A review of shear/slip sensor for improving robotic and human dexterity

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Abstract

The ability to mimic the tactile feedback of the human hand to improve its dexterity, grasp/gripping and manipulation has been widely considered in robotic development. During robotic grasping, three forces are produced: grasp force (pressure), friction force, and tangential force (shear). Most of the tactile sensors are focused on pressure and normal force. However, shear stress is of great importance in manipulation for the prediction of gripping slippage and the implementation of force control. Improved measurement of shear stress can facilitate robots that mimic human-like robot gripping techniques and achieve advanced manipulation tasks. This paper reviews the state-of-the-art of shear/slip sensors for improving robotic and human dexterity. Tactile shear sensors for robotics and biomedical are reviewed, with an analytical comparison of the advantages and disadvantages of different sensing technologies.

Keywords: tactile sensor, shear stress, robotic, gripping.

1 Introduction

Tactile sensors have been developed and widely used in the past few decades in robotics and biomedical fields. For a robot to pick up an object, we need to indicate to the robot what force should apply, and how much force it needs to apply so it can prevent slippage and breaking. In general, three types of forces are produced during gripping: grasp force (pressure), friction force, and tangential force (shear). Shear stress is one of the important factors to prevent slip which can help robots and humans to improve their dexterity, grasp/gripping, and manipulation so that human and robotic devices can function effectively.

Most of the tactile sensors are focused on pressure and normal force. Less attention has been given to direct measurement of shear (tangential) force, which is nevertheless important for applications such as determining if a gripped object will slip or not. Shear force is one of the most common physical forces encountered in everyday life; with shear foce measurements being useful for varied applications ranging from allowing clinicians to monitor foot ulcers to detecting slippage during grasping and manipulation of objects. However, most of current tactile sensors are not capable of shear force measurements.

It is relatively easy for a human to pick up an egg without breaking or dropping it because humans have sensory (haptic) feedback to predict the grip force to grasp an object. However, without the shear sensing information, robots and biomedical surgical devices [1] may only have poor dexterity, which results in many complicating problems, e.g., the incorrect application of contact force resulting in damage to an object or dropping it. Researchers learned that shear measurements have an important role to play in biomedical fields and robotics for gripping objects [2]-[5], thus, many studies have tried to integratee shear sensing into tactile sensors [6]-[10]. However, many tactile sensors only offered normal force measurements and only a few of them have offered shear (tangential) force measurement [11][12].

This review begins with an overview of the need for tactile shear sensing used in robotics and biomedical fields. Next, we describe the importance of shear sensing in tactile sensing development, and also the present state of tactile shear sensors, including different types of tactile shear sensors and their advantages and disadvantages. Finally, we summarise work done in current research in the area of shear sensing and the areas that can be improved.

2 Tactile sensing with shear measurement

Over the past few decades, many researchers have focussed on developing tactile sensors to improve robotics grasping and manipulation capability[13]-[18]. Also, there has been a growing interest in the development of soft robotic devices for interfacing soft tissue or handling delicate objects [19]-[22]. However, the tactile sensors with shear measurement are still immature products[23][24], and have not yet achieved widespread commercial use in robotics.

Tactile feedback information and the exactness of force are important factors to provide the action of perception in biomedical equipment. Using tactile sensors to acquire kinaesthetic (forces) and tactile information as haptic perception is very useful for surgeons. In general, tactile sensors could provide contact force measurements, besides the contact forces (shear force and normal force) measurements are very helpful for clinical diagnoses, such as diabetic foot ulcer[25][26], as well as minimally invasive surgery [27].

In recent years, surgical equipment developers have begun to employ tactile sensing as part of the surgery system. Using tactile sensors during surgical operations, surgeons can find out the operating position and exact force to apply [28]. Several studies have tried to intergrade shear sensing into tactile sensors. Currently, most tactile sensors only offer normal force measurement and only a few of them are compatible with the measurement of shear (tangential) force [11][12][29][30]. Most shear sensors currently measure parallel shear (sliding force) with limited accuracy[31] and limited reliability[32], which means that current shear sensor products available are limited in flexibility[33], reliability[34] and are also costly[35].Innitial examples of commercial sensors include the shear sensor system from Tactilus® [36]and an in-shoe based foot plantar pressure sensor F-Scan® System[37] by Tekscan. However, the precision of tactile sensor measurements that use in biomedical fields is still unsatisfactory[38]. Due to the inaccuracies of shear measurements, tactile sensors are still not used widely in many clinics, such as diabetic clinics[39].

Alvares et al.[40] reports that many tactile shear sensors have been developed and used in the architectural area, but only a few in robotic and biomedical areas. Although many tactile sensors developed and used in robotic and biomedical fields[1][41] in recent years, most of them measure normal force and not many of them recognise measure shear (tangential) force[42].

As these have received comparatively little attention relative to tactile sensors with shear sensing capability that is used in robotics and biomedical fields [31]. Therefore, there would be some gaps for tactile shear sensing to be developed widely to use in robotic and biomedical fields.

2.1 Motivation for Tactile Shear/Slip sensing

During any object manipulation and grasping, a variety of forces are produced, which gives tactile information. When we pick up an object, to prevent slippage, we need to know the normal force and shear force during grasping [43]. For humanoid devices to work well, they need to have sensory (haptic) feedback like us, which should include normal force and shear force [41]. Normal force and shear force are part of the ensemble of tactile (sensing), helping to prevent slippage, as well as improving understanding of how to interact with a real-world object. Alongside this, there is a growing interest in the development of soft robotic devices that interface soft tissue or handle delicate objects. Examples include fruit sorting robotics [44] through to surgical robots such as The Da Vinci robot [45].

Researchers often employ tactile sensors to measure the tactile perception of the sense of touch. Particularly when grasping an object, this tactile sensibility is essential [46][47][48]. This typically involves pressure sensing. Currently, there is a growing awareness of the need to combine pressure sensing with shear sensing [43][49][50]. Pressure and shear force measurements applications as diverse as help to achieve stable grasps [51], also help to predict and prevent diabetic foot ulcers [52][53].

Shear force measurement is an important factor in many fields, such as humanoid robots and biomedical fields. For example, scientists and clinicians believe the shear stress acting on the shoe sole could be the main cause of certain kinds of foot disease, therefore accurate shear measurements in the insole can help clinicians to monitor diabetes patients with foot ulcers [25][54]-[56]. As well, many studies have focused on developing tactile shear sensors for use in rehabilitation and prosthetics [57][58] for affected patients. Accurate shear measurements in an ‘active’ sole would enable clinicians to monitor these complications [56]. The shear force also should not be neglected to detect slippage during grasping and manipulation, as well as shear measurement could be useful for improving tactile exploration that is used in robotic hands and biomedical equipment. Many studies show that shear measurement is a very important factor, and is very useful for robotics manipulation as well as use for biomedical devices [20][59][60].

Shear sensing technology has progressed in the biomedical field[60]-[62], but the accuracy of shear measurement requires improvement, especially for the measurement of distributed shear over small areas[31]. Most available shear sensors only measure parallel shear with limited accuracy [58][63], and some of the shear sensors are either rigid[64][65] cannot stretch, or are very bulky in size[66][67]. Also, shear data is not readily obtained, and also lacks validation [34][68]. Therefore, it is still necessary to develop a flexible shear sensor that has greater stretchability, three-dimensional measurement capabilities, improved reliability, and accuracy.

For this reason, tactile shear sensing has received much attention due to shear measurement offering important benefits in robotic and biomedical fields in recent years. Many researchers have named tactile shear sensing as well as tactile tangential sensing. To understand tactile shear sensors, we first need to understand what is shear or tangential stress.

2.2 Tactile Shear Sensor Theory

Stresses involve and occur in most of our daily activities. It includes normal and shear stresses, which refer to the local normal or tangential force divided by the surface area of application of the force. Shear stress incules parallel shear stress(tangential force induced sheat stress) and pinch shear stress (normal force gradient induced shear stress), whereas normal stress is the forces perpendicular to a cross-sectional area of the material[69]. The two forces in opposite directions is called parallel shear; if two different amounts of forces acting in the same direction is the pinch shear. Thus, those stresses are commonly been defined as the normal force (pressure) and shear forces (tangential). Moreover, the shear stresses could likely be high if pressures are high. [69].

Therefore, when the shear stress causes the object to change shape (deform), that results from a force parallel (tangential) to the surface of an object. This shear stress τ can express as[70]:

$$\tau = \frac{F}{\mathrm{A}} \qquad (1)$$

where F is tangential force applied (N) ; A is area of application of force(m^2).

Shear stress exists when there is sliding between two surfaces and this is related to friction [34][69]. For solid surfaces which are often referred to Amontons' law, the coefficient of friction μ can express as [71][72]:

$$\mu = \frac{F}{W} = \frac{A}{W} . \tau \qquad (2)$$

where F is the ratio of the tangential force / is the tangential force needed to initiate motion;

W is the normal force/ load force.

It is extremely hard to measure shear accurately [56], so to get an accurate shear measurement, the first step requires an understanding of the definition and the relationship between shear and pressure. Huston et al. [73] conclude that normal stress means the force is directed normal to the area, but if the force is directed tangent (parallel) to the cross section which is called shear force, and the corresponding stress is called shear stress, illustrated in Figure 1.

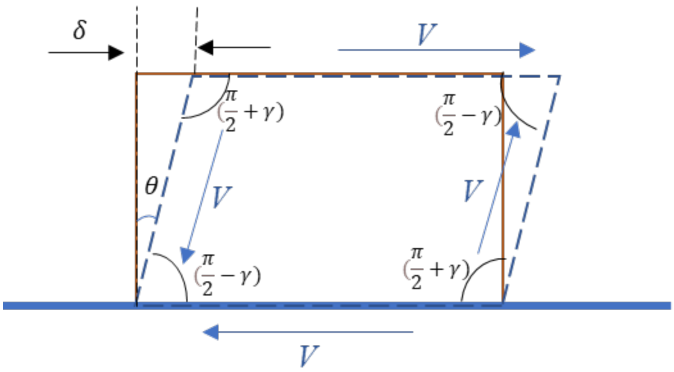

Figure 1: Relationship between normal force and shear stress interpretation: where V is the shearing force, δ is small displacement, γ is the shear strain, and θis the distortion angle

Shear occurs when two forces are in opposing directions (Figure 1) [69]. Medical interest in shear stress is in the measurement scales for diabetic ulcers, which is one of the factors that may trigger foot ulcers [34]. The current market has a variety of sensors to measure the shear force [34]. However, many existing shear sensors lack a validated and commercially available because shear data is not obtained[68], and for this reason, many clinicians prefer not to use existing shear sensors as a diagnostic tool [74].

Shear or tangential stress also will occur while manipulating and grasping an object. The friction force is the resistive shear or tangential force that acts directly opposite to the direction of motion [75]. The adhesion mechanism is described as a relationship between the frictional forces (F), the interfacial shear (τ) stress, and the real contact area (A) [76] as:

$$F = \tau A \qquad (3)$$

The shear stress can be influenced by contact pressure and sliding velocity, furthermore, it depends on sensor materials and environmental factors such as temperature and humidity [77]. Many studies show that shear measurement is a very important factor, and is very useful for robotics manipulation as well as used for biomedical devices[59][60].

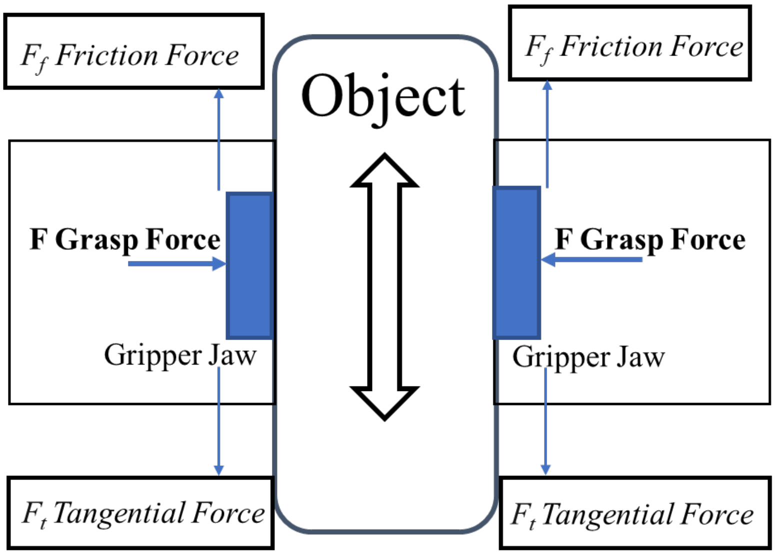

Figure 2: Forces produced during object gripping: which involve Grasp force (Pressure), Friction force, and Tangential Force (Shear)

Detecting slippage during grasping and manipulation through shear measurement should be able to improve tactile exploration in robotic hands and biomedical equipment. During gripping, the shear stress is where a deforming force is applied parallel to surface as shown in Figure 2.

Balasubramanian et al.[78] point out that shear (tangential) forces also relate to haptic perception, as the perception of shear forces can help to prevent slippage, however, there is a challenge to measuring those shear forces. When a hand picks up an object, there are two acting forces which are normal force (contact) and shear (tangential) force (sliding) [79]. An object's surface difference (i.e. roughness, hardness, softness, etc.) can influence the relationship between grip force and shear force [80] during grasping, that detects pressure and shear through fingers. Napier et al. [81] report that humans can achieve stability for any grasping action by the power grip and the precision grip. Figure 3 illustrates the difference between the power grip and the precision grip. When the object is held and pressure being applied by the thumb lying more or less in the palm plane is the power grip; while the object is pinched between the flexor aspects of the fingers and the opposing thumb, that is the precision grip. [81]. The relative force direction between hand and object depends on the posture of grasping [82]. Furthermore, Siciliano et al.[83] has summarized tactile sensing in robotics into three functional categories: manipulation, exploration, and reaction/haptics. So that we can take advantage of robotic tactile sensing by understanding human manipulation characteristics. Haptic [78] gives sensations such as stiffness, texture, and weight when touching/ grasping an object. Therefore, understanding human manipulation characteristics can help us to take advantage of the influence of the ability to distinguish objects for robotic tactile sensing.

1) Manipulation [78][84] -- grasp force control; contact locations and kinematics; stability assessment

2) Exploration [78][83] -- surface texture, friction, and hardness; thermal properties; local features

3) Reaction or haptics [78][85] -- detection and reaction to contacts from external agents.

Figure 3: Power grip and precision grip posture; the power grip involves an extensive area of contact between the hand and the object; the precicion grip is opposition pinch that pinched between the flexor aspects of the fingers and the opposing thumb.

Accordingly, for a robot to pick up a fragile object such as an egg without breaking or dropping it, it needs to satisfy two requirements:

- The need to prevent slippage during manipulation (slippage prevention)
- The need to prevent breakage during manipulation (adequate grasp force)

In summary, a tactile shear sensor would be very useful in many areas, including measuring human-produced forces in biomedical devices and developing humanoid robots.

2.2.1 The shear measurement used in robotic and biomedical fields

As the normal force and the static coefficient of friction are related to shear force, to get accurate force measurements one should not only use pressure sensors but also sensors that can measure shear force[86]. Most pressure sensors can only measure normal force, but not shear force. An object's surface difference can influence the relationship between grip force and shear force [80].

In current years, there is a growing awareness of the need to combine pressure sensing with shear sensing [49][87][88]. Robotic systems have been developed for many decades, to be as flexible as humans, but still have a long way to go, such as the sense of touch, for the robotic hardly to have the same sensing feedback as a human, tactile replication still expects to develop. The accuracy of manipulation for robot still need to improve. There still is a challenge for robots to handle objects safely on contact and static force [89].

2.3 Tactile shear sensing techniques

In recent years, many types of flexible tactile shear sensors have been developed. Those tactile sensors have been fabricated in many different ways for many different kinds of functional measurements. Researchers have worked on many technologies to develop tactile sensors, and tactile sensing technologies have been well developed in many areas. There are many synthetic approaches on fabricate the tactile sensor, and the most common tactile shear sensors used in robotic and biomedical fields are including capacitive sensors [90]–[92][93][94][95], piezoresistive sensors [96][97][98], piezoelectric sensors [30][99][100], optical sensors [12][88][101] and multi-component tactile sensors [63], etc. The benefits and drawbacks of these techniques have been stated below. Many tactile shear sensors have been developed in recent years [5][7][102][103], but in addition to improving to the accuracy of the shear force measurement, researchers are still working on improving the sensors' accuracy, robustness as well as low cost, and easy fabrication.

2.3.1 Piezocapacitive/Capacitive tactile shear/slip sensor

There are various ways to fabricate capacitive sensors for measuring shear force. Capacitive sensing is one of the most commonly used methods in tactile sensing development. The reason for that is capacitive sensors have high sensitivity, low power consumption, low-temperature sensitivity, high spatial resolution, good frequency response, and long-term drift stability and immunity to thermal noise [104][102]. Because of these advantages, capacitive sensors have been widely used nowadays to use for tactile sensing and shear measurements [32][94][105]–[108].

There are many designs of fabricated capacitive shear sensor [4][17][61][87][92][109]-[113]. One example is the sensor of Cheng et al.[114] used 2 x 2 array that the top electrode with each bottom electrode forms a capacitor; when the top electrode moves relative to the bottom electrodes in the overlap area, the four capacitances change. Lee et al.[115] used a similar working principle of four top electrodes and four bottom electrodes.

The electroactive polymer dielectric elastomer (DE) is commonly used to achieve wearable capacitive tactile shear sensors that are flexible and stretchable. Some capacitive tactile shear sensors have been presented in recent years, but the accuracy of the shear measurement is still not satisfactory due to the level of noise continues to be an issue during measurement and crosstalk issues [11][17].

2.3.2 Piezoresistive tactile shear/slip sensor

Piezoresistive is one of the common techniques that have been used in tactile shear sensing [97][98][116]–[118], which changes the resistance during a mechanical stimulus is applied. Piezoresistive tactile sensors have the advantages of low cost, low noise, and good sensitivity, but the limitation of low-frequency response, poor stability, and large hysteresis effect which is not helpful for tactile shear sensors [119].

Kappassov et al.[49] reports that some of the piezoresistive tactile sensors are fragile to shear force. Implementations of piezoresistive and Quantum Tunnel Composite(QTC) sensors suffer sensitivity decreases due to wear and tear through usage as they are not flexible as human skin and cannot cover the space between the links for closing the finger of robot hands [120]. Shi et al. [121] developed a piezoresistive normal and shear force sensor using liquid metal alloy which aims to improve the flexibility and durability of the force sensor but has wiring issues.
Jung et al.[97] has developed a piezoresistive type tactile sensor that can measure the shear force, however, the shear force measurement is not accurate, as the normal force interferes with the shear force. Noda et al. [98] believe their piezoresistive sensor sensitivity can be improved by changing the elastic material, which can reduce the error of the shear force measurement.

However, Wen et al. [122] have pointed out that there is no straightforward way to determine the shear force using the conventional piezoresistive sensor.

2.3.3 Piezoelectric tactile shear/slip sensor

The piezoelectric property of Polyvinylidene Fluoride (PVDF) was found by Kawai et al.[123] in 1969. Piezoelectric tactile sensors are effect by the pressure change with stain/ stress polarization [64][100][124]. Xin et al.[67] concludes that the piezoelectric property of polymer polyvinylidene fluoride (PVDF) tactile sensors has the advantages of low permittivity, wide frequency response, good sensitivity, high dynamic range, flexibility, and lightweight. Therefore, it has also been commonly used in tactile sensor development.

Choi et al.[125] claims that their PVDF tactile sensor can detect contact force and slippage, which only measure the normal forces. Moreover, the research Dargahi et al. [126] completed was based on piezoelectric tactile sensors with shear force (detacting slippery) measurements. However, the measurement was unreliable, also piezoelectric sensing could be more difficult in low frequency applications.

2.3.4 Optical tactile shear/slip sensor

Optical sensors are based on optical reflection between media of different refractive indexes. Optical tactile sensors have also been used for shear force measurements, as have been reported in [12][23][60][127]–[130].

Lincoln et al. [60] developed a 3D force optical sensor for shear measurement, but it can only measure the parallel shear with unsatisfied error rates, and also very high error rates in normal force measurement.

The optical sensor gives a far-reaching recurrence reaction and also requires significant processing power, but the size of the sensor and its unbending nature become the major disadvantages of optical sensors [131]-[133].

2.3.5 Other technologies

There are also many other ways to make shear tactile sensors. Such as, Chuang et al.[134] study where they used angle detection for shear measurement, but the work they have done still has alignment challenges. Zhang et al.[112] found a new way to develop a flexible three-axis tactile sensing array sensor by using Quantum Tunnelling Composite (QTC). Johansson et al.[135] has developed multi-modal tactile sensors; Accounting Tjin's article [136], has talk about the fiber Bragg grating (FBG) that was first discussed by Hill in 1978, and which Tjin used the

FBGs to develop a new type of shear force sensor, however, the shear force measurement was unsatisfactory.

2.3.6 Tactile Sensing Array

The most common sensing array techniques used in tactile sensing are Capacitive sensing arrays and resistive sensing arrays.

Wang et al. [103] have developed an 8x8 capacitive tactile sensor array with a spatial resolution of 1.6mm for grasping force measurement, however, this work has given an unsatisfactory and inaccurate measurement of shear force. Also, other work that Wang et.al [24] have done shows that the capacitive sensor array has limited spatial resolution, measurement range, and a slow response time.

Table 1 : a list of some example shear sensor technologies developed, with a summary of the advantages and disadvantages; also includes sensor size, resolution, force ranges, sensitivity, and structures of the most common sensor types.

Method	Advantages	Disadvantages	Sensor size /Resolution/Force Range/Sensitivity	Structures
Capacitive [32][94] [103] [105]-[107][115] [134] [137]	high sensitivities, low power consumption, low temperature sensitivity, high spatial resolution, good frequency response, long term drift stability, immunity to thermal noise	Dynamic and creep responses,	20pF, 14N, 2.8x10^{-4} kPa^{-1} [32] ; 0.05N, 10N [94]; 62mm X 62mm, 8 X 8, 0.49%/mN, 0.50%/mN, 0.32%/mN[103]; 3 X 3 X 2(mm^3) 2.02pF/N, 0.472pF/N, 0.496 pF/N [106]; 4X4 array, 1.67%/mN [107]; 8X8 array, 10mN-131kPa, 2.5%/mN, 3.0%/mN, 2.9%/mN [115]; 9 X 9(mm^2), 0.85pF/N(range), 4.43pF/N [137]	Polyethylene terephthalate (PET) and polydimethylsiloxane (PDMS) with an inkjet-printed bump [137]; PET substrate with PDMS[134]; PDMS with an air gap and a pillar[115]; Cross-section, multi-element structure liquid-based PDMS [106]; Parallel-plate capacitor with Kelvin guarding that consists of two electrode arrays (reference array and sampling array)[94]; capacitive sensors with a four MEMS linear array[138]; four sensing capacitors separated by a wall structure[139];

Piezoelectric (PVDF) [7][51][64][67][100][124]	Low permittivity, wide frequency response, biocompatibility	External noise issue when the applied force is small	0.003N with sampling rate 50Hz, 8.2mm/s, 10N/mm, 15.5N [51]; 1.5N, 14.93pC/N, 14.92pC/N, 6.62pC/N [100]; 3cmX3cm, 49.8kPa, (12.6±0.8)mV/N, (223.9±20.3)mV/N, (55.2±11.9)mV/N[124]	Sandwiched between four square-shaped upper electrodes and one square-shaped lower electrode[100]; Sandwiched between two elastic layers fied to a rigid foundation[64]
Piezoresistive [97][98][104] [116]–[118] [140] [141]	Small cross-talk, low cost, low noise, and good sensitivity,	Fragility and rigidity, Temperature sensitivity, high-precision limitation, limitation of low-frequency response	2 X 2 array, 15mm X 15mm X 5mm, 12.9kPa, 0.165k.Pa^{-1}, 0.0173k.Pa^{-1} [97]; 20 X 20 (mm^2), 5.0kPa, 1.30 X $10^{-3}kPa^{-1}$, 0.06 X $10^{-3}kPa^{-1}$ [98]; 2.0mm X 2.0mm X 0.3mm, 100kPa, 4.5X10^{-5}(kPa^{-1}) [116]; 11mm X 11mm X 2mm [117]; 300µm X 300µm, 26mV/(V.kPa)[141]; 10 X 10(mm^2), 25kPa, 8.3 X $10^{-7}Pa^{-1}$, 4.0 X $10^{-8}Pa^{-1}$[142]	Piezoresistors sensor chip composed of three pairs of silicon beams[117]; Five basic sensing elements (one for normal force and four for shear force measurement), each of them with two flexible composite films interlocking each other[97]; using cantilevers embedded with a liquid-filled elastomer[142]

Optical [12][23][60][127][143]	Low profile, physically robust, good spatial resolution, sensitivity	noise ratio, bulky.	3.2mm X 1.7mm X 1.1mm(small size), 15.7 mV/kPa, 19.4 mV/kPa, 0.96mV/kPa [60]; 2X2 matrix array, 950X950μm^2, 0.1N (resolution) [127]; 11.4mm X 11.4mm, 40N[143]	Used LED-phototransistor couples base with a deformable elastic layer[143]; incorporates a mesh by using crisscrossing waveguides with tactile sensor array, injection molding with (PDMS) as the optical medium.[127] Using four gaskets of soft fiber optic sensor[110]
Others [102][112][135][144][145]		Repeatability and limited time performance	7 mm X 7 mm X 0.52 mm, 29.8 nF N^{-1}[102]; 2 X 6 cell array, 20N,0.47 V/N, 0.45 V/N, and 0.16 V/N[112]; 0.01 pF/mN, 7.37 pF/N and 7.1 pF/N without driving voltage, 0.016 pF/mN, 10.1 pF/N and 9.3 pF/N with 60 volts driving voltage[144]; 1.93 kPa^{-1}, 29.88 N^{-1}, 3.39 $(N\ cm)^{-1}$,50kPa[145]	a pyramid-plug with different types of external mechanical loadings[145]

3 Conclusions

In recent years, tactile shear/slip sensing technology has progressed in biomedical fields [2][9][40][54][61][145], most of the tactile sensors used in robotic and biomedical fields with shear measurement function only measure parallel shear with limited accuracy, and shear data is not readily obtained, also the lack of a validated and commercially available shear strain sensor [34][68]. Moreover, the accuracy of shear measurement is still unsolved as yet.

In clinical trials, shear stress and strain have been mentioned many times, and shear measurement has received much attention in the biomedical field. Shear sensors are attracting widespread interest in fields such as the prevention of diabetic foot ulcers [146], stroke retraining for grip capacity, mainstream soft-robotic applications, etc. However, shear stress is notoriously hard to measure [56], and researchers do not always agree on how to define shear. There are many questions and concerns about the accuracy of shear measurements. Therefore, there should be greater consideration of the different ways in which shear stress operates and how this should be measured in a clinical setting.

There are many tactile sensors have been developed in the past four decades; since the 1980s many researchers have been working on tactile shear (tangential) sensing and it has been developed in many different technologies [102][103], but due to the accuracy of the shear measurement, researchers still working on improving the response time [102], the sensors accuracy, robust, low cost and easy fabrication. Moreover, traditional tactile sensing has not paid much attention to shear measurements and also lacks sensitivity, dynamic range, and metrical strength [147].

Although much work has been done to date, to develop a human-like tactile shear sensory system, more studies need to be focused on [104][148][149]:

- The ability to give humanoid devices the "sense of touch"
- Providing humanoid devices with the ability to manipulate delicate objects
- Enabling the optimisation of grippers for low-power operation by minimizing the grasping force
- Collecting data using the most sensitive and repeatable tactile sensors for robotic applications

As well as to investigate:

- Novel ways to fabricate shear sensors
- The accuracy of shear measurement

According to these findings, tactile shear sensing research should work to develop an appropriate shear sensor that could resolve the concerns about the accuracy and how to solve the shear methods of the current shear sensors. This should include the capability of mimicking the human sense of touch, and also the sensor should be flexible, has a greater stretchability, and has three-dimensional measurement capabilities, with improved reliability, and accuracy. For any new development, tactile shear force sensors require high sensitivity under small external forces and have a large measurement range on how to improve the accuracy of shear force measurement, flexibility, and fabrication. It also should consider the complex ways in which shear stress operates and then consider the requirements that a sensor would need to meet to measure this variety of shear stress.

Shear stress and strain have been mentioned many times in Clinical trials. There continue to be many questions and concerns about the accuracy of shear measurements. Existing techniques have produced a wide range of stress sensors with some accuracy of measurement in parallel measurement, but this has not considered other shear stress other than parallel. (E.g. measurements of pinch shear) When drawing down to the definition of shear stress, most engineers have considered parallel shear stress. Up to the present day, the most widely used discussions of shear stress documented appear to consider only parallel shear stress. The identification of other forms of shear stress, such as pinch stress or punch stress is rarely considered or mentioned in the documentation available.

However, shear stress should include more than just parallel shear stress, but should also consider ‘pinch shear’ and other conditions of stress in the measurements. Therefore, there should be greater consideration of the different ways in which shear stress operates and how this should be measured in a clinical setting.

Future shear sensing research may focus on developing an appropriate shear sensor that could resolve the concerns about the accuracy and how to solve the shear methods of the current shear sensors.

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