.

A case study was carried out by attaching a sensor unit to a single finger of a volunteer. The results indicated that the developed sensor system is capable of measuring three-directional pressure and shear stresses simultaneously at the fingertip/surface interface. All these results are very promising, and suggest that there are many potential applications for the sensor system in many fields, such as upper limb prosthetics, robotics, rehabilitation and so on. For example, the measured pressure and shear signals could be fed into a control system for tactile interactions in robotic applications, by detecting movements in the shear direction, as well as pressure applied. Grip on an object could also be assessed for an upper limb prosthetic. This could also lead to an adaptive system, providing real-time adjustments to the grip. Sensor system output could also be exploited to develop assistive technologies for stroke rehabilitation [16]. All of these will be explored in future works.

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