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ABSTRACT:

Approximately one-third of fresh fruits are lost in the supply chain, with half the losses occurring during in-field harvesting and in-plant grading. The complexity of supply chain, waste and economic losses could be reduced through integrated non-destructive harvesting and in-field quality grading. Here we developed a self-decoupled tactile sensor for robotic soft gripper, embedding three-axis self-decoupled triboelectric soft tactile sensors across fingers. During single harvesting operation, the strategy can measure the gripping force, fruit firmness, weight by tactile sensors. Hence, integrated non-destructive harvesting and in-field quality grading can be achieved. Tactile sensors are bioinspired by the deformation mechanics of octopus suckers under normal and tangential forces. It features dual-mode TENG, integrating vertical contact-separation and horizontal sliding modes. This structure can independently respond to normal and tangential forces. It will generate a superimposed triboelectric signal with three spatially decoupled components. Consequently, the three-axis force can be easily decoupled with three triboelectric signals independently, achieving high-precision measurement within the 0-20 N range. Finally, we demonstrate the practical efficacy of the sensing strategy through in-field experiments. During grasping, fruit firmness is evaluated from the normal force response over time. Upon fruit detachment, tactile sensors monitor both normal and tangential forces in real-time to prevent damage. Finally, with the gripper reoriented palm-down, the fruit weight is non-destructively calculated via static equilibrium between the tangential force and the fruit's gravity. We develop a robotic sensing system for integrated, non-destructive fruit harvesting and in-field grading, thereby streamlining the supply chain, reducing waste, and enhancing food safety.

KEYWORDS: triboelectric Nanogenerator (TENG); robotic soft gripper perception; three-axis tactile sensor; non-destructive fruit picking; in-field quality grading

1 Introduction

The global production of fresh fruits is expected to increase by 60% by 2050 [1]. Due to labor shortages and high costs, mechanized harvesting of fresh fruits has become the primary method [2]. However, during the mechanized

harvesting process (such as harvesting, in-plant quality grading, packaging, cleaning, and transportation). Fruits are prone to mechanical damage caused by both static and dynamic external forces (such as compression, impact, and abrasion), leading to bruising, rupture, and even rotting [3].

Currently, agricultural harvesting robots have widely integrated various end-effectors, including vacuum-, hydraulic-, pneumatic-, and electrically driven types, to improve fruit harvesting efficiency^[4]. As shown in Figure S1, soft robotic grippers, owing to their favorable structural compliance, can adapt to the irregular geometries and fragile surface characteristics of fruits, and have become one of the important end-effectors in fruit harvesting. However, fruit harvesting is not a single static grasping process. During grasping, lifting, twisting, and detachment, the gripper–fruit contact interface is subjected to coupled normal force and Tangential force mechanical stimuli. Without effective multidimensional tactile feedback, the soft robotic gripper has difficulty sensing the contact state in real time, which may easily lead to excessive gripping force, local stress concentration, grasping instability, or fruit slippage, thereby causing surface bruising, indentation, and damage to apples, as shown in Figure S2. In addition, fruit quality assessment and grading usually rely on postharvest in-plant processes, including transportation, washing, grading, packaging, cold storage, distribution, and retail, as shown in Figure S3. During these postharvest processes, repeated collision, compression, and mechanical handling may further aggravate fruit damage and reduce commercial value. Hence, damage caused by mechanized harvesting and in-plant grading accounts for more than half of the total^[5]. Hence, by completing harvesting and field grading, the risk of harvest-related damage can be effectively reduced^[6]. Equipping it with both gripping force and the ability to perceive fruit quality can significantly reduce mechanical damage during harvesting and grading. This represents a feasible solution to prevent fresh fruit waste and foodborne diseases^[7]. Hence, it is crucial for robotic soft gripper to possess the ability for multidimensional force sensing and quality grading.

Currently, by integrating soft tactile sensors, such as piezoresistive^[8–12], piezoelectric^[13–16], capacitive^[17–20], and triboelectric sensors^[21, 22], on the robotic soft gripper. Physical stimuli (such as pressure and strain) can be converted into electrical signals^[23–30]. This enables the perception of physical quantities, including object size, shape, hardness, and pressure^[31–36]. Flexible tactile sensors based on resistive, piezoelectric, and capacitive mechanisms have been widely applied in robotic grasping and multidimensional force detection due to their high sensitivity, fast response, and good flexibility. By introducing microstructured interfaces, composite conductive networks, or flexi-

ble multilayer structures^[37–39], previous studies have achieved effective perception of pressure, shear force, and complex deformation. However, fruit harvesting usually involves complex mechanical behaviors, such as normal compression, tangential friction, slipping, and repeated contact, which impose higher requirements on the multidirectional force detection range, response speed, flexible adaptability, and cycling stability of sensors^[40]. Some existing flexible tactile sensors still involve trade-offs among sensitivity, detection range, and durability. In particular, for complex contact scenarios such as harvesting with soft robotic grippers, their long-term stability and self-powered sensing capability still need to be further improved. Based on this, we propose a three-axis self-decoupled triboelectric tactile sensor (3ASD-TET), which can simultaneously detect normal force in the range of 0–20 N and Tangential force in the range of 0–20 N, while exhibiting fast response/recovery characteristics and good cycling stability. The performance comparison with recently reported flexible tactile sensors is shown in Table 1. The results indicate that the proposed device has certain advantages in multidirectional force detection range, flexible adaptability, cycling stability, and self-powered tactile perception. On the other hand, triboelectric flexible sensors can convert mechanical stimuli into electrical signals through contact electrification and electrostatic induction generated during the contact, separation, or sliding between the soft robotic gripper and the fruit surface, thereby enabling the perception of gripping force. Since the fruit grasping process is usually accompanied by obvious contact friction, local deformation, and dynamic load variations, the triboelectric sensing mechanism shows good compatibility with harvesting scenarios^[41]. Meanwhile, triboelectric sensors also have the advantages of simple structure^[42, 43], a wide range of material choices^[44], low cost, and self-powered capability^[45, 46], which helps reduce the complexity of the sensing system in soft robotic grippers and improve its reliability in practical operating environments. In recent years, various TENG-based multi-axis/multidirectional force sensors have been reported and applied to multidimensional force detection, such as normal force and Tangential force detection, in scenarios including robotic tactile perception, human–machine interaction, electronic skin, and underwater grasping. However, research on TENG-based multi-axis flexible sensors for agricultural harvesting scenarios remains relatively limited. During fruit harvesting, normal compressi-

on, Tangential friction, slippage, and large-deformation contact occur simultaneously between the soft robotic gripper and the fruit surface. Therefore, the sensor needs to feature miniaturization, flexible conformal contact, synchronous multidirectional force detection, and easy integration. The performance comparison of related flexible multi-axis force sensors is shown in Table 2.

Existing triboelectric-based flexible multi-axis force sensors have enabled multidimensional tactile perception in electronic skin, underwater sensing, human-machine interaction, and robotic tactile feedback. However, most devices are still mainly designed for general tactile perception or specific non-agricultural application scenarios. As shown in Table 3, these sensors exhibit different characteristics in terms of sensing range, sensitivity, decoupled recognition capability, self-powered performance, stability, and application scenarios. Nevertheless, their direct integration with fruit and vegetable harvesting soft robotic grippers remains insufficient, especially for simultaneously detecting normal compression, Tangential friction, and slip-related mechanical responses at the grasping interface. Therefore, in this work, we propose an octopus-sucker-inspired triboelectric self-decoupled three-axis force flexible tactile sensor and integrate it into the fingers of a soft robotic gripper.

This strategy is applied to the robotic soft gripper, as shown in Figure 1a. The strategy enables simultaneous perception of gripping force and quality detection of fruit firmness and weight during the harvesting process. The tactile unit is embedded within the finger. Its structural design is biomimetic of the octopus sucker's self-decoupling mechanism for three-axis force perception and its embedded structure in the tentacle, as shown in Figure 1b. This ensures a stable and reliable perception of the gripping force exerted by the soft gripper on the fruit during harvesting. The unit integrates two operating modes of the triboelectric nanogenerator (TENG): vertical contact-separation and horizontal sliding modes. Its triboelectric structure mimics the differentiated deformation characteristics of the octopus sucker under normal and tangential forces. When gripping an object, this particular structure can independently respond to normal and tangential forces applied in both vertical and horizontal planes. Then, it will generate a superimposed triboelectric signal with three spatially decoupled components in terms of vertical contact-separation triboelectric signal (along the z direction) and contact-sliding triboelectric signals U_{xz} and U_{yz} (along the x and y directions, respectively).

Consequently, the normal and tangential forces applied on the tactile sensor can be easily decoupled with three triboelectric signals independently. The perception of gripping force, fruit firmness, and weight can be completed during a single fruit harvesting process. As shown in Figure 1d and 1e: Figure 1e I shows the gripping stage (step 1): the tactile sensor perceives the normal force exerted vertically by the fruit on the finger. The firmness of the fruit is then assessed based on its rate of change over time. As shown in Figure 1e II, Step 2 represents the harvesting stage: the tactile sensor continuously detects changes in the normal and tangential forces between the fruit and the fingers during different harvesting actions (such as twisting or pulling). These forces are then combined with the normal force to calculate the gripping force. This prevents the gripping force from exceeding the damage threshold, thus avoiding fruit damage. Figure 1e III shows the placing stage (step 3): the palm of the robotic soft gripper faces downward, vertically towards the ground, and the static equilibrium equation between the gripping force and the gravitational force of the fruit in the vertical direction is established. This enables the non-destructive estimation of the fruit's weight. This strategy does not require additional action from robots or specialized detection systems. It enables the simultaneous in-situ detection of gripping force and multiple fruit quality parameters during a single harvesting process (Figure 1f). Hence, robotic soft gripper sensing strategy that integrates the self-decoupled three-axis force tactile unit is expected to advance the development of integrated harvesting and sorting agricultural robots.

2 Results and Discussion

2.1 The robotic soft gripper sensing strategy integrating a self-decoupled three-axis force tactile unit

Figure 1a shows the application scenario of the soft robotic gripper integrated with the self-decoupled three-axis force tactile sensor. Inspired by the cup-shaped structure of the octopus sucker, the proposed triboelectric tactile sensor can achieve self-decoupled three-axis force sensing and is distributed on the flexible fingers of the soft robotic gripper. Figure 1b establishes a spatial coordinate system centered on the tactile sensor and illustrates the mechanisms of three-axis force detection and signal generation along directions ①, ②, and ③. In addition, Figure 1c presents a comparison between the 3ASD-TET and representative triboelectric flexible multi-axis force sensors in terms of comprehensive force-sensing performance and application implementation level, highlighting the advantage

s of the proposed device in self-decoupled force perception and integration with the soft robotic gripper.

The robotic soft gripper integrated with the aforementioned functions is installed on a smart agricultural harvesting platform. A multi-degree-of-freedom robotic arm is used to conduct field apple harvesting experiments (Figure 1d). The harvesting process is divided into three stages:

(Step 1) gripping, (Step 2) harvesting, and (Step 3) releasing. In step 1, the robotic arm is controlled to approach the target apple and execute the gripping action. The soft fingers then conform to the surface of the fruit, and the tactile sensor generates normal force signals due to the applied pressure. During the gripping process, the rate of change in the normal force value over time is observed. This enables the effective, non-destructive assessment of fruit firmness (Figure 1e).

In step 2, the fruit harvesting operation is carried out. On one hand, frictional force is generated between the fingers and the fruit to separate the fruit from the branch. At this point, the

tactile unit, in addition to the normal force, experiences a tangential force parallel to the inner surface of the fingers. The tactile sensor can simultaneously output both normal and tangential force signals (Figure 1e II). The normal and tangential forces are combined to form the gripping force exerted by the robotic soft gripper on the fruit or vegetable. This force is the key factor in causing fruit harvesting damage. The tactile sensor enables dynamic monitoring of the gripping force. This helps avoid fruit damage caused by excessive gripping force.

In step 3, the apple release operation is carried out. The robotic soft gripper releases the fruit in a palm-down position, vertically aligned with the ground. At this point, the fruit experiences downward gravitational force and upward gripping force along the vertical direction. By establishing a balance equation between the fruit's gravitational force and gripping force, the fruit's weight is estimated (Figure 1e III). Hence, the robotic soft gripper sensing strategy, which integrates the self-decoupled three-axis force tactile unit, is used.

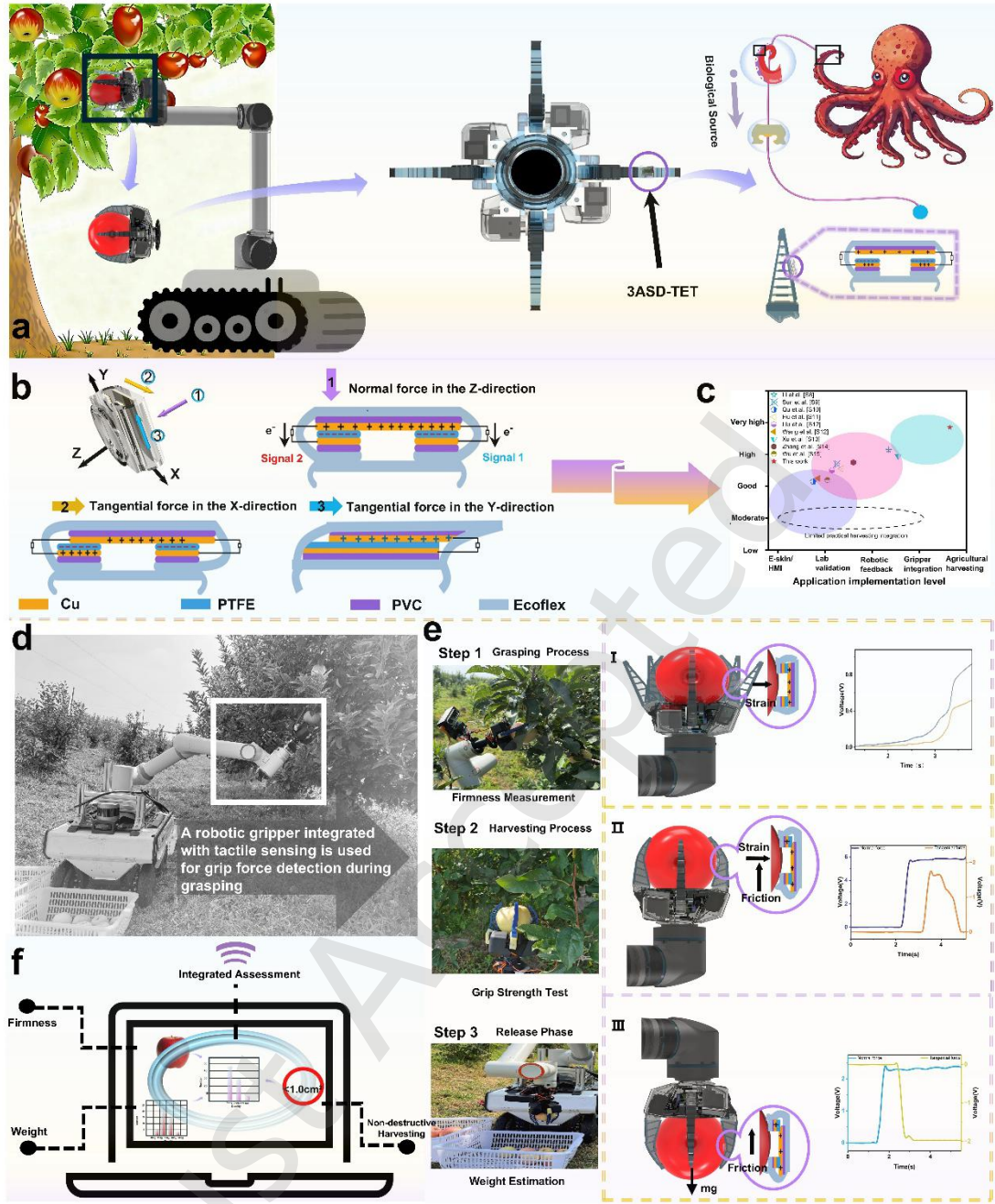


Figure 1. Robotic soft gripper sensing strategy integrated with a self-decoupled three-axis force tactile unit. (a) Application scenario and sensing system of the robotic soft gripper integrated with the self-decoupled three-axis force tactile unit. (b) Principle of the self-decoupled three-axis force tactile sensor. (c) Comparison of the 3ASD-TET with representative triboelectric flexible multi-axis force sensors in terms of comprehensive force-sensing performance and application implementation level (d) Field experiment of fruit harvesting. (e) Fruit harvesting process and corresponding detection indicators: (I) Gripping stage, where the finger tactile sensor detects fruit firmness. (II) Harvesting stage, where the finger tactile sensor dynamically measures the normal and tangential forces and synthesizes the gripping force. (III) Release stage, where the tactile sensor detects the apple's weight. (f) Output values of fruit firmness, weight, and gripping force.

2.2 The triboelectric self-decoupling three-axis tactile(3ASD-TET) sensor inspired by the structure of the octopus sucker cavity.

When the octopus arm grasps an object, the soft lips at the edge of the sucker tightly adhere to the object's surface,

while the central cupped structure of the sucker forms an inverted-cone-shaped indentation. When subjected to external forces from different directions, the cupped structure undergoes targeted and differentiated deformations, efficiently adapting to varying force conditions. When the sucker is subjected to a normal force perpendicular to the adhesion

surface, the octopus adjusts the muscles at the base of the cupped structure to produce a wave-like expansion. This causes the cupped structure to compress in the vertical direction, thereby maintaining the adhesion state, as shown in Figure 2(a).

Meanwhile, when the octopus lifts an object, there will be a tendency for sliding between the object and the sucker, resulting in the generation of tangential force on the adhesion surface. The cupped structure will undergo asymmetric deformation in the direction parallel to the adhesion surface, such as stretching or curling of the cupped edges, to resist the sliding tendency of the object, as shown in Figure 2(b). Hence, the differentiated, direction-dependent deformation principle of the octopus sucker cupped structure can independently respond to both normal and tangential forces. The design of the three-axis force self-decoupled triboelectric tactile sensor is modeled after the sucker cupped structure and its deformation patterns.

The 3ASD-TET is designed based on the principle of triboelectric nanogenerator (TENG), integrating two working modes of TENG: vertical contact-separation and horizontal sliding modes. It consists of two parts: a cavity and a suction cup. The fabrication process, internal structure, and dimensional information of the 3ASD-TET are respectively shown in Figures S4 and S5.

The cavity contains a single top PVC plate with a copper electrode, two bottom PVC plates with copper electrodes, and a polytetrafluoroethylene (PTFE) film. All these components are placed within a cavity structure made of ecoflex. The PVC plates serve as supporting materials for the top and bottom copper electrodes, fixed to the upper and lower surfaces of the cavity. PTFE acts as the surface friction layer for the two bottom copper electrodes, generating triboelectric effects with the top copper electrode. The suction cup ensures a tight attachment between the sensor and the object.

The working principle of the 3ASD-TET is illustrated in Figure 2(c), where the two working modes independently respond to the normal force along the z-axis and the tangential force along the x- and y-axes, generating three distinct triboelectric signals. When the 3ASD-TET is subjected to a normal force along the z-axis, as shown in Figure 2d①, the cavity of the 3ASD-TET undergoes compression along the z-axis. At this point, the top copper electrode and the two bottom PTFE friction layers generate a triboelectric effect in a vertical contact-separation mode.

Due to the triboelectric effect and the strong electronegativity of PTFE, PTFE readily gains electrons, resulting in a negative charge on its surface. At the same time, the top copper electrode loses electrons, resulting in a positive charge on its surface. At this point, the electrons from the two bottom electrodes transfer to the top electrode through an external circuit, generating the triboelectric voltage signal shown in Figure 2e. We represent the open-circuit voltages of the two bottom electrodes (E1 and E2) and the top electrode as signal 1 and signal 2, respectively. Under the action of the normal force along the z-axis, signal 1 and signal 2, as shown in Figures 2e I and II, are added together (signal 1 + signal 2), resulting in the normal force signal of the 3ASD-TET (Figure 2eIII).

At this point, when the 3ASD-TET is subjected to a tangential force along the x-axis again, as shown in Figure 2d②. The left and right edges of the cavity undergo asymmetric stretching/compression deformation along the x-axis. At this time, the top copper electrode and the two bottom PTFE friction layers generate a triboelectric effect in a horizontal sliding mode. When a tangential force is applied in the direction from the E1 electrode to the E2 electrode, the contact area between the E1 friction layer and the top copper electrode gradually decreases. In contrast, the contact area between the E2 friction layer and the top copper electrode remains unchanged.

The positive charge on the E1 electrode increases, while the positive charge on the E2 electrode decreases (Figures 2d② I, II). This results in an opposite change in the potential between the two bottom electrodes and the top electrode, meaning that signal 1 decreases while signal 2 increases, as shown in Figures 2f I and II. The tangential force is calculated as the difference between signal 1 and signal 2 (signal 1 - signal 2) (Figure 2f III). When the tangential force along the x-axis disappears and the top electrode returns to its original position, signal 1 and signal 2 become equal again (Figure 2d② III).

When the 3ASD-TET is subjected to a tangential force along the y-axis, as shown in Figure 2d③, the front and rear edges of the cavity undergo asymmetric stretching/compression deformation along the y-axis. At this point, the top copper electrode and the two bottom PTFE friction layers generate a triboelectric effect in a horizontal sliding mode along the y-axis. Unlike the x-axis direction, the contact area between the E1 and E2 bottom friction layers and the top copper electrode decreases simultaneously in this case.

That is, the positive charge on the E1 and E2 electrodes decreases simultaneously (Figures 2d③ I, II), and the potential change of the two bottom electrodes is identical, as shown in Figures 2g I and II. The tangential force is calculated as the sum of signal 1 and signal 2 (signal 1 + signal 2) (Figure 2g III). When the tangential force along the y-axis disappears and the top electrode returns to its original position, signal 1 and signal 2 simultaneously recover to their initial values (Figure 2d③ III).

It is worth noting that when the 3ASD-TET is subjected to a horizontal tangential force along either the x-axis or y-axis, both the top electrode and the bottom electrode generate a triboelectric effect through horizontal sliding. However, there are significant differences in the deformation of the cavity structure. Hence, we conducted finite element static simulation analysis of the cavity deformation along the x and y axes, respectively (Figure S6).

When the same tangential force is applied along the x and y axes, the total deformation of the cavity structure along the x-axis is 5.5116, with a deformation value of 1.44 (Figures S6 I and II). The total deformation along the y-axis is 2.7043, with a deformation value of 0.72 (Figures S6III and IV). The total deformation differs by 2.8073, and the deformation value differs by 0.72. This indicates that the extent of horizontal sliding friction movement of the cavity along the x-axis and y-axis differs significantly.

Meanwhile, when a force is applied along the x-axis, the opposite changes in the contact area between the E1 and E2 friction layers and the top electrode result in signal 1 outputting a positive voltage and signal 2 outputting a negative voltage. However, when a tangential force is applied along the y-axis, the contact area between the E1 and E2 friction layers and the top electrode decreases simultaneously, causing both signal 1 and signal 2 to output a negative voltage. Based on the above characteristics, effective differentiation between the x and y directions can be achieved either by the final output voltage values or by determining the initial signal polarity.

Based on the above principles, we performed device performance testing by applying different normal and tangential forces to the device using the constant force sensing test setup shown in Figure S7.

The relationship between the normal force along the z-axis and the device output voltage is shown in Figure 2h. The results indicate that as the normal force increases, the

device output voltage also increases. This is because the increase in normal force causes greater compression deformation of the device cavity along the z-axis, which leads to a further increase in the contact area between the top copper electrode and the bottom PTFE friction layers. The triboelectric effect is proportional to the contact area. Hence, the larger the normal force along the z-axis, the more pronounced the triboelectric effect, and the greater the output voltage of the device.

The relationship between the tangential force along the x-axis and the device output voltage is shown in Figure 2i. The results show that as the tangential force increases, the device's output voltage also increases. This is because the increase in tangential force causes greater stretching deformation of the device cavity along the x-axis. At the initial overlapping position, there is no potential difference between the two bottom electrodes (E1 and E2) and the top electrode. Once the E1 friction layer slides outward, its contact area with the top friction layer decreases, reducing the potential difference of E1. In contrast, the contact area of E2 remains unchanged, and its potential difference remains the same.

At this point, E2 compensates for the potential difference of E1 through charge transfer, maintaining the potential balance between the two electrodes. As the sliding distance of the top friction layer increases, the separated charge continues to accumulate. The charge from E2 flows toward E1, causing the value of signal 1 to decrease and the value of signal 2 to increase. Hence, as the tangential force along the x-axis increases, the charge transfer effect becomes more pronounced, resulting in a larger output voltage from the device. Meanwhile, we adjusted the force sensing range of the 3ASD-TET to 0-20N, as shown in Figure S11.

Subsequently, we quantitatively analyzed the force-voltage calibration relationships of the 3ASD-TET for normal force and Tangential force sensing. As shown in Figures 2j and 2k, under normal and tangential loading conditions, the output voltage gradually increased with the applied force. For each force value, more than three repeated tests were performed under the same loading conditions, and the results are presented as the mean $\pm$ standard deviation. Furthermore, linear fitting was used to evaluate the correlation between the applied force and the output voltage, and a 95% confidence interval was added to characterize the reliability of the fitting results. The coefficients of determination (R^2) of the normal force-voltage and Tangential force-voltage calibration curves were 0.989 and 0.982, respectively, indicating good

fitting quality and stable force-dependent output behavior. These results demonstrate that the 3ASD-TET can generate reliable and distinguishable electrical signal responses to normal and Tangential mechanical stimuli.

To further verify the self-decoupled three-axis force-sensing capability of the 3ASD-TET under complex loading conditions, we conducted simultaneous multi-axis loading experiments. In the experiment, a high-precision electrometer and a multichannel data acquisition board (NI USB-6009) were used to collect the output signals of the 3ASD-TET under combined loading along the Z/X/Y directions, respectively, so as to verify the response consistency and decoupling reliability of the three-axis force signals under different testing conditions.

As shown in Figures 2l and 2m, when the Z-axis normal force and X/Y-axis tangential forces were applied simultaneously, the normal output signal first increased rapidly, followed by significant changes in the tangential output signals. When the external load was gradually released, the normal signal decreased with the reduction of contact pressure, while the tangential signals gradually recovered with the restoration of the relative sliding state. The variation trends of the three-axis signals obtained using the multichannel data acquisition board were consistent with those measured by the electrometer, indicating that the sensor exhibits stable

multi-axis force response characteristics under different acquisition systems.

During simultaneous multi-axis loading, the 3ASD-TET usually responds first to the Z-axis normal force, followed by the X/Y-direction tangential force response. This is mainly attributed to the synergistic mechanism of the vertical contact-separation mode and the horizontal sliding mode. The normal pressure first changes the contact area and interfacial spacing between the triboelectric layers, causing the vertical contact-separation mode to generate electrical signals first. In contrast, the generation of tangential signals depends on the relative sliding or microslip process after normal contact is established; therefore, their response is usually slightly delayed compared with the normal signal. This phenomenon indicates that, during complex contact processes involving simultaneous pressure and friction, the 3ASD-TET can distinguish normal and tangential stimuli according to the physical sequence of the loading process.

These results demonstrate that the 3ASD-TET can not only detect normal force and tangential force under single-axis loading conditions, but also maintain good self-decoupled capability under simultaneous multi-axis loading conditions.

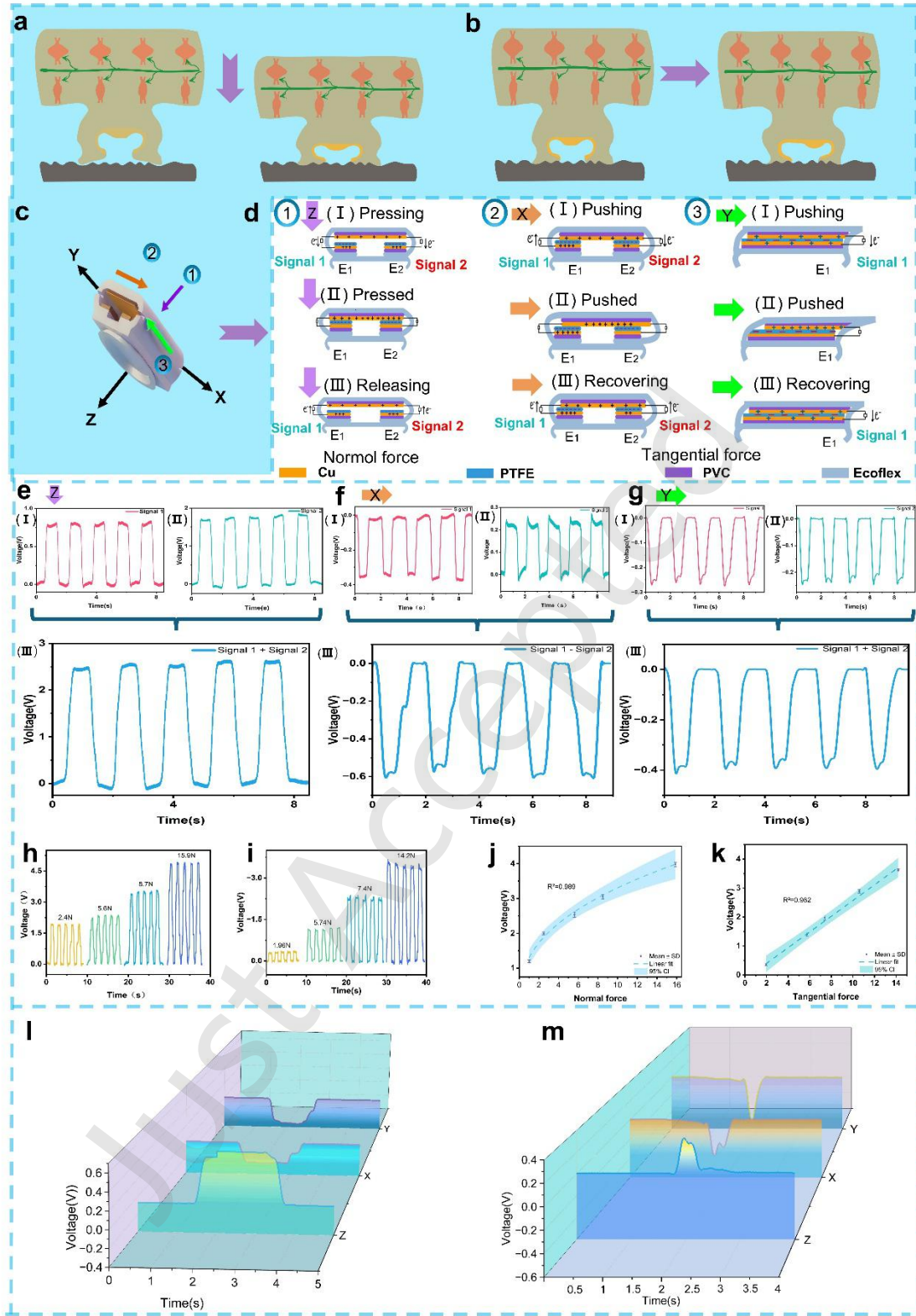


Figure 2. Principles, structure, and performance of the three-axis force self-decoupling triboelectric haptic sensor. (a) and (b) Schematic diagrams of the deformation of the octopus suckers under normal and tangential forces. (c) and (d) Schematic diagrams of the 3ASD-TET three-axis force detection principle. The voltage signals recorded by E1 and E2 represent signal 1 and signal 2, respectively. (e) Under the action of normal force, the triboelectric voltage signals generated between the top copper electrode and the bottom E1 and E2 electrodes are (i) signal 1, (ii) signal 2, and (iii) the normal force signal (signal 1 + signal 2) voltage curve. (f) Under the action of tangential force along the x-axis, the triboelectric voltage signals generated between the top copper electrode and the bottom E1 and E2 electrodes are (i) signal 1, (ii) signal 2, and (iii) the tangential force signal (signal 1 - signal 2) voltage curve. (g) Under the action of tangential force along the y-axis, the triboelectric voltage signals generated between the top copper electrode and the bottom E1 and E2 electrodes are (i) signal

1, (ii) signal 2, and (iii) the tangential force signal (signal 1 + signal 2) voltage curve. (h) Normal force signal of the 3ASD-TET under different normal forces. (i) Tangential force signal of the 3ASD-TET under different tangential forces along the x-axis. (j) Calibration curve between normal force and output voltage, including linear fitting, 95% confidence interval, and R^2 value. (k) Calibration curve between Tangential force and output voltage, including linear fitting, 95% confidence interval, and R^2 value. (l) Output voltage signals collected by the electrometer when forces were simultaneously applied along the Z/X/Y directions on the device. (m) Output voltage signals collected by the data acquisition board (NI USB-6009) when forces were simultaneously applied along the Z/X/Y directions on the device.

2.3 Output performance of 3ASD-TET

To investigate the reliability of the output performance of 3ASD-TET, we conducted studies on the effects of environmental temperature and humidity, durability, and device structural parameters on 3ASD-TET. The application of normal and tangential forces was controlled using a self-built constant force sensing detection device (Figure S7 in the supplementary information), with the testing setup shown in Figure 3a. In the normal force test, a glass sheet (26 mm × 76 mm) was placed 10 mm in front of the device as the contact object (Figure 3a I). In the tangential force test, the glass sheet was replaced with a hook, also placed 10 mm in front of the device (Figure 3a II).

To evaluate the environmental stability of the 3ASD-TET, we tested the output responses of the device to normal force and Tangential force under different temperature and humidity conditions. As shown in Figures 3b and 3c, when the temperature varied within the range of 5–40 °C, the output voltages corresponding to normal force and Tangential force remained relatively stable without obvious signal fluctuations. To further quantitatively evaluate the stability of the output signals, we statistically analyzed the mean values and standard deviations of the normal force and Tangential force responses under different temperature conditions. As shown in Figure 3f, the mean values of the normal and Tangential output signals changed only slightly, and the corresponding standard deviations also remained within a small range, further demonstrating the stable output performance of the device under temperature variations.

Similarly, when the ambient humidity varied within the range of 20%–71%, the output signals of normal force and Tangential force also exhibited good stability, as shown in Figures 3d and 3e. The statistical results of the mean values and standard deviations under different humidity conditions further indicate that humidity variation had no significant effect on the output stability of the device, as shown in Figure 3g. Subsequently, 100 consecutive cycle tests were performed under each of the above temperature and humidity conditions, and the relative errors of the normal force and Tangential force

outputs were statistically analyzed. As shown in Figures S12 and S13, under different temperature conditions, the relative errors of the normal force and Tangential force signals were controlled within 1.92% and 1.18%, respectively. Under different humidity conditions, the corresponding relative errors were controlled within 2.14% and 0.83%, respectively. These results demonstrate that the 3ASD-TET can maintain stable signal output under different temperature and humidity conditions, indicating good environmental adaptability, output stability, and operational reliability.

It is worth noting that, as seen in Figure 3b and 3d, the normal force signal exhibits a spike below the zero baseline. Adhesion between the testing device's glass sheet (Figure 3a I) and its silicone rubber shell accounts for this result. During the recovery process of the test, the silicone rubber undergoes a rebound effect, causing slight changes in the normal force signal. These changes do not affect the final test results.

Meanwhile, considering that dust and dirt may be important factors affecting the output performance of the 3ASD-TET during in-field agricultural applications, we further simulated dust and dirt interference conditions in practical agricultural environments. The device was placed in dust- and dirt-contaminated environments, respectively, and then taken out to test its output performance for normal force and Tangential force. As shown in Figures S14 and S15, after exposure to dust and dirt environments, the peak values of the normal force and Tangential force output signals exhibited only slight fluctuations.

To further quantitatively compare the signal stability under different surface conditions, we statistically analyzed the output voltage amplitudes under clean, dust, and dirt conditions, and presented the results as the mean ± standard deviation. As shown in Figure 3h, under dust and dirt conditions, the amplitudes of the normal and Tangential output voltages remained close to those under clean conditions, showing only slight changes in the mean values and small standard deviations.

Specifically, under the dust condition, the relative errors of the output voltages corresponding to normal force and

Tangential force were controlled within 0.48% and 3.12%, respectively. Under the dirt condition, the relative errors of the output voltages corresponding to normal force and Tangential force were controlled within 2.57% and 5.89%, respectively. These results demonstrate that even under complex environmental interference conditions such as dust and dirt, the 3ASD-TET can still maintain relatively stable signal output, indicating good environmental adaptability and output stability.

The response time is related to the device's real-time detection capability. We analyzed the response characteristics of the device, with the test results shown in Figure 3k. The 3ASD-TET exhibits a very fast response speed, with both the response time and recovery time of the normal force signal being 125 ms (Figure 3kl). The response time and recovery time of the tangential force signal are both 100 ms (Figure 3k II). This demonstrates its fast and efficient performance in detecting normal and tangential force signals.

The durability of the device is closely related to its ability to provide continuous and stable output signals. Therefore, we first conducted 5000 cycles of contact-separation and horizontal sliding tests on the device (Figure S16(a) and statistically analyzed the normal force and tangential force output signals every 1000 cycles. As shown in Figure S16(b)(c), after 5000 cycles, the normal and tangential output voltages of the device remained basically stable, with relative errors of 0.82% and 0.88%, respectively.

In addition, to evaluate the signal stability, attenuation, and drift after long-term operation, we further conducted 10,000 cyclic tests under normal force and Tangential force loading conditions, and statistically analyzed the output signals at different cycle numbers. As shown in Figures S17c and S17d, after 10,000 cycles, the relative errors of the normal force and Tangential force output signals were 2.19% and 2.03%, respectively, indicating that the 3ASD-TET still maintained good output stability and anti-fatigue performance after long-term cycling. On this basis, we further quantitatively analyzed the performance degradation behavior after long-term cycling, as shown in Figures 3i and 3j. The attenuation rates of the normal force and Tangential force signals after 10,000 cycles were approximately 3.02% and 7.34%, respectively. The more pronounced degradation in the Tangential force mode was mainly attributed to friction layer wear, interfacial contact variations, and surface charge attenuation caused by repeated horizontal sliding friction. These results indicate that the 3ASD-TET can still maintain

reliable mechanical signal detection capability within the tested range, although the dual-mode TENG structure still has a potential risk of sensitivity drift caused by frictional wear and charge attenuation during long-term high-frequency operation.

Optimizing the structure of the 3ASD-TET is crucial for enhancing its output voltage and ensuring measurement accuracy. The device's output is based on the triboelectric effect of a triboelectric nanogenerator (TENG), where the cavity gap plays a key role in influencing the relative motion between the triboelectric electrodes. Different cavity structures can lead to varying degrees of deformation, and the extent of deformation directly affects the output voltage of the device. The greater the deformation, the larger the effective friction area between the electrodes, thereby resulting in a higher output voltage. Hence, we designed three devices with different gaps: 1 mm, 2 mm, and 3 mm (Figure 3I) (Figure S8).

We performed output performance tests for the normal and tangential force signals of devices with three different cavity gaps, as shown in Figure 3m and Figure 3n. Under normal force, the device with a 1 mm cavity gap shows slightly higher output voltage than the 2 mm and 3 mm gap devices before 9 N (Figure 3m I). This is due to the larger contact area between the top copper electrode and the bottom friction layer in the 1 mm structure under the same pressure.

After exceeding 9 N, the 1 mm structure shows a slow increase in output voltage due to the saturation of deformation and contact area. The 2 mm structure, due to the further increase in contact area, generates a higher charge transfer, leading to a higher output voltage (Figure 3m II). The 3 mm cavity device begins to show output voltage only after 5 N (Figure 3m I), exhibiting low sensitivity to small forces, and its subsequent output voltage remains lower than the other two devices.

Under tangential force, the output voltage of the 3 mm and 2 mm structures is higher than that of the 1 mm structure across the entire force range (Figure 3n I, II), with the difference becoming more significant after 6 N. This is because the 3 mm and 2 mm cavities undergo greater deformation under the same tangential force, increasing the sliding distance between the top copper electrode and the E1 friction layer, which facilitates charge transfer and enhances voltage output. In summary, the 2 mm cavity structure performs particularly well in responding to both normal and tangential force signals, with overall better output

characteristics. Hence, we selected this structure for subsequent experiments.

Meanwhile, to quantitatively evaluate the stability of the device and the sample-to-sample repeatability, we performed supplementary tests on three 3ASD-TET samples fabricated using the same preparation process. As shown in Figure S18, normal loads of 2.51, 6.24, 9.23, and 16.5 N and Tangential loads of 2.14, 5.5, 8.14, and 15.2 N were applied in the normal force and Tangential force tests, respectively, and the output signals of the three samples under different loads were compared and linearly fitted. Furthermore, to intuitively characterize the sample-to-sample differences, we statistically analyzed the output voltages of the three devices under the same normal or Tangential load and presented the results as the mean $\pm$ standard deviation.

The results are shown in Figure S18h. Under the same applied load, the normal and Tangential output voltages of the three devices remained at similar levels, with small standard deviations. Further quantitative analysis showed that the relative errors of the normal output signals of the three samples were all controlled within 2%, and the coefficients of determination (R^2) of the linear fittings were all higher than 0.98. The relative errors of the Tangential output signals were all controlled within 3%, and the coefficients of determination (R^2) of the linear fittings were all higher than 0.97. These results demonstrate that the 3ASD-TET samples fabricated using the same process exhibit good sample-to-sample repeatability and output stability in both normal and Tangential force detection.

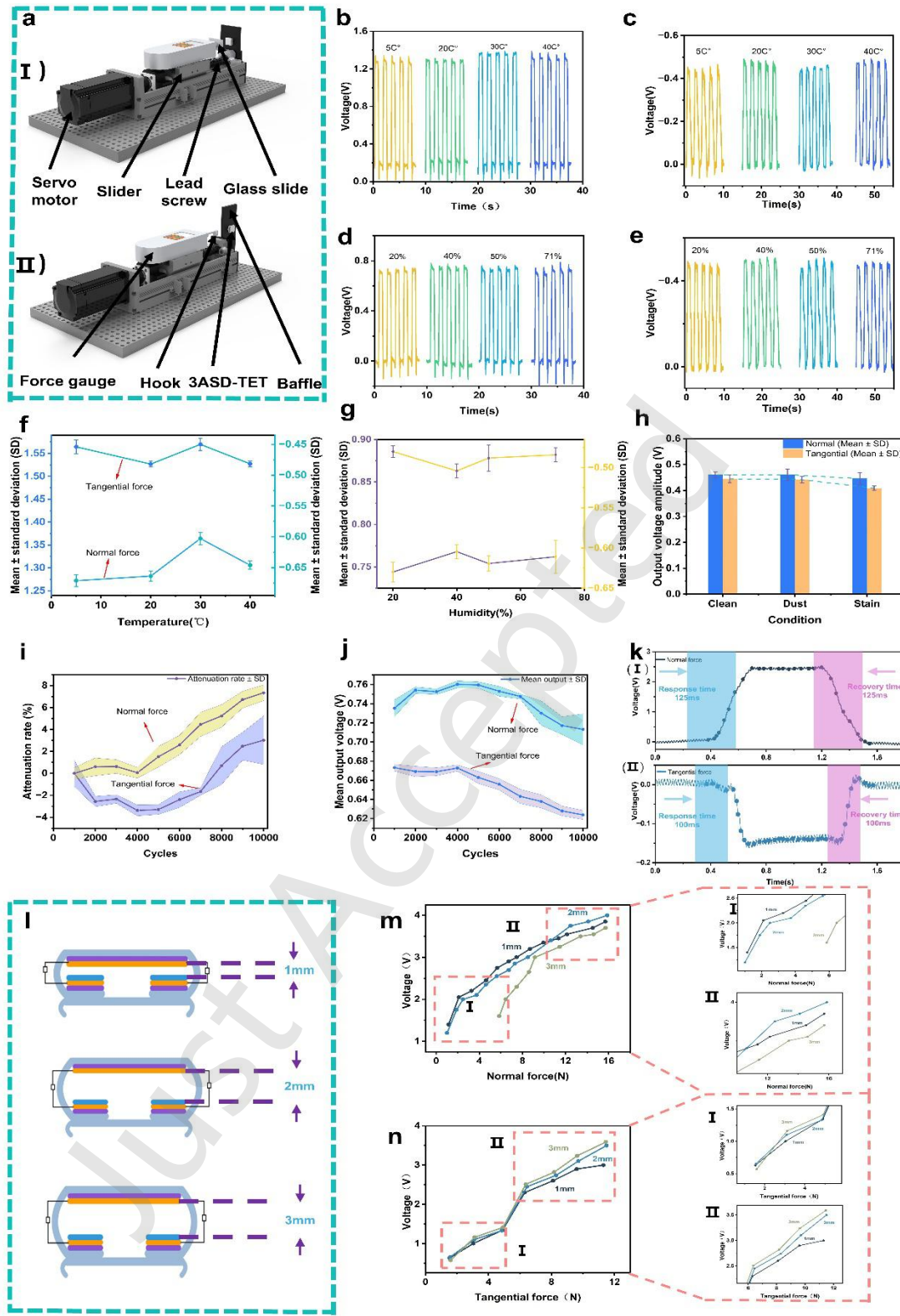


Figure 3. Voltage output performance and structural optimization of 3ASD-TET. (a) Schematic diagram of the device's normal and tangential force testing setup. (b) Normal force signal output voltage of 3ASD-TET under different temperature conditions. (c) Tangential force signal output voltage of 3ASD-TET under different temperature conditions. (d) Normal force signal output voltage of 3ASD-TET under different humidity conditions. (e) Tangential force signal output voltage of 3ASD-TET under different humidity conditions. (f) Temperature-dependent output stability of the normal and Tangential signals. (g) Humidity-dependent output stability of the normal and Tangential signals. (h) Comparison of output signals under clean, dust, and stain conditions. (i) Changes in the attenuation rates of the normal and Tangential output signals during 10,000 cyclic loading tests. (j) Changes in the average output voltages of the normal and Tangential signals during 10,000 cyclic loading tests. (k) Response time and recovery time of the normal force and Tangential force signals of the

3ASD-TET.(I) Schematic diagram of the cavity structure with different gaps (1 mm, 2 mm, 3 mm). (m) Voltage-normal force relationship (I, II are local magnifications). (n) Voltage-tangential force relationship (I, II are local magnifications).

2.4 A robotic soft gripper sensing strategy is used for fruit harvesting, achieving non-destructive harvesting by detecting the gripping force

In conclusion, the 3ASD-TET can accurately and reliably perceive three-axis forces. Hence, we further applied the 3ASD-TET for gripping force perception in a fruit-harvesting robot with a robotic soft gripper. We conducted a study on robotic soft gripper sensing strategies using the four-finger symmetric fin-ray robotic soft gripper (Easy Griper, Dongguan), which is widely used in fruit harvesting.

Inspired by the embedded biological structures between octopus tentacles and suckers, the 3ASD-TET is also embedded in soft fingers. Compared to the current adhesive installation of sensors, embedding the sensor enhances the structural integrity and operational stability during the robotic soft gripper's grasping. This makes it more suitable for fruit harvesting scenarios under complex force conditions. To identify the effective observation points for the robotic soft gripper's gripping force, we determined the optimal installation position of the 3ASD-TET on the finger. We used finite element theory simulations to analyze the deformation and force distribution of the fingers during fruit grasping, as shown in Figure S9 I and II.

The results show that the deformation and force at the middle part of the finger are the most significant. This means that, during fruit harvesting with the robotic soft gripper, as long as the gripping force at the middle part of the finger does not exceed the fruit damage threshold, non-destructive harvesting can be achieved. Hence, installing the 3ASD-TET at the middle part of the finger, as shown in Figure S9 III and S10, enables effective perception of the gripping force on the fruit by the robotic soft gripper. Compared to the multi-point layout scheme, this significantly reduces the complexity of the robotic soft gripper perception system.

Apples are one of the world's major fruits ^[47], so we used apples as an example to conduct robotic soft gripper gripping force perception tests during the harvesting process, as shown in Figure 4(a). When the robotic soft gripper grasps the fruit, the suction cup structure of the 3ASD-TET firmly adheres to the fruit's surface, as shown in Figure 4(b). The sensor structure prevents sliding between the fruit and the soft finger, which could otherwise cause bruising to the fruit.

The harvesting robot mimics four human-like actions to pick fruit using a multi-degree-of-freedom robotic arm, as shown in Figure 4(c). A coordinate system is established with the apple at the centre, and the four harvesting actions are performed by pulling along the X and Y axes, pulling vertically downward along the Z axis, and rotating around the Z axis to pick the apple. Hence, we conducted dynamic gripping force detection with the robotic soft gripper under the four harvesting actions.

It should be noted that the 18 N threshold set in this work refers to the total gripping force applied by the soft robotic gripper to the apple, rather than the local contact force at a single sensing position. As shown in Figure S9, the finite element analysis results indicate that obvious stress concentration occurs in the middle region of the flexible finger during apple grasping. Therefore, this region was selected as the installation position of the 3ASD-TET to monitor the mechanical response and potential damage risk during the grasping process. Previous studies have shown that the gripping force of apples grasped by soft robotic grippers is generally in the range of 15.66–20.04 N [48]; when the gripping force exceeds 20 N, it may go beyond the safe harvesting range and induce apple damage [49, 50]. Therefore, the total gripping force threshold of the soft robotic gripper was set to 18 N in this work. During the experiment, when the total gripping force approached 18 N, the soft robotic gripper stopped closing to avoid further increases in gripping force. The methylene blue staining results showed that no obvious damage was observed on the apple surface under the 18 N grasping condition, as shown in Figure S19, indicating that this threshold can ensure stable apple grasping while effectively reducing the risk of grasping-induced damage.

At the same time, we analyzed the apple harvesting process and divided it into three stages, as shown in Figure 4(d). At time t₁, shown in Figure 4(d) I, the robotic soft gripper is in the preparation stage for grasping the apple, with no contact between the hand and the apple. At time t₂, shown in Figure 4(d) II, the robotic soft gripper begins to grasp the apple, with the fingers gradually bending and deforming until the fruit is fully grasped. At time t₃, shown in Figure 4(d) III, after the robotic soft gripper secures the apple, the harvesting process begins with a specific action driven by the multi-degree-of-freedom robotic arm.

Subsequently, we tested the gripping force of the robotic soft gripper on the apple under four different harvesting actions. The 3ASD-TET output voltage during the entire harvesting process is shown in Figure 4(e)-(h). In the figure, the blue line represents the normal force, and the yellow line represents the tangential force. From the results, it can be seen that at stage t1, under all four harvesting actions, the 3ASD-TET output voltage is 0, indicating that both the normal and tangential forces are 0. This indicates that the robotic soft gripper does not exert any gripping force on the apple, as the hand has not yet grasped the apple at this stage.

In stage t2, the blue line representing the normal force shows a gradual increase until it reaches the set value, while the yellow line representing the tangential force remains at 0. This means that only the normal force exists between the robotic soft gripper and the apple, with no tangential force. This is because during this stage, when the robotic soft gripper grips the apple, there is only a normal force in the vertical direction at the interface between the fingers and the apple. In contrast, there is no relative motion in the direction parallel to the contact interface, meaning there is no tangential force.

In stage t3, the blue line remains unchanged, while the yellow line first gradually increases from the initial position, then stabilizes, and finally decreases, returning to the initial position. This indicates that the normal force remains constant, while the tangential force undergoes significant changes. This is because, during stage t2, the robotic soft gripper is already in a tightly gripped state, and it no longer continues to grip, resulting in a constant normal force. Stage t3 is the harvesting stage, where the robotic soft gripper picks the apple using a harvesting motion. Since the apple is connected to the branch by the fruit stem, in order to separate the apple, a frictional force will be generated between the robotic soft gripper and the apple, which is the tangential force parallel to the contact interface between the fingers and the apple.

At this point, the top copper electrode inside the 3ASD-TET cavity slides horizontally against the two bottom friction layers, generating a triboelectric signal, and the yellow line rises. After the harvesting is completed, a normal gripping force exists between the apple and the robotic soft gripper,

causing the blue line to briefly remain stable. Due to the elasticity of the device casing and the smooth interface between the top copper electrode and the two bottom friction layers, the deformation generated by the device in the tangential direction gradually recovers, causing the yellow line to gradually decrease. This also results in the stabilisation time of the yellow line being relatively shorter than that of the blue line.

It can be observed that the yellow line, representing the tangential force, exhibits a period of stability between its rise and fall. This is because the triboelectric nanogenerator (TENG) is a charge source with extremely high internal resistance. Our measuring instrument (electrostatic meter) has a very high input impedance, which prevents charge leakage. Hence, after the harvesting, there is a sustained voltage output, which gradually decreases as the device recovers from deformation.

It is noteworthy that the tangential force signals generated by pulling along the X and Y axes, pulling vertically downward along the Z axis, and twisting around the Z axis are 3.99V (Figure 4e), 4.46V (Figure 4f), 4.49V (Figure 4g), and 1.75V (Figure 4h), respectively. Hence, we conclude that there are significant differences in the tangential force under different harvesting actions. Based on the mechanical composition, the gripping force of the robotic soft gripper is primarily the combination of the normal force and the tangential force. Hence, when harvesting the apple using a rotational motion, the gripping force of the robotic soft gripper on the apple is minimal, making it the easiest motion to achieve damage-free harvesting.

To verify whether the above results are applicable to apples of different sizes, we selected three apple sizes for repeated experiments, and the results are shown in Figures S20–S22. The experimental results were consistent with the aforementioned results, indicating that the rotational harvesting method generated the lowest Tangential force. In addition, we statistically analyzed the Tangential peak output voltages of the 3ASD-TET under four typical harvesting actions to further quantify the changes in Tangential force during the harvesting process, as shown in Figure S23.

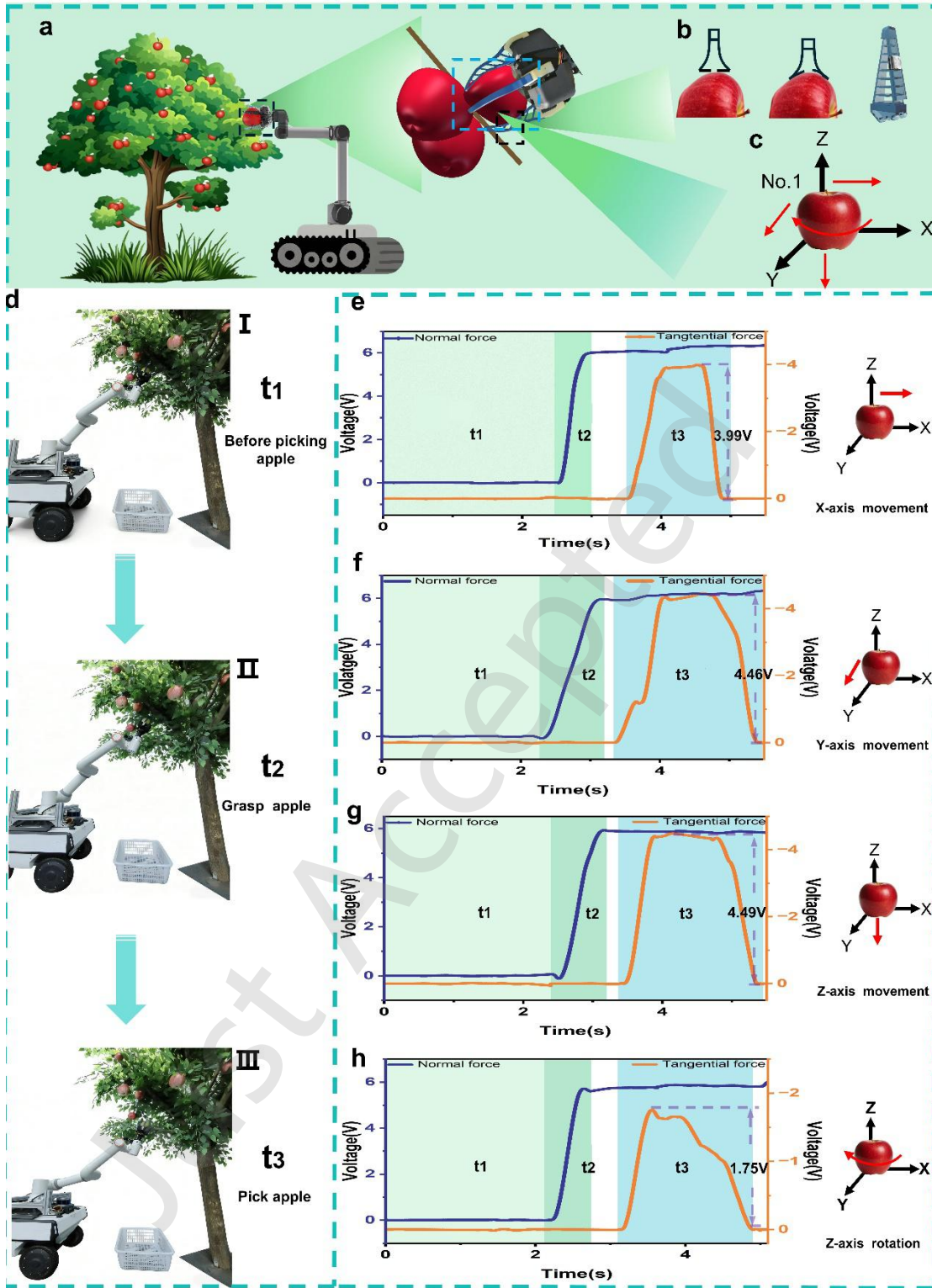


Figure 4. Dynamic detection of the robotic soft gripper gripping force during the harvesting process. (a) Schematic diagram of the robotic arm harvesting an apple. (b) Schematic diagram showing the 3ASD-TET suction cup structure attaching to the apple surface and embedding into the robotic soft gripper. (c) Four human harvesting actions. (d) Three stages of the robotic soft gripper approaching the apple: (I) grasping preparation, (II) grasping the apple, and (III) harvesting the apple. Here, t1 represents the approach stage, t2 represents the grasping stage, and t3 represents the harvesting stage. (e) Harvesting apples along the X-axis direction and the normal and tangential force signals generated during the harvesting process. (f) Harvesting apples along the Y-axis direction and the normal and tangential force signals generated during the harvesting process. (g) Harvesting apples along the Z-axis direction and the normal and tangential force signals generated during the harvesting process. (h) Rotating the apple around the Z-axis and the normal and tangential force signals generated during the harvesting process.

2.5 The fruit firmness measurement is achieved based on the normal force-time response relationship of the 3ASD-TET method

Figure 4 shows the entire apple harvesting process and the dynamic variation of the gripping force. It is noteworthy that during the apple grasping process with the robotic soft gripper, the normal force exhibits time-dependent characteristics (Figure 4e-h). However, so far, we have only considered the equilibrium pressure at specific moments and have not analyzed the response relationship between the normal force of the robotic soft gripper and the grasping time. This will further expand the application of the 3ASD-TET method in fruit harvesting. The hardness of an object can be characterized by the pressure-time response relationship [31]. Fruit firmness is a guarantee for storage and transportation performance. Hence, we investigated the ability of the robotic soft gripper embedded with the 3ASD-TET to perceive fruit firmness.

First, a polyurethane hardness block with standard hardness (Polyurethane, Shenzhen Kangfuxing Technology Co., Ltd.) was selected as the object for the robotic soft gripper to grasp. This is to verify the 3ASD-TET's ability to perceive hardness. During the experiment, we will continue using the previously set gripping force threshold. Figure 5a shows the test scenarios where the robotic soft gripper grasps two hardness blocks, A30 and A40. At the moment shown in Figure 5(a) I, the robotic soft gripper is in the preparatory stage of grasping the hardness block, during which no deformation occurs on the surface of the robotic soft gripper.

At the moments shown in Figure 5(a)II and III, the robotic soft gripper begins to grasp the hardness blocks with hardness values of A30 and A40. The fingers gradually bend and deform, and due to the interaction of forces, the blocks are also compressed by the fingers, resulting in deformations with compression depths of $h_a = 1.2$ mm and $h_b = 1.1$ mm. Since $h_a > h_b$, this implies that, under the same gripping force, the higher the hardness, the less deformation occurs. The output voltage signal of the 3ASD-TET in the normal direction during the grasping process is shown in Figure 5(b). The orange line in the figure represents the output voltage signal generated by the A30 hardness block, and the grey line represents the output voltage signal generated by the A40 hardness block.

The results show that when grasping the A40 hardness block, the 3ASD-TET starts to generate a normal electrical

signal at 1.57 s, while for the A30 hardness block, the signal starts at 2.4 s. The higher the hardness, the greater the rate of change of the 3ASD-TET's voltage signal over time, making it easier to reach higher voltage values. This is because, with higher block hardness, the robotic soft gripper undergoes greater deformation speed and magnitude under the same gripping force. The triboelectric effect generated by the 3ASD-TET is stronger, resulting in an accelerated rate of change of the voltage signal over time.

To further verify the testing performance of the 3ASD-TET on hardness, we selected seven blocks with hardness values ranging from A30 to A90 for testing, as shown in Figure 5d. Figure 5e shows the electrical signals generated by the 3ASD-TET in the normal direction during the grasping process of blocks with different hardness levels. The results indicate that as the block hardness increases, the response speed of the voltage signal over time gradually accelerates, and the generated voltage becomes higher.

Subsequently, we fitted the hardness-voltage curves separately, as shown in Figure 5(f). Under the same force, we performed more than three repetitions of tests on blocks with different hardness values and calculated the average. The goodness of fit was assessed by calculating the coefficient of determination (R^2), which yielded a value of 0.987. This indicates that the 3ASD-TET provides highly accurate results for hardness detection.

We have demonstrated that the 3ASD-TET can measure object hardness during the grasping process with a robotic soft gripper. On this basis, we further recorded the voltage-time responses of the 3ASD-TET during the grasping of objects with different hardness values by the soft robotic gripper. Since hardness evaluation mainly relies on the normal voltage-time characteristics during the grasping process, the gripper closing speed may affect the voltage rising rate and therefore needs to be controlled as a key operating parameter. To clarify the influence of this factor, we grasped apples of the same size at different closing speeds ranging from 50 to 400 RPM and analyzed their effects on the voltage response. As shown in Figure 5c, with increasing closing speed, the instantaneous response rate of the output voltage of the 3ASD-TET gradually increased, indicating that the gripper closing speed affects the voltage-time response characteristics. It should be noted that the soft robotic gripper used in this work is an actively controlled electric gripper, and its operating parameters, such as the closing speed, can be preset through the control software before signal acquisition.

Therefore, the closing speed was regarded as a controllable experimental variable in this study rather than an uncontrollable interference factor. To reduce the influence of speed differences on the hardness evaluation results and ensure the comparability of the test results among different samples, the gripper closing speed was fixed at 200 RPM in subsequent experiments.

Next, we simulated the harvesting process and validated the robotic soft gripper's ability to measure fruit firmness during the grasping phase. As the fruit harvest time gets later, the fruit firmness decreases ^[51]. Hence, we selected experimental apples (variety: Fuji) from orchards with above-average management levels in Tai'an, Shandong Province, China, during September to October 2025. The trees were 7 to 10 years old. Based on preliminary research and the fruit development period, the experiment was divided into five harvest periods (September 25, October 5, October 15, October 25, and November 5), referred to as harvest periods I, II, III, IV, and V, respectively.

The firmness testing scenario is shown in Figure 5g, where the robotic soft gripper grasps apples from the five harvest periods. The output voltage signal of the 3ASD-TET in the normal direction during the grasping process is shown in Figure 5h. The results indicate that when the robotic soft gripper grasps apples from harvest periods I-V, the response speed of the 3ASD-TET's output voltage signal in the normal direction gradually decreases over time. This is because the later the harvest period, the more mature the apples become, resulting in lower fruit firmness. Under the same gripping force, the deformation of the robotic soft gripper is smaller, which ultimately leads to a reduction in the triboelectric effect of the 3ASD-TET embedded in the fingers.

To further illustrate the effect of different fruit firmness on the deformation of the robotic soft gripper, we performed a simulation analysis of finger deformation using Explicit Dynamics, as shown in Figure S24. The results indicate that the higher the apple firmness, the greater the deformation of the fingers. The deformation of the fingers caused by the highest firmness and the lowest firmness differs by up to 1.34 cm, making the fingers more susceptible to force. The simulation results are consistent with the testing conclusions of the 3ASD-TET. Subsequently, we used a fruit firmness meter (GY-4) to test the actual hardness of apples from harvest periods I-V, as shown in Figure S25.

We performed a firmness-voltage fitting between the actual firmness measured by the GY-4 and the normal force

signal measured by the 3ASD-TET, as shown in Figure 5(i). The goodness of fit was evaluated by calculating the coefficient of determination (R^2), which yielded a value of 0.977. This further validated the application potential of the 3ASD-TET in detecting apple firmness. Using the above firmness testing method, we further conducted firmness testing on kiwifruit (variety: Xu Xiang), pear, nectarine and tomato, as shown in Figure S26, 27, 28, 29. The test results were consistent with the firmness testing results of the apples. This demonstrated that the 3ASD-TET has good adaptability in fruit firmness testing.

2.6 Weight perception is achieved by establishing the mechanical equilibrium relationship between the tangential force of 3ASD-TET and the gravitational force of the fruit

After the harvesting is completed, the release phase begins. The robotic soft gripper, with the palm facing downward and perpendicular to the ground, places the apple into the collection box under the guidance of the robotic arm. At this point, the apple will experience its own gravitational force (G) and the gripping force (F) of the robotic soft gripper in the vertical direction. These two forces are in equilibrium ($G=F$) to ensure that the apple remains stationary. Hence, the gripping force is measured by the 3ASD-TET during the release phase. Based on the principle of mechanical equilibrium and the gravitational formula ($G=mg$), the apple's weight (m) can be estimated.

We selected a standard weight reference as the test object to verify the 3ASD-TET's ability to estimate weight. As shown in Figure S30, the robotic soft gripper grips the weight with the palm facing downward, and the weight makes contact with the 3ASD-TET. The weight resists its own gravity under the gripping force of the robotic soft gripper, and at this point, the weight is in a state of force equilibrium, as shown in Figure S30(a). F is the horizontal normal force applied by the robotic soft gripper to the weight, and N is the horizontal normal force applied by the weight to the robotic soft gripper. f is the vertical frictional force applied by the robotic soft gripper to the weight, and f_n is the vertical frictional force applied by the weight to the robotic soft gripper. G is the vertical gravitational force of the weight itself. Here, F and N , f and f_n represent the action and reaction forces, respectively. An analysis of the forces on the weight reveals that in the vertical direction, it is only affected by f and G , and the relationship between them is as follows:

$$\vec{f}=\vec{G} \quad (1)$$

Based on the principle of force interaction, in the equation, f and f_n are equal in magnitude but opposite in direction. It is essential to note that f_n can be measured through the tangential voltage signal output by the 3ASD-TET, indicating that the tangential force measured by the 3ASD-TET is indeed f_n . At this point, $f = f_n$. The relationship between the weight (m) and the gravitational force (G) is as follows:

$$f_n=G=mg \quad (2)$$

In the equation, g represents the gravitational acceleration, 9.8 m/s^2 . Based on the above formula, the weight is estimated using the tangential force measurement from the 3ASD-TET. The output of the 3ASD-TET during the measurement process is shown in Figure S30(b). Based on the above method, we selected four weights of different masses (50g, 100g, 150g, and 200g) to test the weight estimation capability of the 3ASD-TET. The testing scenario is shown in Figure S30(c). The output voltage of the 3ASD-TET under different weight conditions is shown in Figure S30(d). The results show that as the weight increases, the output voltage signal also increases gradually.

This is because the greater the weight, the larger the tangential force received by the 3ASD-TET. The larger the frictional displacement in the tangential direction between the top electrode of the device cavity and the bottom friction layer, the stronger the triboelectric effect generated. Subsequently, the goodness of fit is assessed by calculating the coefficient of determination (R^2), as shown in Figure S30(e). The results show that the coefficient of determination is 0.996. This indicates that the 3ASD-TET has a significant capability for weight estimation.

To investigate the adaptability of the 3ASD-TET to fruits with different sizes and weights, we tested its minimum detectable response. Four apple models with different weights (5.31 g, 6.35 g, 7.16 g, and 8.19 g) were selected to evaluate the minimum detectable response capability of the 3ASD-TET. The experimental results showed that even under a small load of 5.31 g, the 3ASD-TET could still generate a stable and distinguishable output signal. The test setup is shown in Figure S31a. The output voltages of the 3ASD-TET under different small-weight conditions are shown in Figure S31b.

The results indicate that the output voltage gradually increased with increasing weight. Subsequently, the goodness of fit was further evaluated by calculating the coefficient of determination (R^2), as shown in Figure S31c. The R^2 value was 0.996, indicating that the 3ASD-TET also exhibited a significant response capability to small weight signals. To further quantitatively evaluate the prediction accuracy of the weight detection results, the actual weights were statistically compared with the predicted weights obtained based on the output signals of the 3ASD-TET, and the results were presented as the mean $\pm$ standard deviation. As shown in Figure S31d, the predicted weights of apple models with different weights were basically consistent with the actual weights, with only small deviations, demonstrating that the sensor can accurately distinguish different small-weight loads and achieve reliable weight prediction. These results further demonstrate the application potential of the 3ASD-TET in small-weight fruit detection and quantitative weight evaluation.

Next, we applied the 3ASD-TET for fruit weight estimation. We selected four apples of different weights and recorded their actual weights using an electronic scale, as shown in Figure S32(a). Subsequently, we conducted a test to evaluate the weight estimation capability of the 3ASD-TET for apples. The testing scenario is shown in Figure 5(j). During the measurement, the output of the 3ASD-TET is shown in Figure S32(b), and the trend of its output signal is consistent with that in Figure S30(b). Figure 5(k) shows the corresponding results of the 3ASD-TET output voltage and apple weight.

The results show that as the weight of the apple increases, the tangential force signal generated by the 3ASD-TET gradually increases. This trend is consistent with the test results of the weight (Figure S30(d)). Subsequently, we performed a weight-voltage fitting by comparing the actual weight of the apple with the output voltage signal of the 3ASD-TET, as shown in Figure 5(l). The goodness of fit was evaluated by calculating the coefficient of determination (R^2). The results indicate that the coefficient of determination is 0.995, further validating the 3ASD-TET's capability to estimate the weight of the apple.

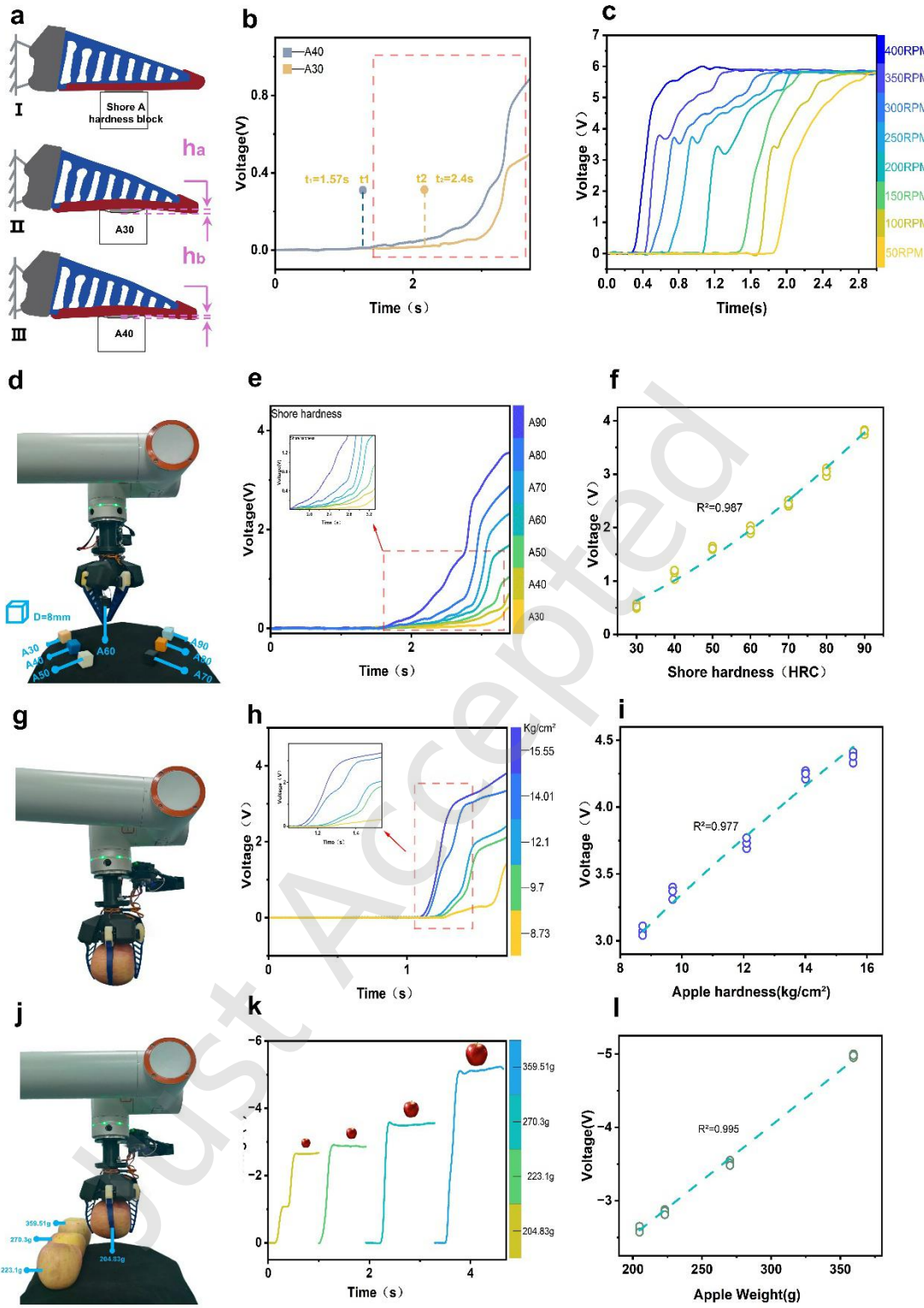


Figure 5. The perception of fruit firmness and weight is achieved by analyzing the variations in the normal and tangential forces of the 3ASD-TET over time. (a) The indentation depth produced by the same normal force on blocks of different hardness ($h_a = 1.2$ mm, $h_b = 1.1$ mm, $h_a > h_b$, depending on the hardness of the object). (b) The time response of the voltage signal output by the 3ASD-TET in the normal force when gripping blocks of different hardness (under the same gripping force, A30 response time = 2.4s, A40 response time = 1.57s). (c) Response rate of the device's output voltage over time under different closing speeds. (d) The testing scenario for evaluating the hardness estimation capability of the 3ASD-TET using seven blocks of different hardness. (e) The time response of the voltage signal output by the 3ASD-TET in the normal direction for seven blocks of different hardness. (f) The fitting relationship between block hardness and the 3ASD-TET output signal. (g) The testing scenario for measuring apple firmness using the 3ASD-TET. (h) The time response of the voltage signal

output by the 3ASD-TET in the normal direction for apples with different harvesting cycles. (i) The fitting relationship between apple firmness and the 3ASD-TET output signal. (j) The experimental scenario to verify the weight perception capability of the 3ASD-TET for apples. (k) The tangential voltage signal output by the 3ASD-TET for apples of different weights. (l) The fitting curve for the relationship between apple weight and tangential force signal.

2.7 The robotic soft gripper with integrated tactile units performs nondestructive harvesting and quality inspection in the orchard

We designed a practical harvesting experiment to apply the robotic soft gripper tactile perception strategy proposed in this paper to a fruit-harvesting robot in the orchard. As shown in Figure 6a, this experiment was conducted to verify the practical application potential of the tactile unit integrated perception strategy.

The harvesting robot mainly consists of a soft robotic gripper integrated with tactile perception, an autonomous mobile platform (OS-lite by YuHesen), a multi-degree-of-freedom robotic arm (FR5 robotic arm by Faoywei), and signal acquisition and communication modules. The three-axis force tactile sensors mounted on the fingers of the soft robotic gripper are used to perceive contact force signals in real time during the harvesting process. These signals are collected by an NI USB-6009 data acquisition card and then wirelessly transmitted to a computer via Wi-Fi for further processing (Figure 6b). It is worth noting that the 3ASD-TET itself does not require an external power supply, whereas the signal acquisition and processing modules still need external power. According to the technical specifications of the NI USB-6009, under a 5 V power supply, its typical and maximum power consumptions are approximately 0.40 W and 2.50 W, respectively. When powered by a 10000 mAh power bank, the system can theoretically operate continuously for approximately 78.6 h under typical power consumption conditions and approximately 12.6 h under the maximum load condition (Figure S32). To ensure the stable operation of this system, a low-power acquisition circuit strategy will be developed in future work to further improve its long-term outdoor application capability.

The apple harvesting process is entirely autonomously performed by the harvesting robot, with the actual harvesting scenario shown in Figure 6c. The single apple harvesting process is divided into three stages, as shown in Figure 6d. Step 1 involves the robotic soft gripper gripping the apple, with the fingers gradually bending and deforming until the apple is tightly grasped. Step 2 is the apple-harvesting stage, during which the robotic soft gripper, driven by the multi-degree-of-freedom robotic arm, separates the fruit from

the branch. Step 3 is the release stage for apple. After the fruit is harvested, the robotic soft gripper places the apple into a collection box with the palm facing downward, completing one harvesting cycle by the robot. During the single harvesting process, the gripping force, fruit firmness, and weight are simultaneously measured in all three stages.

The fruit firmness measurement is completed in step 1. As the fingers gradually bend and deform, the normal force between the fingers and the apple increases over time. By analyzing the time-dependent response of the output voltage signal of the 3ASD-TET in the normal direction, the firmness of the fruit can be measured. The experimental results, shown in Figure 6d (I), indicate that the firmness measurements based on the 3ASD-TET are consistent with those obtained from a firmness tester (50 apples (variety: Fuji) were collected on-site, with an average error of 0.374). The dynamic measurement of gripping force is completed in step 2. The robotic soft gripper, driven by the robotic arm, separates the fruit from the branch by pulling and twisting, achieving apple harvesting. At this point, the apple experiences both normal and tangential forces. To prevent the robotic soft gripper from causing compressive damage to the apple. The normal and tangential forces applied by the robotic soft gripper are continuously monitored to ensure that the final gripping force remains below the safety threshold (18N). Figure 6d (II) shows an analysis of apple damage after harvesting. Methylene blue solution was used to stain the flesh, with the edges of the apple appearing light blue, indicating no damage to the fruit. This indicates that the 3ASD-TET can reliably and accurately detect changes in gripping force during the actual harvesting process.

The fruit weight measurement is completed in step 3. After harvesting is completed, during the robotic soft gripper's placement of the apple into the collection box, the fruit weight is measured by analyzing the tangential output voltage signal from the 3ASD-TET, as shown in Figure 6d (III). The results show that the fruit weight estimated by the 3ASD-TET is consistent with the actual weight of the fruit (50 apples (variety: Fuji) were collected on-site, with an average error of 0.4875). This indicates that the 3ASD-TET can accurately and rapidly estimate the fruit weight in practical applications.

It is noteworthy that during the single harvesting process, the gripping force, fruit firmness, and weight information of the robotic soft gripper can be processed and displayed in real-time on a computer, as shown in Figure 6e. The results of the practical harvesting experiment demonstrate that the robotic soft gripper sensing strategy, integrated with the tactile unit proposed in this paper, can simultaneously perceive the gripping force and multiple fruit qualities during a single

harvesting process. This enables non-destructive harvesting and quality detection of fruit in the orchard. Compared to the current quality grading process in the plant. The application of this sensing strategy will significantly reduce fruit damage and effectively minimize economic losses and waste risks in the fresh fruit harvesting process.

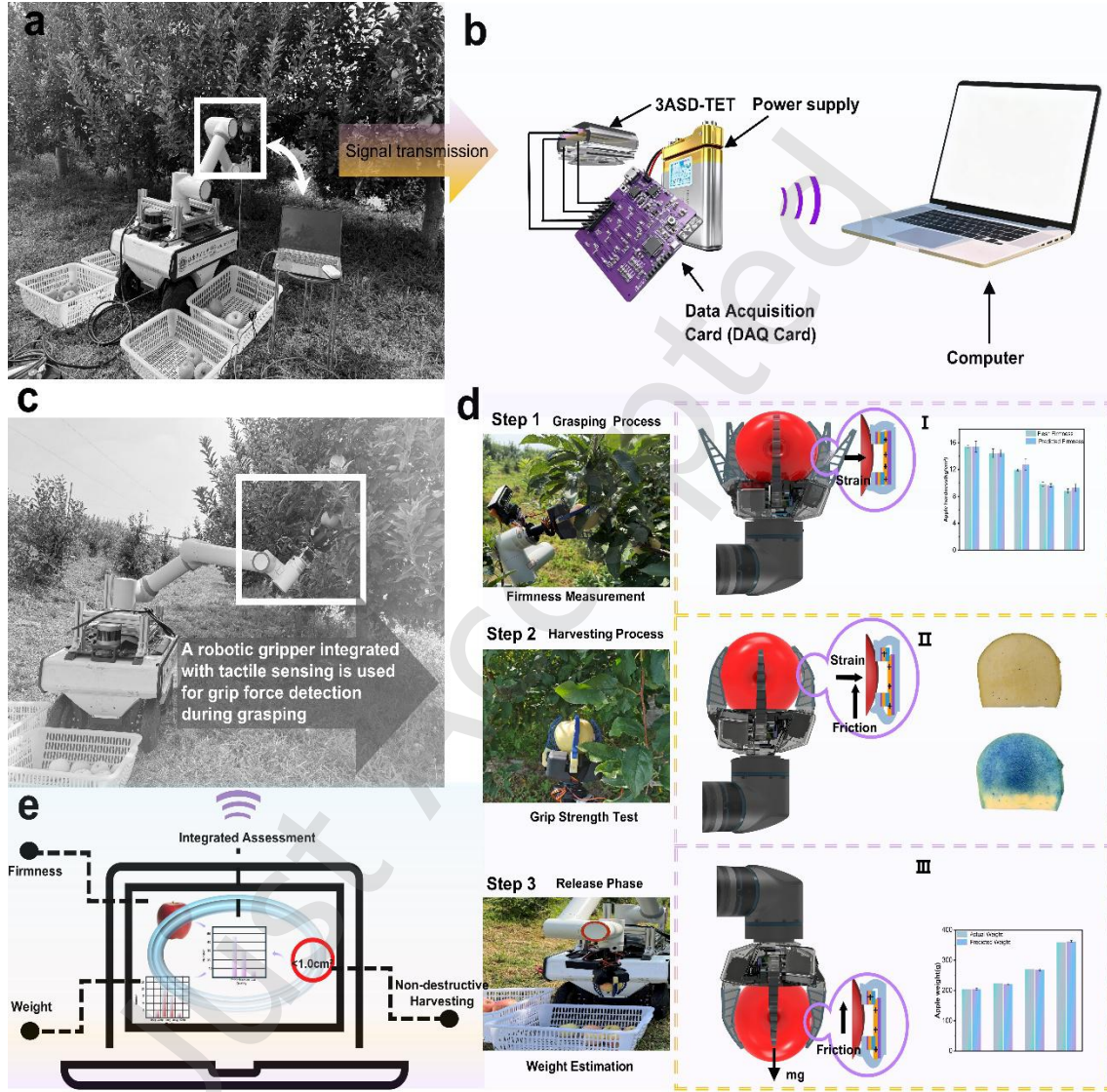


Figure 6. Application of the robotic soft gripper sensing strategy integrated with the tactile unit in on-site apple harvesting. (a) On-site harvesting scenario. (b) Signal acquisition, transmission, and processing of the tactile sensing unit. (c) Single apple harvesting process. (d) Three stages of the single harvesting process and the integration scheme with the robotic soft gripper sensing strategy. (I) Grasping stage: fruit firmness measurement is completed, and the control group fruit firmness is measured using a firmness tester. (II) Harvesting stage: dynamic gripping force measurement is completed. Fruit damage identification is performed using methylene blue solution staining. (III) Release stage: fruit weight measurement is completed, and the control group fruit weight is measured using an electronic scale. (e) Output values of fruit firmness, weight, and gripping force.

3 Discussion

In this study, we propose an octopus-sucker-inspired triboelectric self-decoupled three-axis force tactile sensing strategy and apply it to a soft robotic gripper to achieve non-destructive fruit harvesting and in-field quality assessment within a single robotic operation process. By embedding the 3ASD-TET into the flexible fingers, the soft robotic gripper can dynamically sense the normal force and Tangential force at the fruit–grripper contact interface. This enables fruit hardness to be evaluated based on the normal force–time response during the grasping stage, compression-induced fruit damage to be reduced by monitoring the gripping force during the harvesting stage, and fruit weight to be estimated based on the balance relationship between Tangential force and gravity during the placement stage.

The core contribution of this work lies in the biomimetic structural decoupling design of the 3ASD-TET. By integrating the vertical contact–separation mode and horizontal sliding mode of triboelectric nanogenerators into an octopus-sucker-like tactile sensor, the sensor can independently respond to normal and Tangential mechanical stimuli and output three spatially decoupled electrical signals. This mechanism enables reliable three-axis force-sensing without relying on complex signal coupling correction, providing a stable tactile perception interface for soft robotic grippers operating under dynamic harvesting conditions.

The integration of the 3ASD-TET with the soft robotic gripper further demonstrates the feasibility of advancing fruit quality assessment from the traditional in-plant sorting stage to the in-field harvesting stage. Through the synergistic interaction between the compliant fingers and the three-axis tactile sensor, the soft robotic gripper can achieve fruit grasping, hardness evaluation, damage prevention, and weight estimation within a unified process. This strategy is expected to reduce the dependence on separate postharvest grading systems, simplify the harvesting–grading process, and help decrease handling-induced fruit damage and postharvest losses.

Nevertheless, the current study still has certain limitations. Since the 3ASD-TET relies on both vertical contact–separation and horizontal sliding triboelectric working modes, long-term high-frequency reciprocating operation may cause friction layer wear, contact interface variations, and surface charge attenuation, leading to a certain degree of

output degradation or sensitivity drift. Therefore, future studies will further optimize the friction layer materials and device structure, for example, by introducing wear-resistant or protective coatings and improving the surface microstructure and charge retention capability, to reduce frictional wear and sensitivity drift and enhance long-term reliability. In addition, the current tactile sensor mainly detects force-related information, while the perception of surface texture, roughness, and more complex contact states still needs further development. The experimental validation in this study was mainly conducted using apples, and broader tests on more fruit and vegetable samples with different shapes, surface textures, and mechanical properties are still needed. Future work will also further improve signal analysis methods to enhance the long-term stability, robustness, and generalization capability of this strategy in complex agricultural harvesting environments.

Overall, by integrating three-axis force sensing, non-destructive harvesting, and in-field quality assessment, this work provides a biomimetic tactile sensing pathway for intelligent agricultural robots. The proposed strategy offers a promising approach for simplifying the fresh fruit supply chain, reducing postharvest damage and food loss, and improving the intelligence and reliability of robotic harvesting systems.

4 Method

4.1 Preparation of 3ASD-TET

3ASD-TET is fabricated using a silicone rubber casing, copper foil friction electrodes, PTFE as the friction material, and PVC as the supporting component. First, the bottom friction layer is formed by bonding a 100 μ m thick PTFE film to the copper foil, with wires welded onto the copper foil. Then, both components are bonded onto PVC to form the bottom friction layer. The top friction layer consists of copper foil bonded to the PVC, with wires welded onto the copper foil to form the top copper electrode. The casing and suction cup of the 3ASD-TET are formed by proportionally blending Ecoflex oligomer. Silicone rubber solutions A and B (Ecoflex-00-30) are mixed in a 1:1 weight ratio and poured into a 3D-printed mold. The mixture is then subjected to a curing process for 4 hours. The top copper electrode layer is then encapsulated on the upper surface of the Ecoflex casing using adhesive, while the bottom friction layer is encapsulated on the lower surface. The fabricated cavity shell (15mm x 14mm x 5mm) and suction cup (12mm x 12mm x 1mm) are

then bonded together and placed at room temperature for two hours. Following this procedure, the 3ASD-TET with dimensions of 15mm x 14mm x 6mm is completed.

4.2 Simulation Experiment on Stress Analysis of Robotic soft gripper Grasp and the Effect of Apple Hardness on Its Deformation

First, a 3D model of the four-finger robotic soft gripper and the apple is constructed using SolidWorks (2022). The model is then imported into ANSYS (2021) for explicit dynamic finite element analysis. The simulation models the bending deformation process when the robotic soft gripper grasps the apple under an 18 N gripping force. The meshing settings are as follows: the robotic soft gripper uses tetrahedral elements with a size of 4 mm, and the apple uses hexahedral dominant elements with a size of 5 mm. The total deformation contour plot is shown in Figure S9.

To investigate the effect of apple hardness on the deformation of the robotic soft gripper, further simulations were conducted in which the robotic hand grasps apples with maturities of 70%, 80%, and 90% under a force of 18 N (maturity is determined based on soluble solid content). In this set of simulations, both the robotic soft gripper and the apple are meshed with elements of 2 mm in size, where tetrahedral elements are used for the robotic soft gripper and hexahedral dominant elements for the apple. The mesh quality index (Quality Index) is set to 0.02. The corresponding total deformation contour plot is shown in Figure S15.

Data Availability

Data will be made available on request.

Acknowledgments

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Declaration of Competing Interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Contributions

Linlin Sun: Investigation, Writing-original draft. Zhengwen Chen: Investigation, Writing-original draft. Zeshuo Wang: Investigation. Yufeng Li: Investigation. Zixu Chen: Methodology, Conceptualization. Mingyang Lu: Methodology, Conceptualization. Haidi Chu: Methodology, Conceptualization. Xianglong Liu: Methodology, Conceptualization. Linlong Jing: Conceptualization. Xinpeng Cao: Conceptualization. Yongxian Wang: Methodology, Conceptualization. Shenghui Fu: Conceptualization. Shuangxi Liu: Conceptualization. Shuo Kang: Conceptualization. Jing Wang: Writing-original draft. Hongjian Zhang: Conceptualization, Writing-review. Jinxing Wang: Conceptualization, Supervision. Wei Tang: Conceptualization, Writing-review & editing, Supervision.

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Electronic Supplementary Material

An octopus-sucker inspired triboelectric self-decoupling three-axis force-sensing strategy

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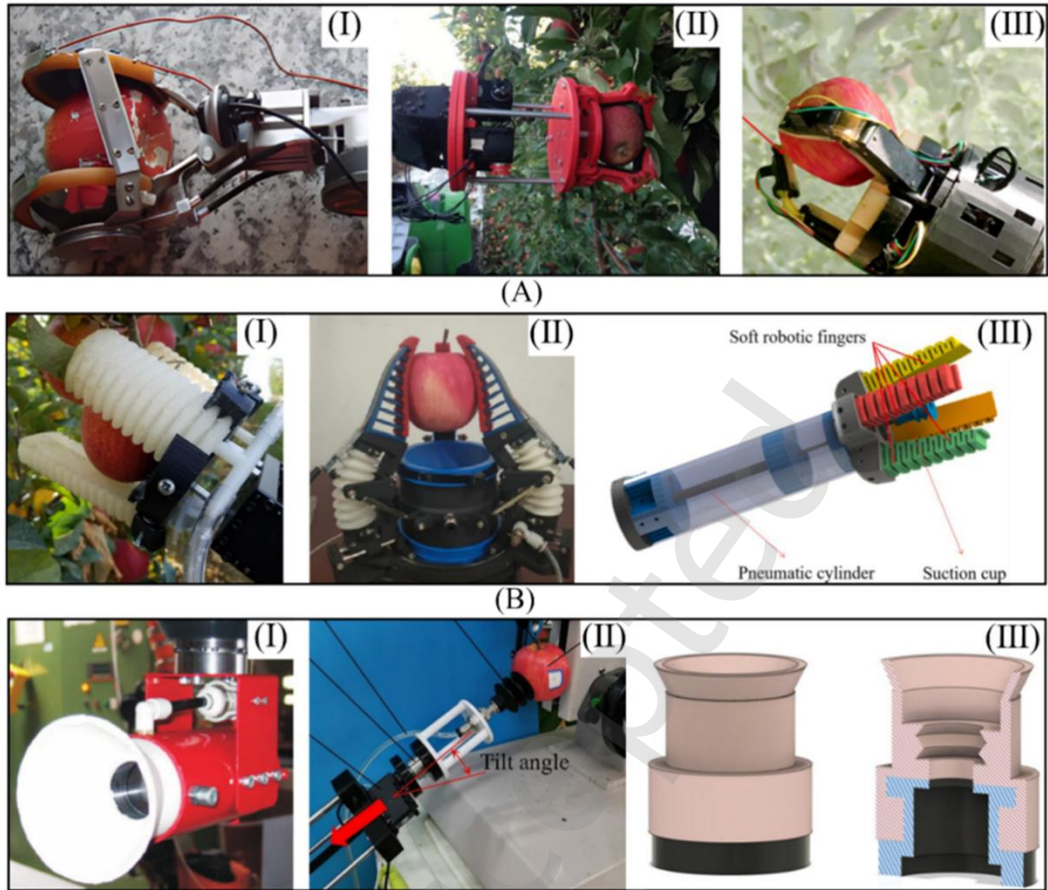


Figure S1. Representative applications of different types of robotic grippers in agricultural harvesting robots. Robotic grippers used for fruit harvesting can be classified into vacuum-, hydraulic-, pneumatic-, and electrically driven types according to their actuation mechanisms. According to the number and structure of fingers, soft tactile grippers can also be divided into two-finger, three-finger, and four-finger configurations. Owing to their structural compliance and adaptability to irregular fruit surfaces, soft robotic grippers have become promising end-effectors for reducing harvesting-induced fruit damage.

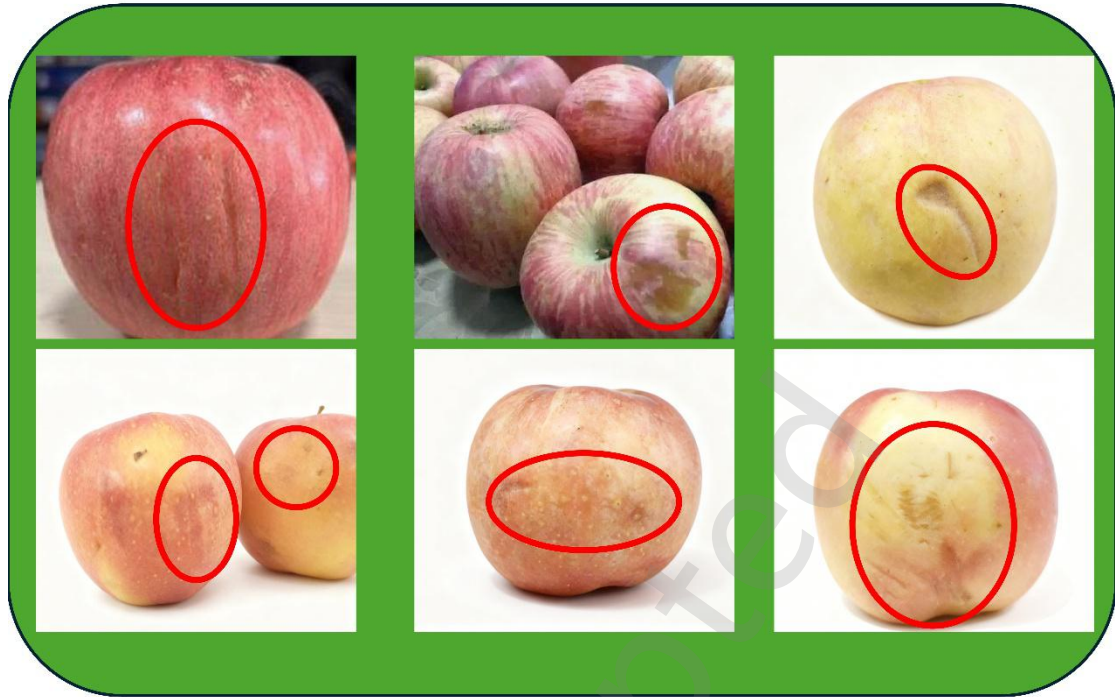


Figure. S2: Representative examples of apple surface damage caused by improper gripping or mechanical handling. During robotic harvesting, excessive gripping force, unstable contact, local stress concentration, or fruit slip may lead to bruising, indentation, and surface defects. These damage phenomena highlight the need for real-time tactile feedback and nondestructive force regulation during soft robotic gripping.

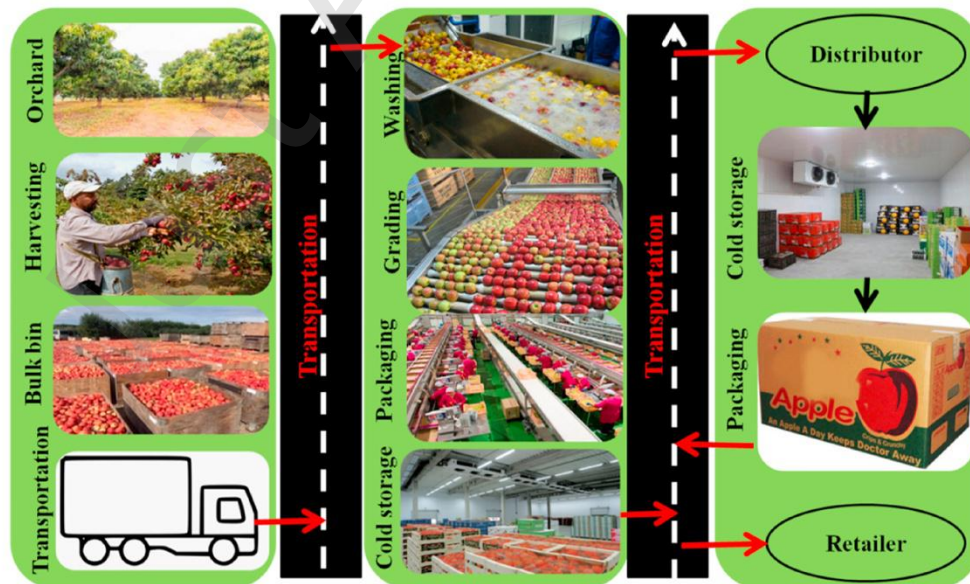


Figure. S3: Schematic illustration of the conventional apple quality sorting process after harvesting^[2]. Apples usually undergo multiple postharvest stages, including orchard harvesting, transportation, washing, grading, packaging, cold storage, distribution, and retail. Collision, compression, and repeated mechanical handling

during these in-plant and postharvest processes may cause additional fruit damage, indicating the importance of advancing fruit quality assessment to the in-field harvesting stage.

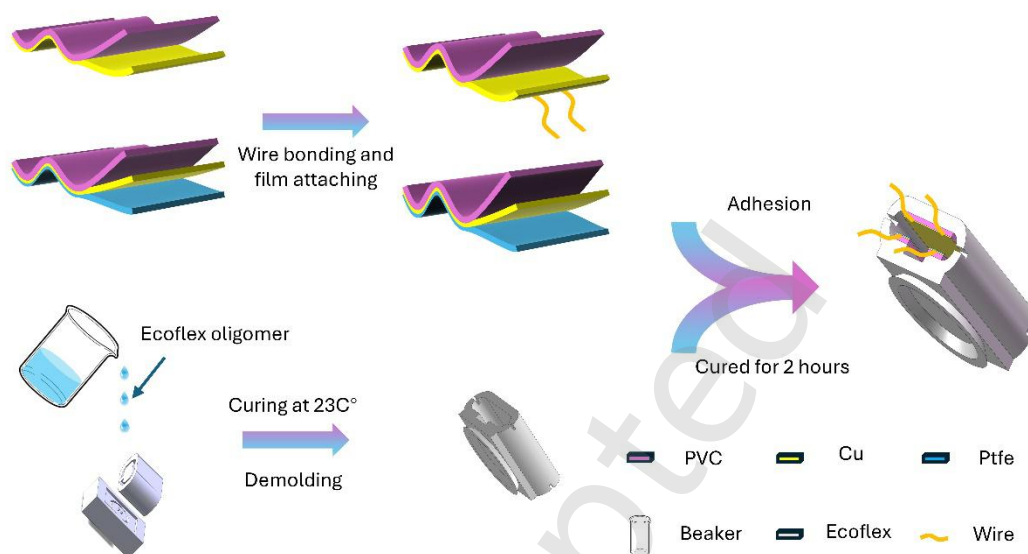


Figure. S4 : The production process of 3ASD-TET.

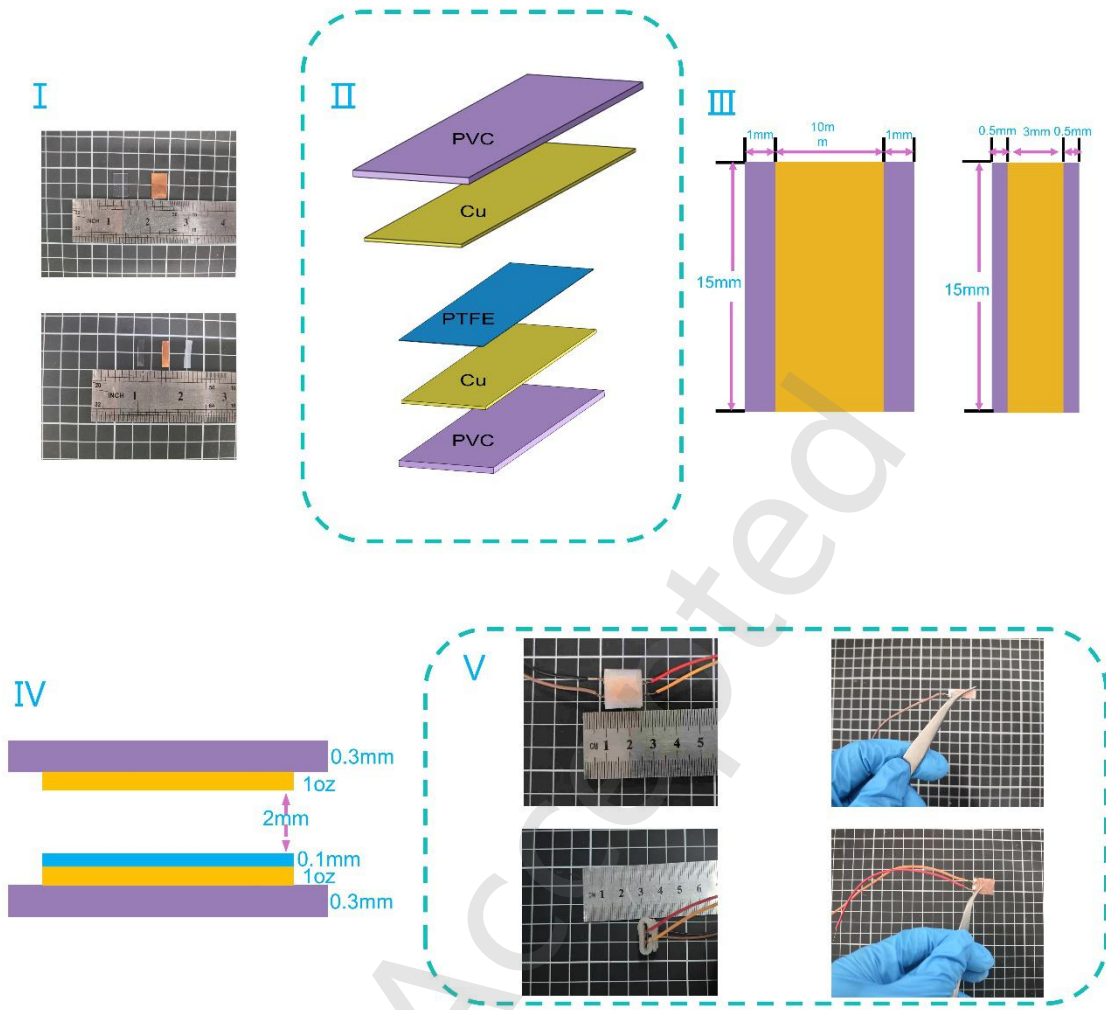


Figure. S5 : Internal dimension information of the 3ASD-TET. (I) Fabrication dimensions of the top and bottom triboelectric electrodes; (II) Schematic diagram of the selected materials for the triboelectric electrodes; (III) Schematic diagram of the length and width dimensions of the triboelectric electrodes; (IV) Schematic diagram of the internal structure of the 3ASD-TET; (V) Actual dimensions of the 3ASD-TET;

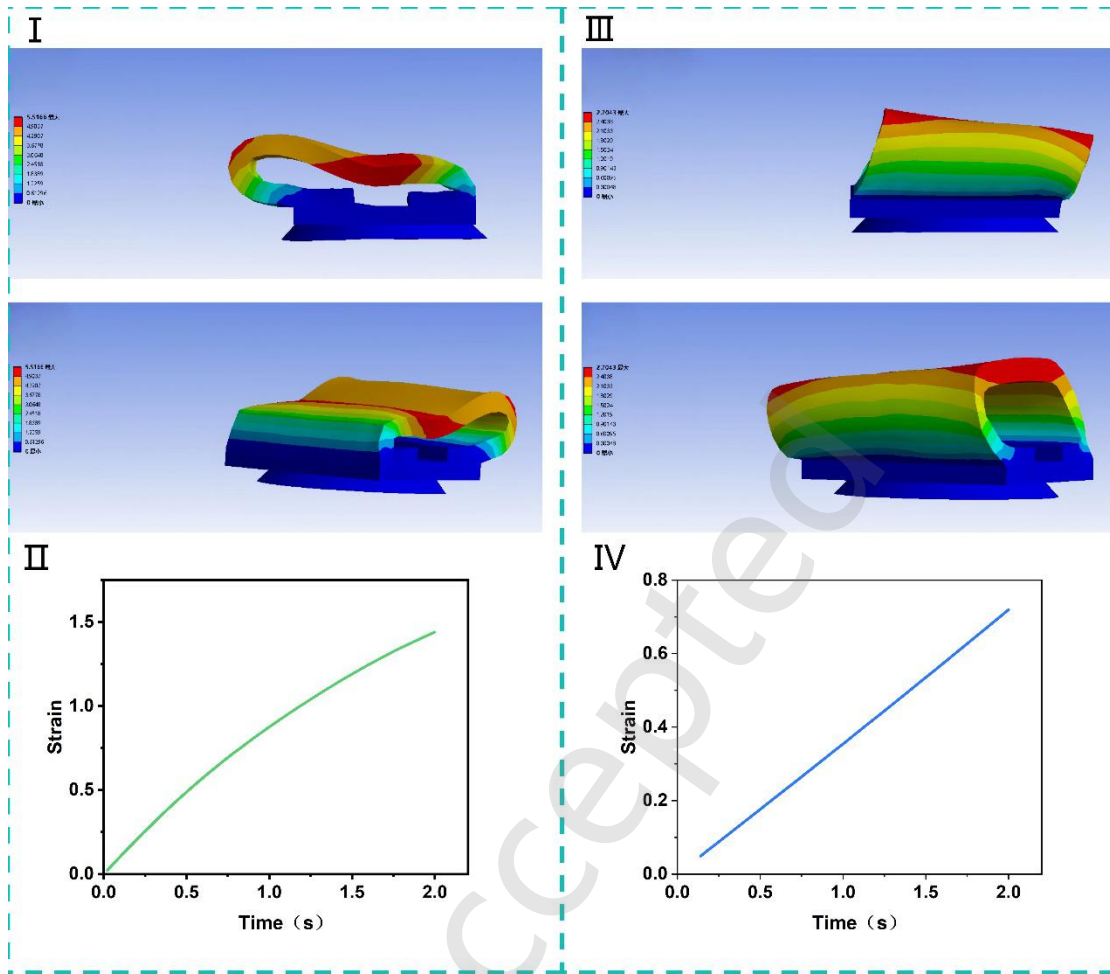


Figure. S6 : Finite element static analysis of the 3ASD-TET structure. (I) The total deformation of the 3ASD-TET along the X-axis (Figure 2c) under a 9N force; (II) The deformation of the 3ASD-TET; (III) The total deformation of the 3ASD-TET along the Y-axis (Figure 2c) under a 9N force;(IV) The deformation of the 3ASD-TET along the Y-axis (Figure 2c);

Through finite element static analysis, the shell material was selected as silicone rubber, and a force analysis of the 3ASD-TET along the X and Y axes (Figure 2c) was conducted. A mesh size of 2mm was established. Under the application of the same 9N force, the maximum total deformation along the X-axis was 5.5116, while the maximum total deformation along the Y-axis was 2.7043. The deformation along the X-axis was approximately 1.5, while the deformation along the Y-axis was approximately 0.8. This indicates that under the same tangential force, the tangential force signal along the X-axis is nearly twice that along the Y-axis.

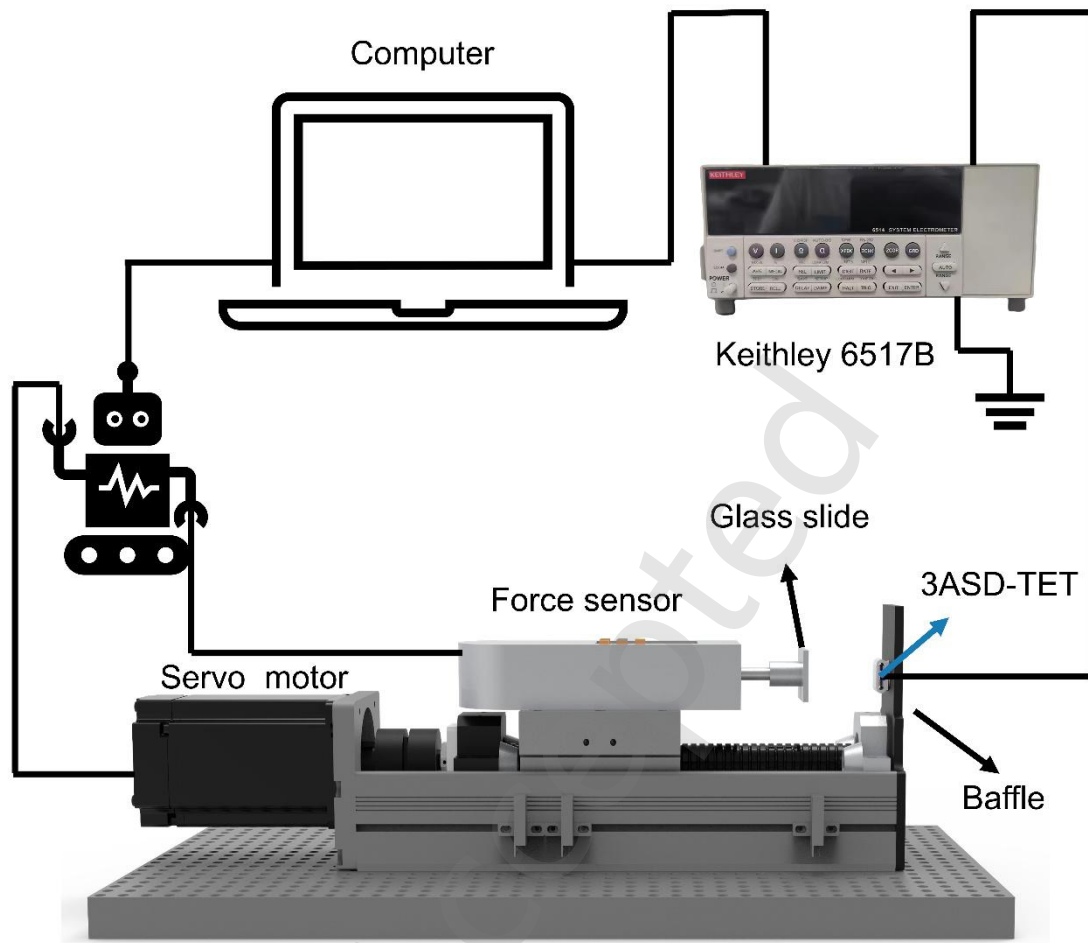


Figure. S7 : Schematic diagram of the 3ASD-TET constant force sensing testing device. The 3ASD-TET is fixed at one end of a screw, and the force sensor is connected to a sliding platform driven by a servo motor. A computer precisely controls the contact gap and applied pressure of the 3ASD-TET, and its output voltage is measured using the Keithley 6517B electrometer, with real-time data displayed via a computer interface.

The 3ASD-TET is attached to a baffle placed horizontally, and a ball screw (FUYU, FSC-2A) driven by a servo motor is used to achieve a contact-separation motion to simulate the normal force along the z-axis. The direction of the baffle and the fixture on the data measurement device are changed to simulate the tangential force along the x-axis. The data measurement device (HANDPI HP-50, range 50 N, accuracy 0.05 N) continuously monitors the force variation in real time. Motion control is based on the Modbus RTU communication protocol, with the controller regulating the motion frequency and feed depth. The open-circuit voltage is collected using the Keithley 6517B electrometer, thereby constructing the constant force testing system.

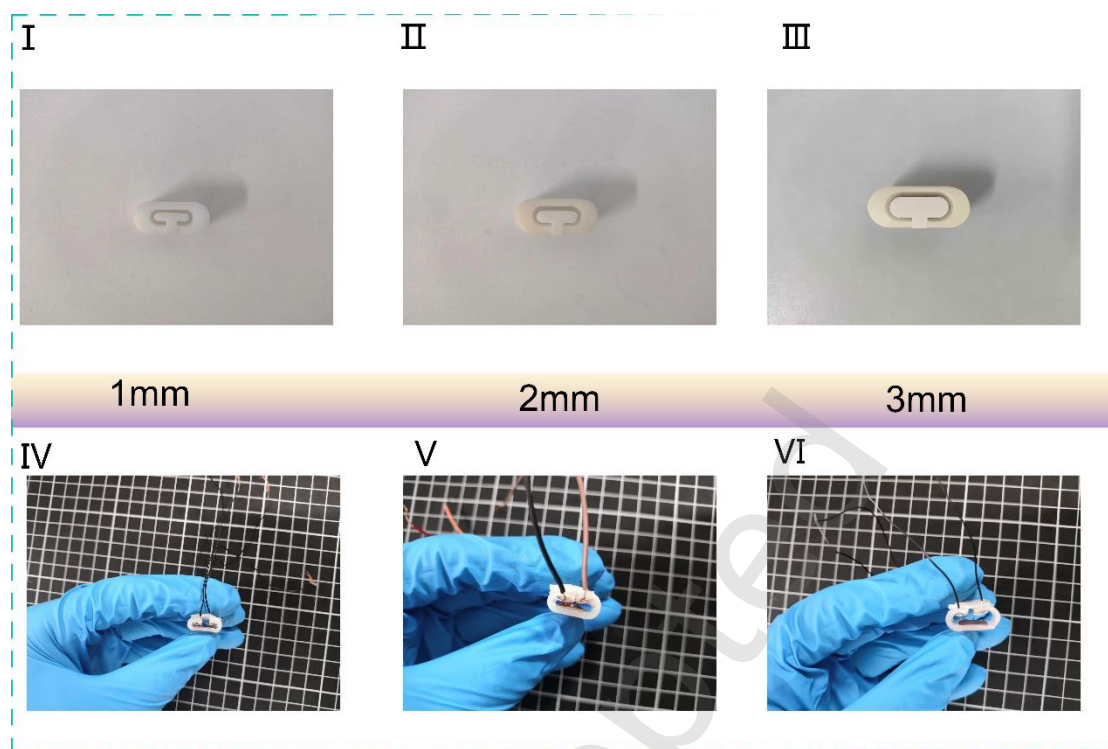


Figure. S8 :(I) 1mm cavity mold produced by 3D printing; (II) 2mm cavity mold produced by 3D printing; (III) 3mm cavity mold produced by 3D printing; (IV) 3ASD-TET with a 1mm gap produced; (V) 3ASD-TET with a 2mm gap produced; (VI) 3ASD-TET with a 3mm gap produced;

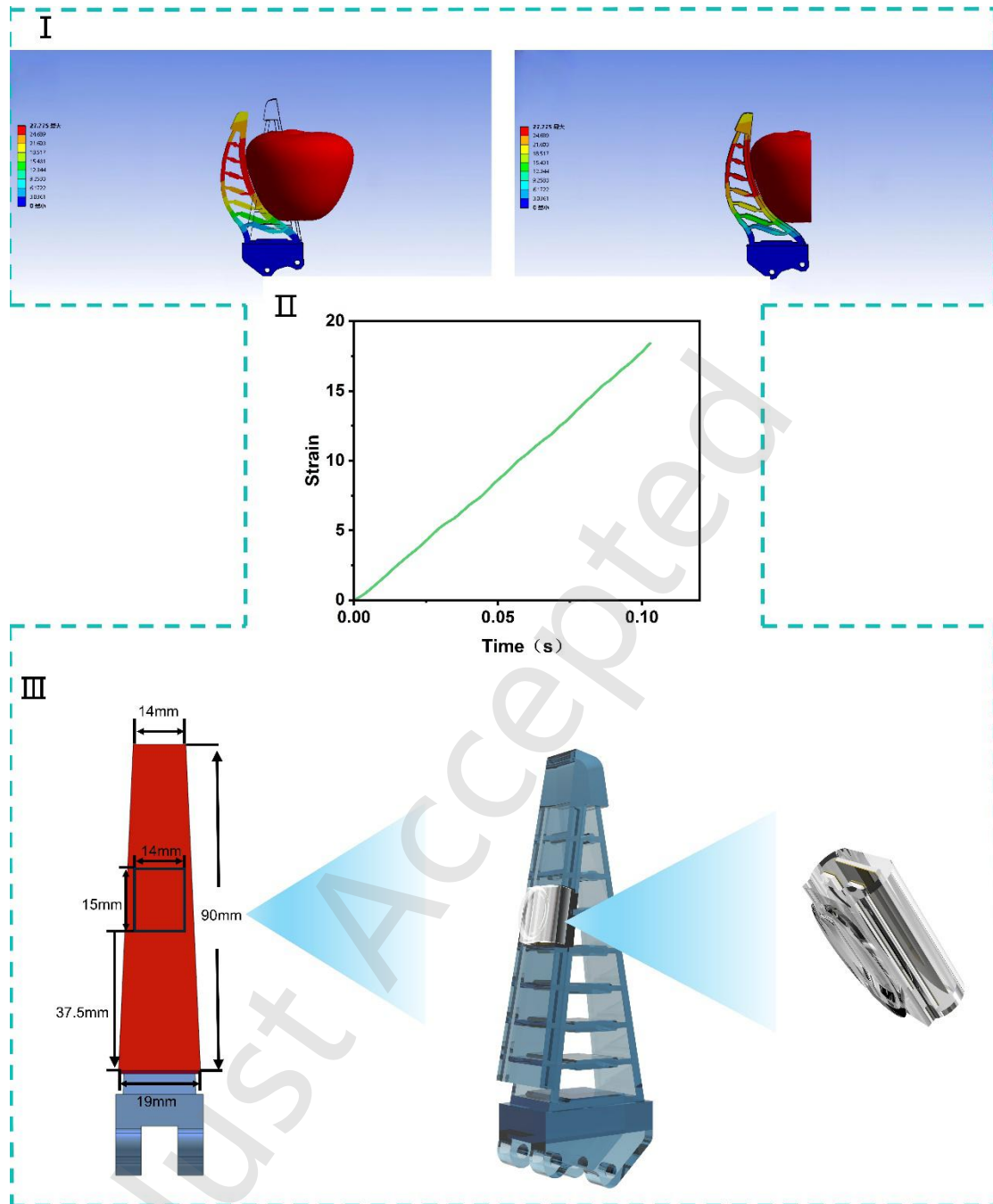


Figure. S9 : Finite element analysis of the soft tactile sensors grasping an apple. (I) Evolution contour plot of the total deformation of the soft tactile sensors while grasping the apple; (II) Total deformation-time graph from the simulation analysis of the soft tactile sensors; (III) Dimension measurement of the soft tactile sensors and layout planning of the 3ASD-TET;

We applied explicit dynamics, with the soft tactile sensors material selected as silicone rubber. The mesh of the soft tactile sensors was divided into 4mm, and the apple's mesh was divided into 5mm. Based on

the simulation results, the maximum stress generated by the soft tactile sensors was 27.775. The deformation and stress were the greatest at the center of the soft tactile sensors.

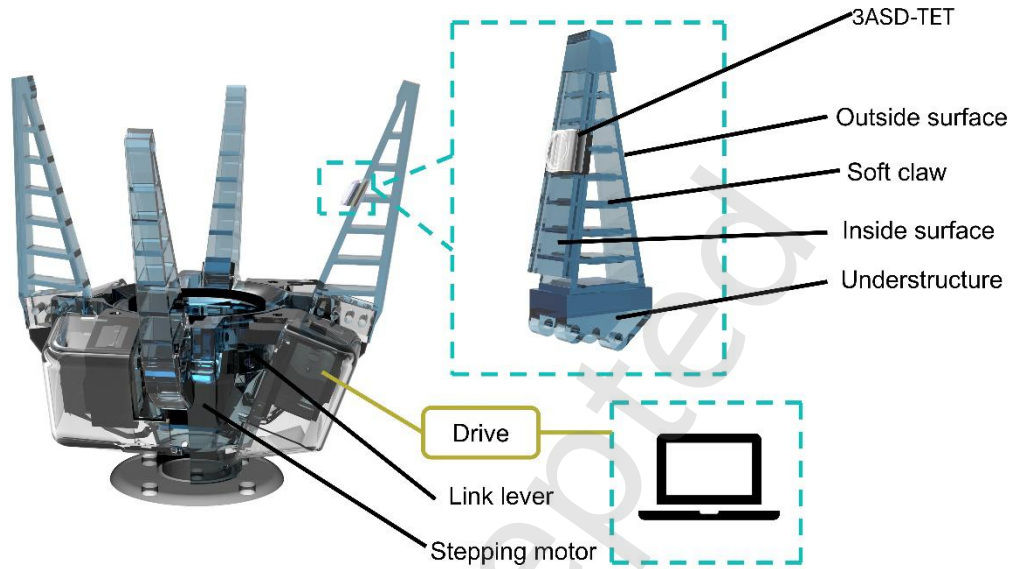


Figure. S10 :Schematic diagram of the 3ASD-TET three-axis force sensor integrated with a soft end effector.

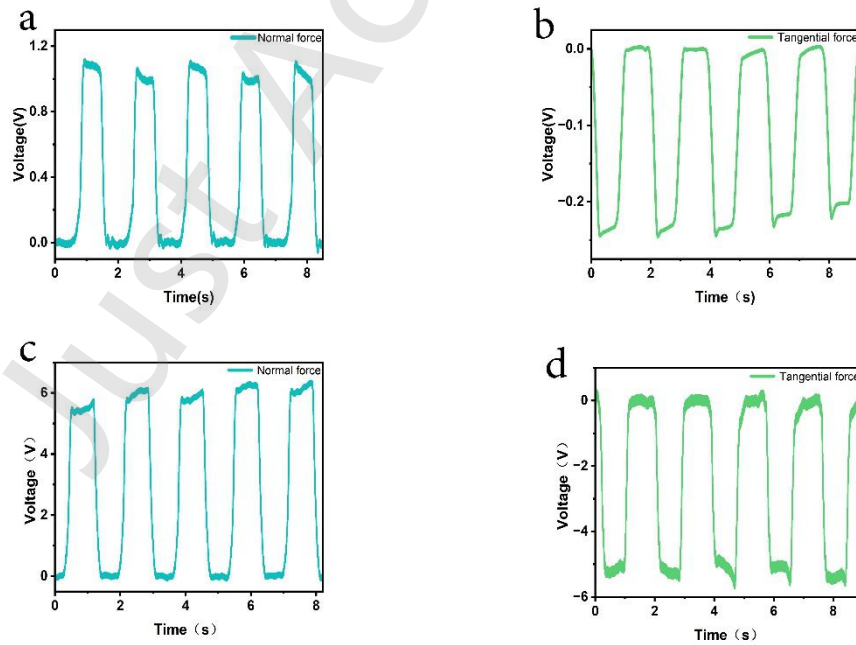


Figure. S11: (a) Voltage signal under a 1N normal force; (b) Voltage signal under a 1N tangential force; (c) Voltage signal under a 20N normal force; (d) Voltage signal under a 20N tangential force;

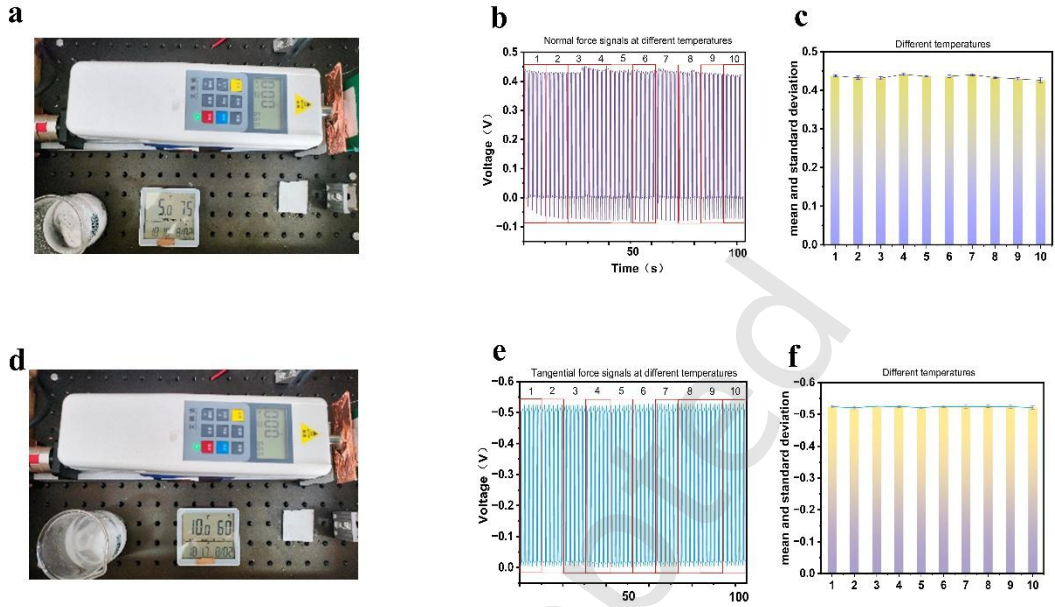


Figure. S12: Stability tests of the device under different temperature conditions.(a, d) Test setup of the device under different temperature conditions.(b) Variation of the device's normal force output signals under different temperature conditions.(c) Mean values and standard deviations of the device's normal force output signals under different temperature conditions.(e) Variation of the device's tangential force output signals under different temperature conditions.(f) Mean values and standard deviations of the device's tangential force output signals under different temperature conditions.

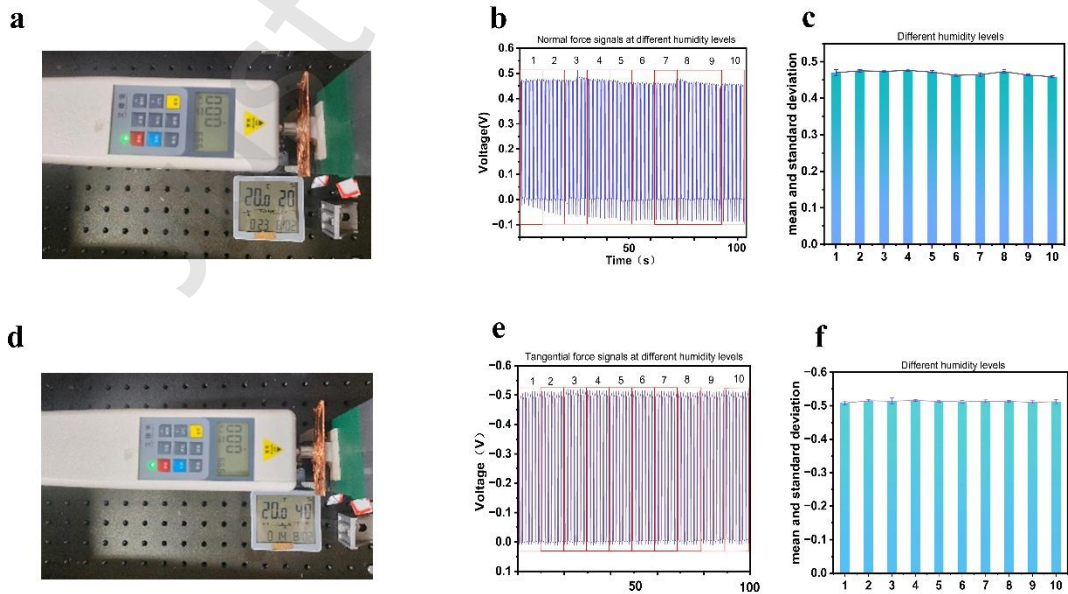


Figure. S13: Stability tests of the device under different humidity conditions.(a, d) Test setup of the device

under different humidity conditions.(b) Variation of the device's normal force output signals under different humidity conditions.(c) Mean values and standard deviations of the device's normal force output signals under different humidity conditions.(e) Variation of the device's tangential force output signals under different humidity conditions.(f) Mean values and standard deviations of the device's tangential force output signals under different humidity conditions.

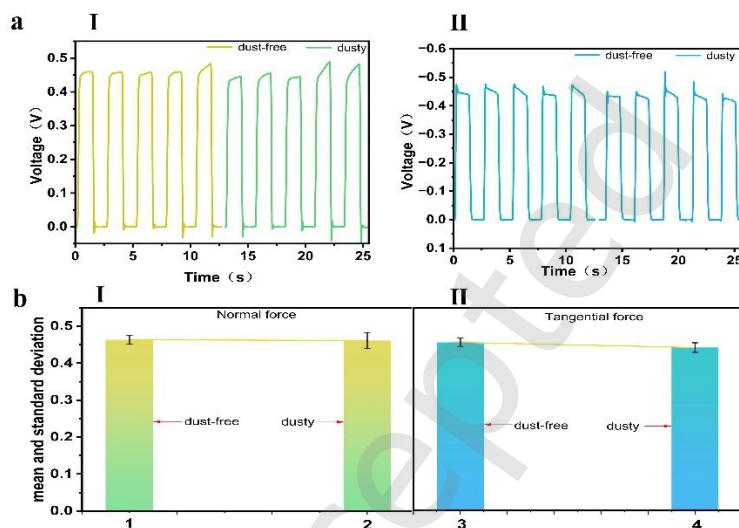


Figure. S14: Stability tests of the device under dust conditions.(a) Variation in the output signals of the device under a dust environment: (I) variation in the normal force signal; (II) variation in the tangential force signal.(b) Mean values and standard deviations of the output signals of the device under a dust environment: (I) mean value and standard deviation of the normal force signal; (II) mean value and standard deviation of the tangential force signal.

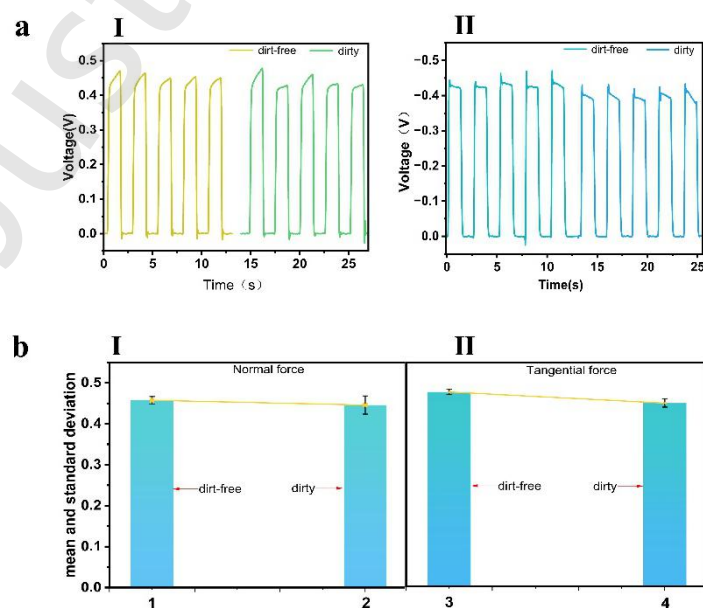


Figure. S15: Stability tests of the device under dirt conditions.(a) Variation in the output signals of the device

under a dirt environment: (I) variation in the normal force signal; (II) variation in the tangential force signal.(b) Mean values and standard deviations of the output signals of the device under a dirt environment: (I) mean value and standard deviation of the normal force signal; (II) mean value and standard deviation of the tangential force signal.

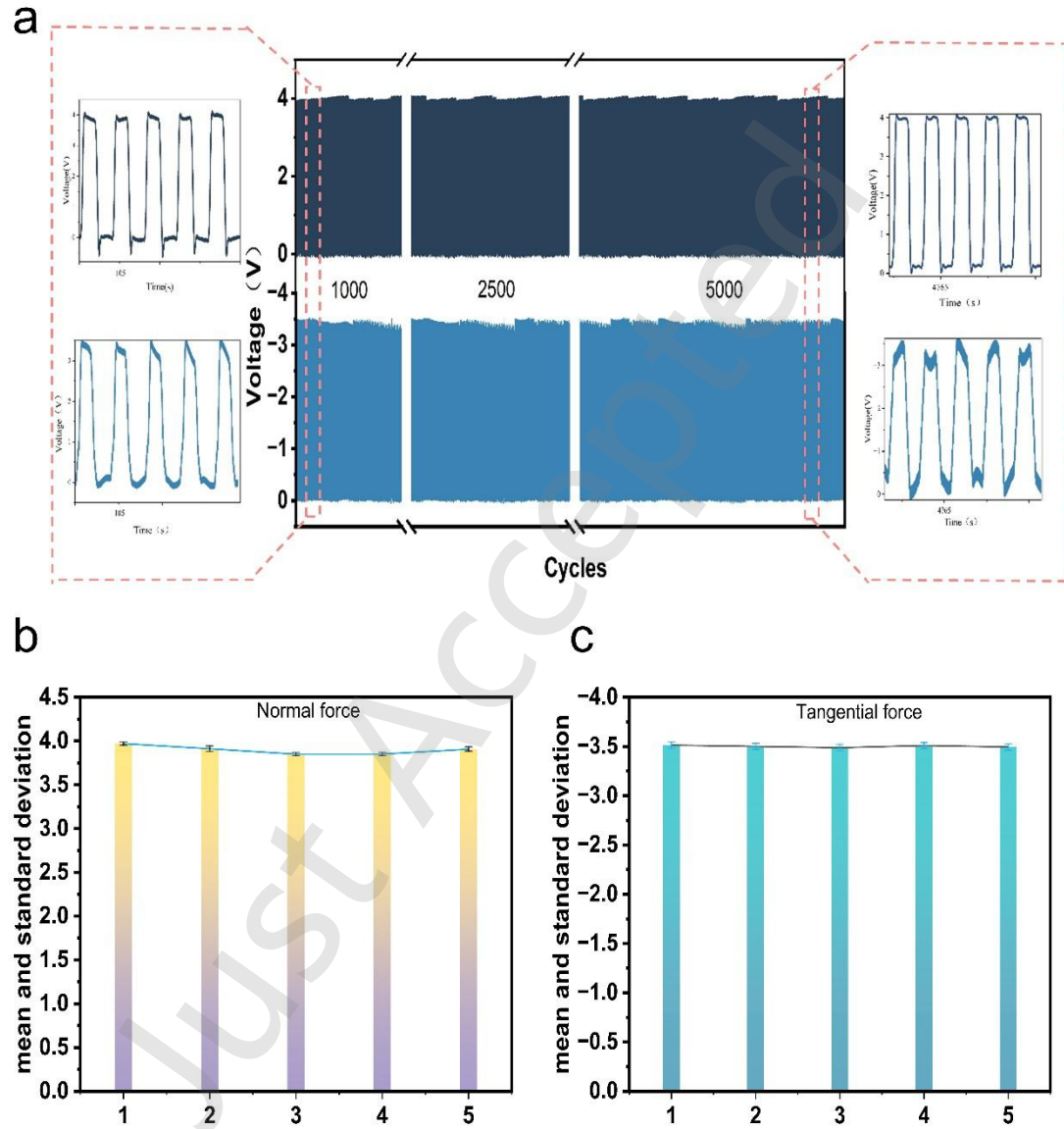


Figure. S16: (a)Output signals of the device's normal force and tangential force during 5000-cycle testing. (b)(c) Mean values and standard deviations of the device's normal force and tangential force signals after 5000 cycles of testing.

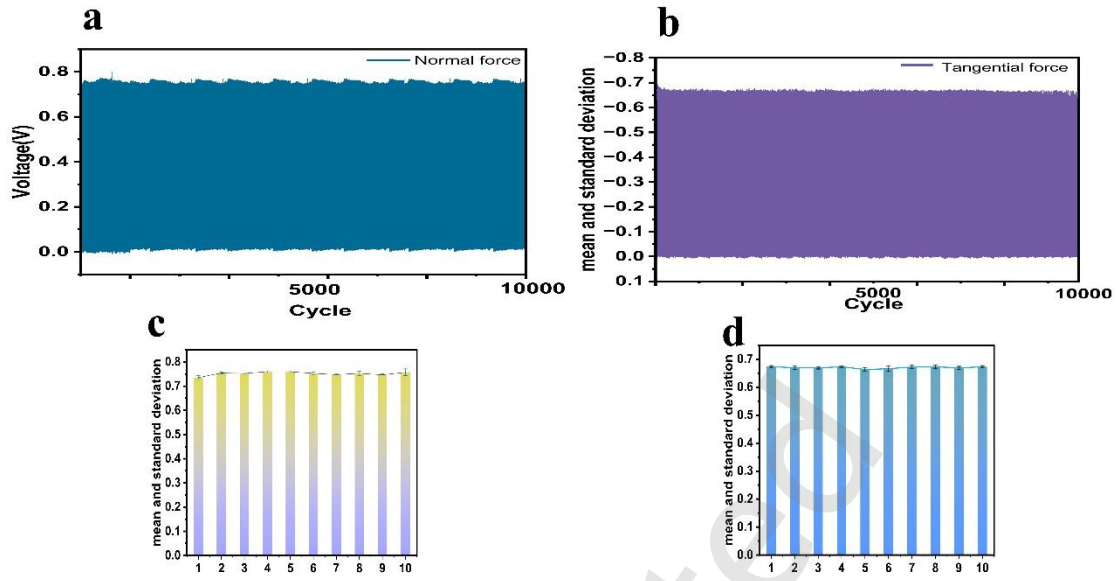
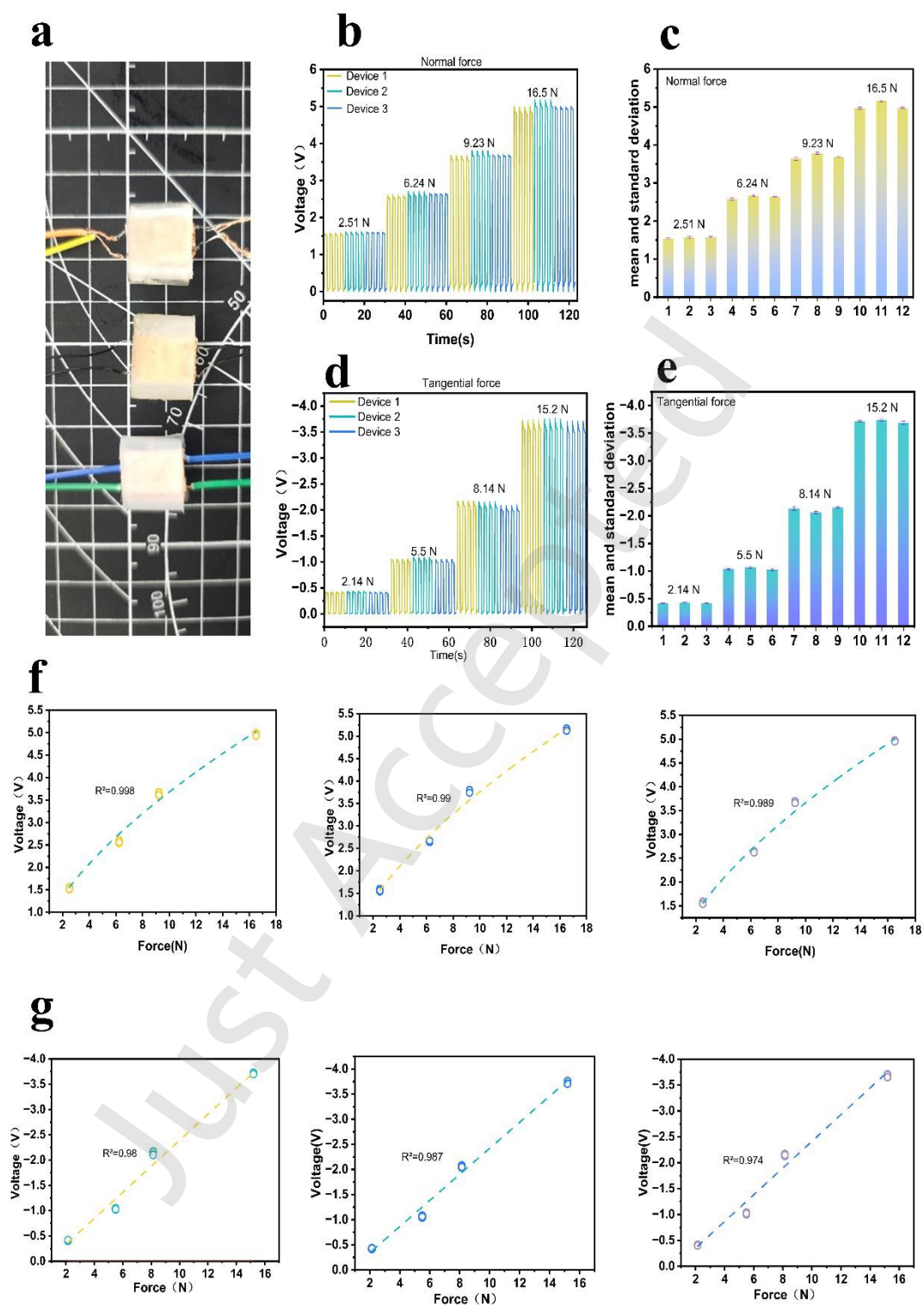


Figure. S17: Output signals, mean values, and standard deviations of the device's normal force and tangential force under 10000 cycles of continuous operation. (a) Normal force output signals of the device during 10000 cycles of continuous operation. (b) Tangential force output signals of cycles. (c) Mean values and standard deviations of the normal force output signals measured every 1000 cycles. (d) Mean values and standard deviations of the tangential force output signals measured every 1000 cycles.



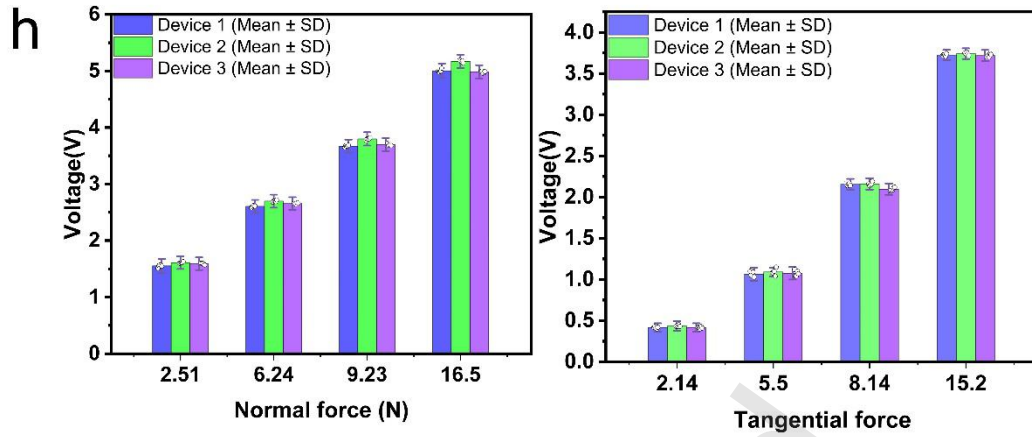


Figure. S18: Normal force and tangential force output signals of three identical devices and their fitting results.(a)Photographs of the three identical device samples.(b) Normal force output voltage signals of the three devices under different applied loads.(c) Mean values and standard deviations of the normal force output signals of the three devices under different applied loads.(d) Tangential force output voltage signals of the three devices under different applied loads.(e) Mean values and standard deviations of the tangential force output signals of the three devices under different applied loads.(f) Fitting results of the normal force output voltage signals for the three devices under different loads.(g) Fitting results of the tangential force output voltage signals for the three devices under different loads.(h) Output responses of three devices under different normal force and Tangential force loadings. The bars represent the average output voltages, and the error bars represent the standard deviations.

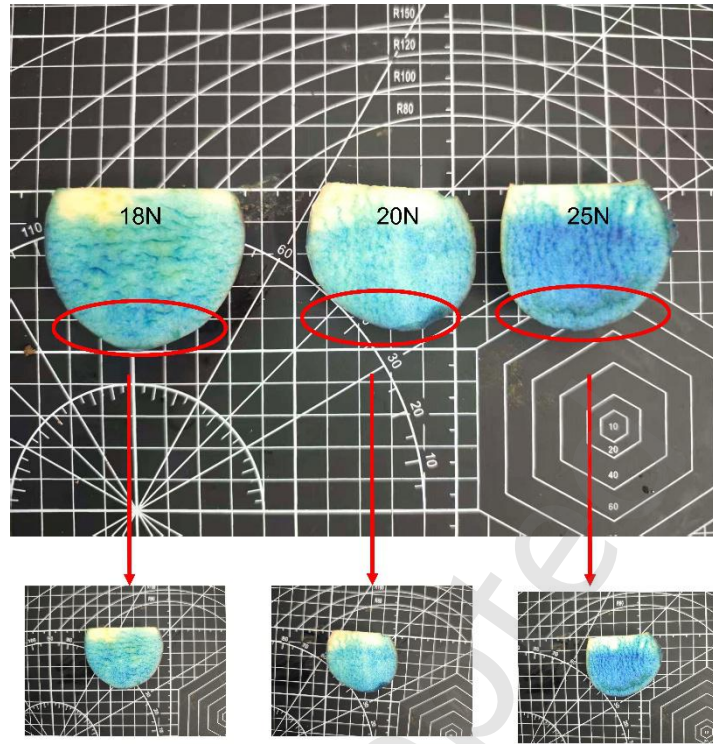


Figure. S19: Apple grasping tests were conducted under different gripping forces (18 N, 20 N, and 25 N), and the methylene blue staining method was used to identify and evaluate surface and internal damage to the fruit.

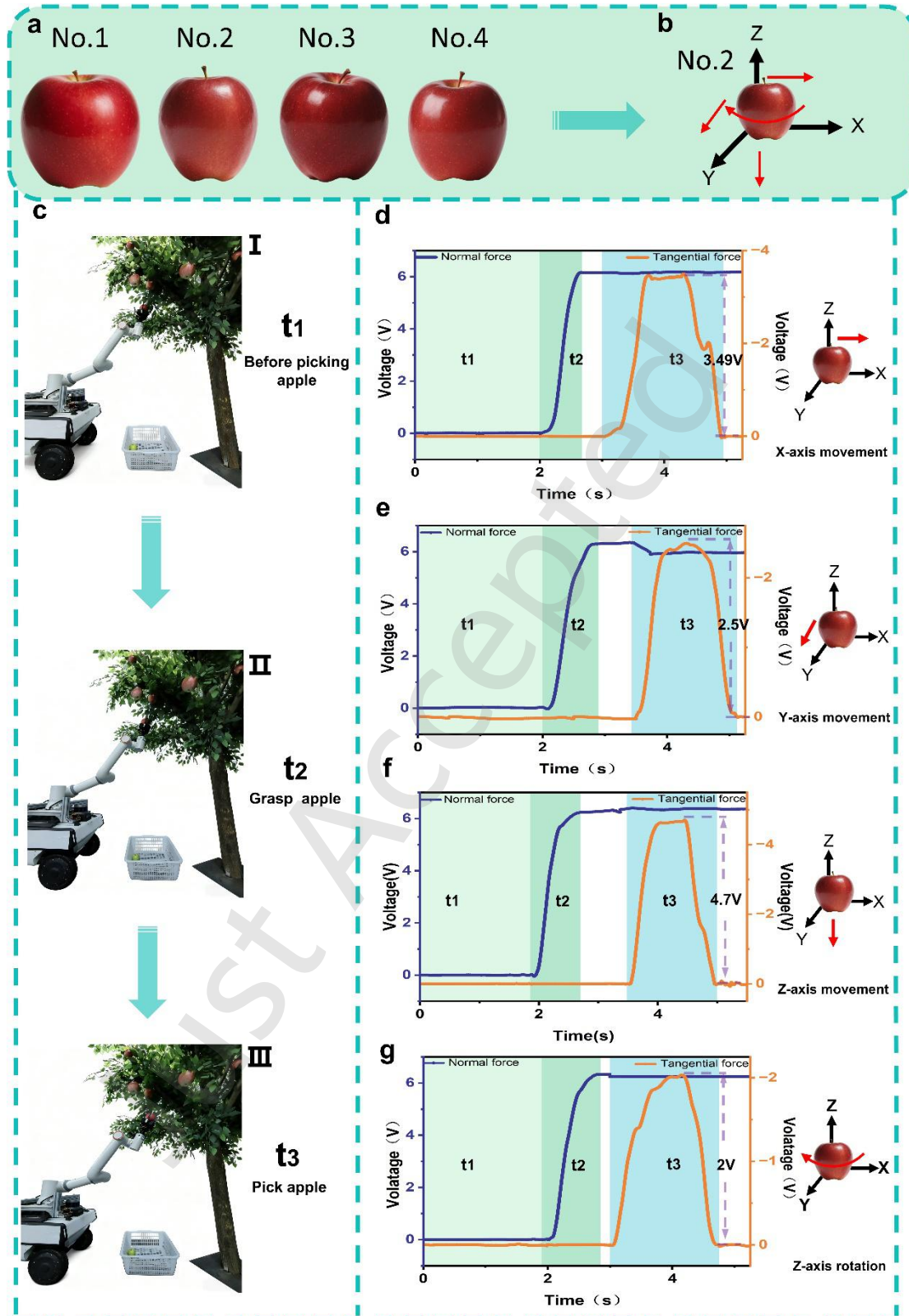


Figure. S20 : (a) Apple No. 2. (b) Four types of human harvesting actions. (c) The soft tactile sensors approaches the apple in three stages: (I) gripping preparation, (II) grasping the apple, and (III) harvesting the apple. Here, t1 represents the approach stage, t2 represents the gripping stage, and t3 represents the

harvesting stage. (d) Apple harvesting along the X-axis and the normal and tangential force signals generated during the harvesting process. (e) Apple harvesting along the Y-axis and the normal and tangential force signals generated during the harvesting process. (f) Apple harvesting along the Z-axis and the normal and tangential force signals generated during the harvesting process. (g) Apple harvesting with rotation around the Z-axis and the normal and tangential force signals generated during the harvesting process.

The tangential force signals generated by pulling along the X and Y axes, pulling vertically downward along the Z-axis, and twisting around the Z-axis are 3.49V (Figure 4d), 2.5V (Figure 4e), 4.7V (Figure 4f), and 2V (Figure 4g), respectively.

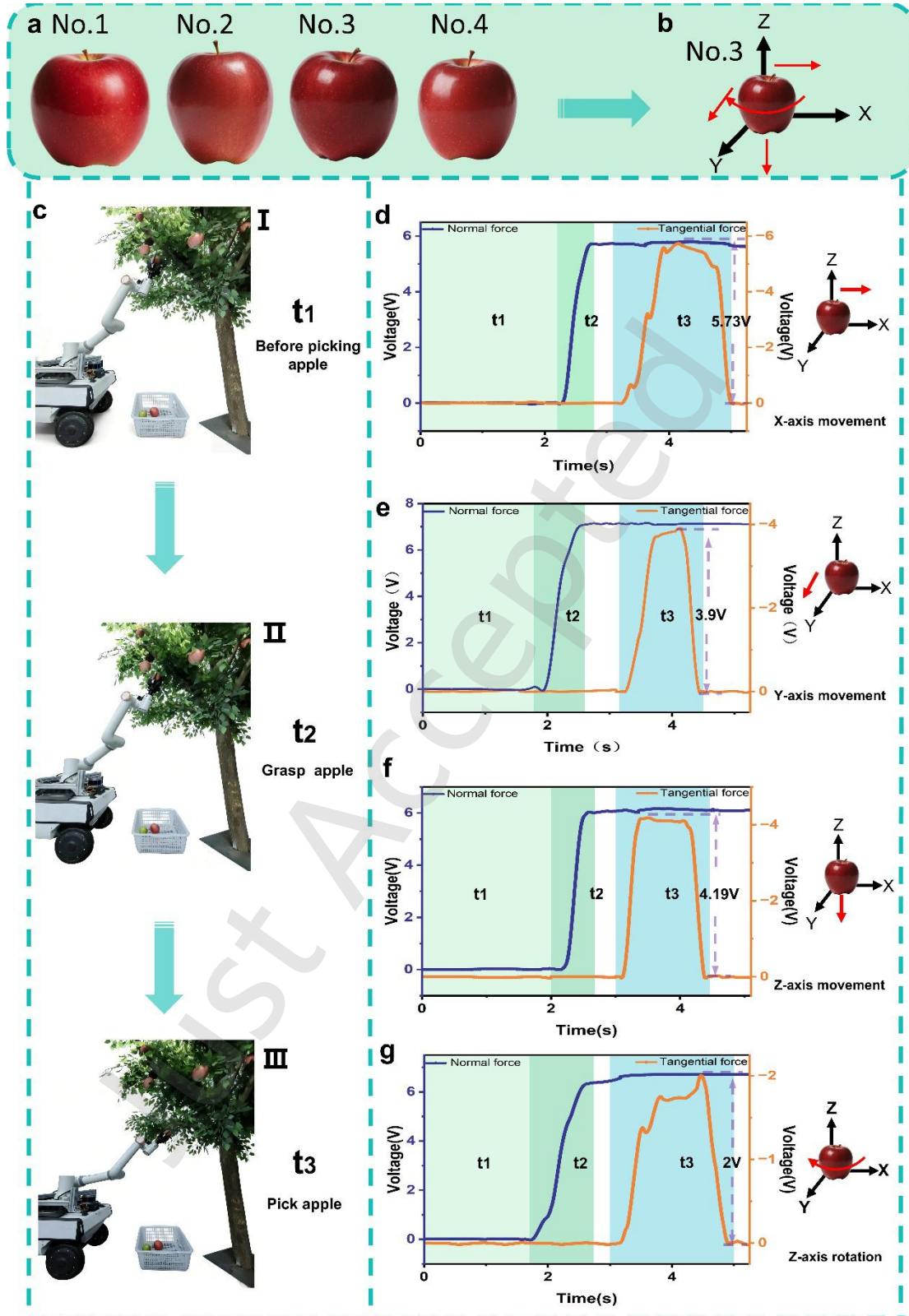


Figure. S21 : (a) Apple No. 3. (b) Four types of human harvesting actions. (c) The soft tactile sensors approaches the apple in three stages: (I) gripping preparation, (II) grasping the apple, and (III) harvesting the apple. Here, t₁ represents the approach stage, t₂ represents the gripping stage, and t₃ represents the

harvesting stage. (d) Apple harvesting along the X-axis and the normal and tangential force signals generated during the harvesting process. (e) Apple harvesting along the Y-axis and the normal and tangential force signals generated during the harvesting process. (f) Apple harvesting along the Z-axis and the normal and tangential force signals generated during the harvesting process. (g) Apple harvesting with rotation around the Z-axis and the normal and tangential force signals generated during the harvesting process.

The tangential force signals generated by pulling along the X and Y axes, pulling vertically downward along the Z-axis, and twisting around the Z-axis are 5.73V (Figure 4d), 3.9V (Figure 4e), 4.19V (Figure 4f), and 2V (Figure 4g), respectively.

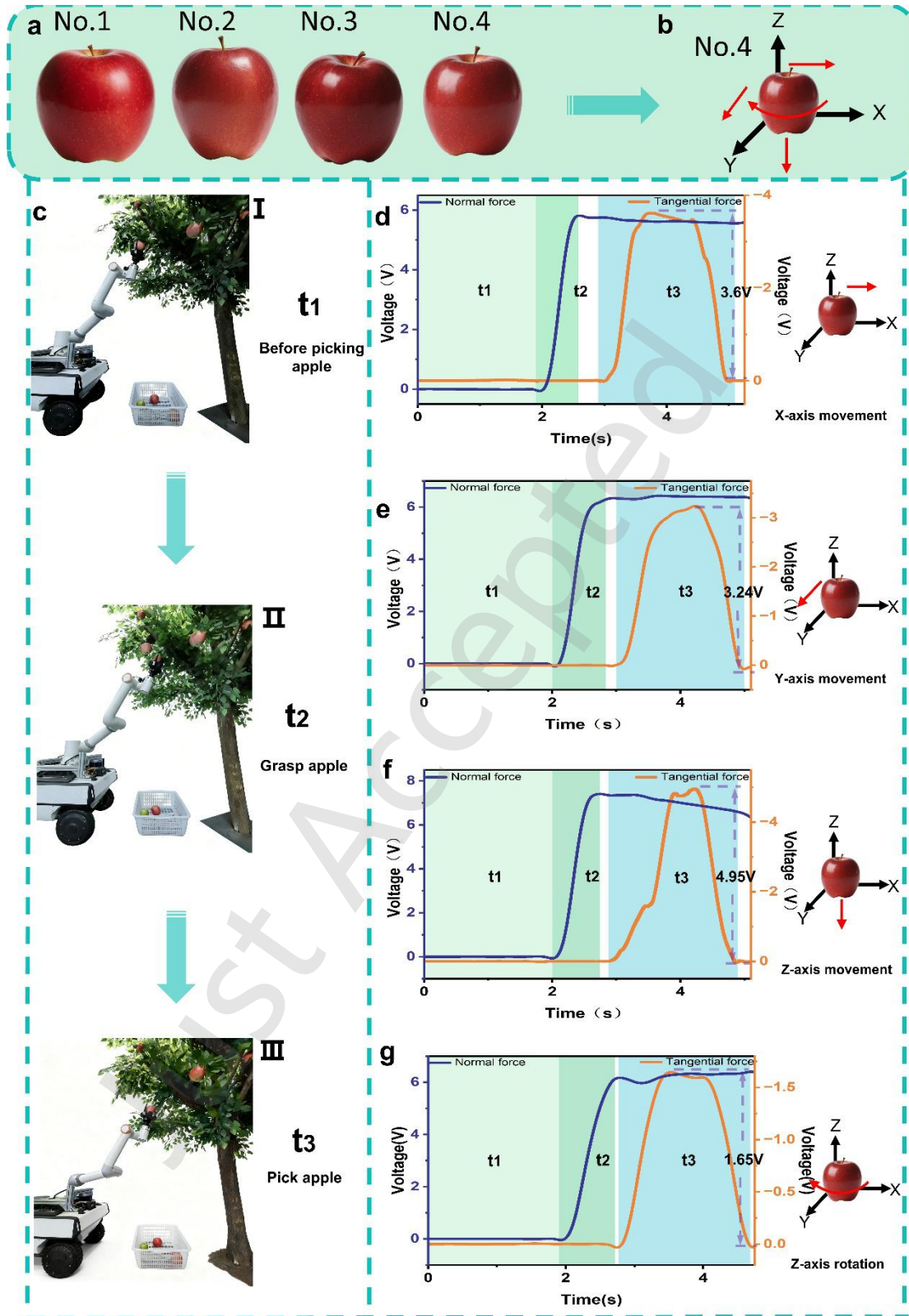


Figure. S22 : (a) Apple No. 4. (b) Four types of human harvesting actions. (c) The soft tactile sensors approaches the apple in three stages: (I) gripping preparation, (II) grasping the apple, and (III) harvesting the apple. Here, t1 represents the approach stage, t2 represents the gripping stage, and t3 represents the

harvesting stage. (d) Apple harvesting along the X-axis and the normal and tangential force signals generated during the harvesting process. (e) Apple harvesting along the Y-axis and the normal and tangential force signals generated during the harvesting process. (f) Apple harvesting along the Z-axis and the normal and tangential force signals generated during the harvesting process. (g) Apple harvesting with rotation around the Z-axis and the normal and tangential force signals generated during the harvesting process.

The tangential force signals generated by pulling along the X and Y axes, pulling vertically downward along the Z-axis, and twisting around the Z-axis are 3.6V (Figure 4d), 3.24V (Figure 4e), 4.95V (Figure 4f), and 1.65V (Figure 4g), respectively.

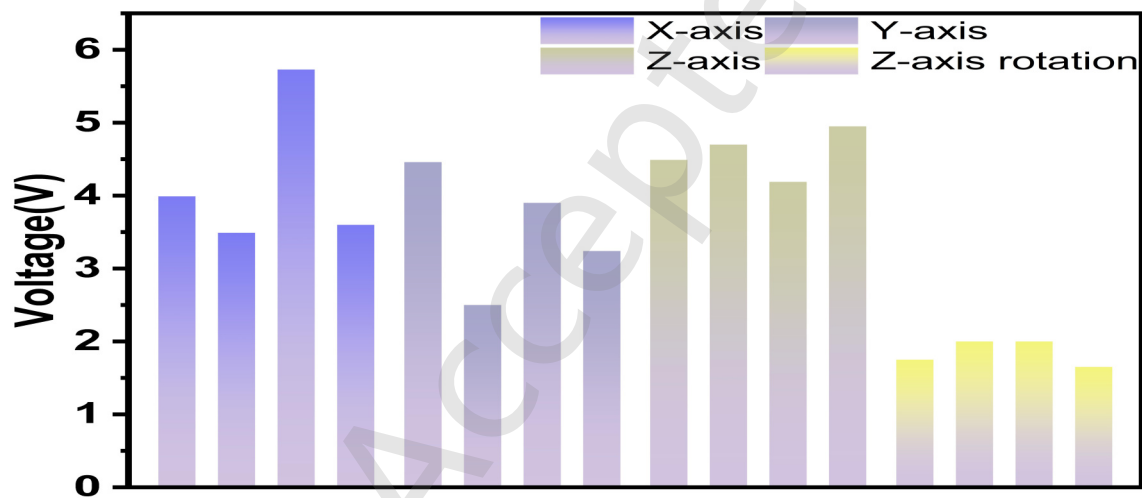


Figure. S23 : Statistical bar chart of the Tangential force generated by the 3ASD-TET during the harvesting process under four harvesting actions.

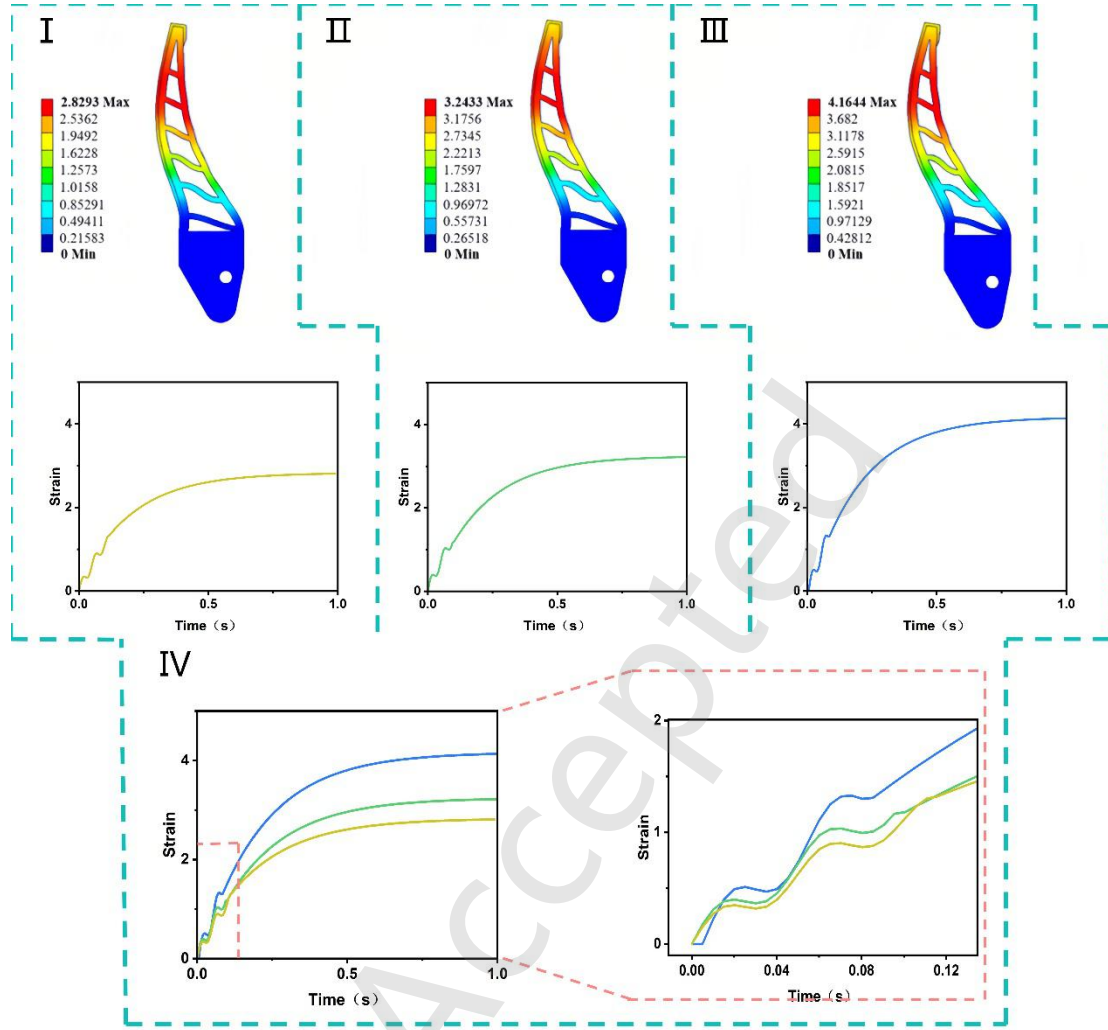


Figure. S24 : The deformation results of the soft tactile sensors grasping apples at different maturity levels were analyzed using the Explicit Dynamics analysis module. (I) At a maturity of 70%, the evolution contour plot of the total deformation of the soft tactile sensors and the deformation data graph; (II) At a maturity of 80%, the evolution contour plot of the total deformation of the soft tactile sensors and the deformation data graph; (III) At a maturity of 90%, the evolution contour plot of the total deformation of the soft tactile sensors and the deformation data graph; (IV) Comparison of the correlation between apple maturity and the deformation of the soft tactile sensors.

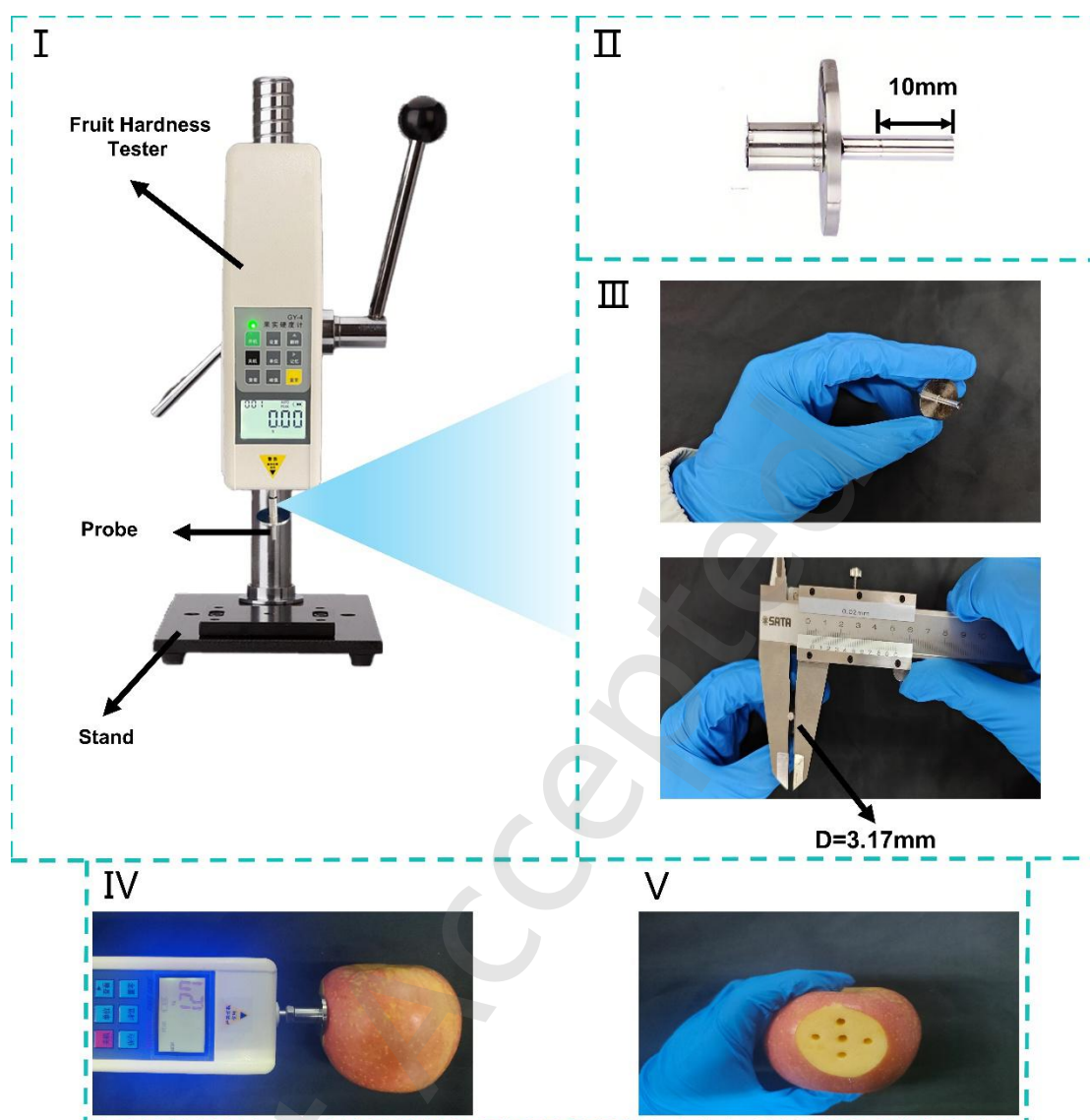


Figure. S25 : (I) Schematic diagram of the structure of the fruit firmness tester (GY-4); (II) Probe penetration size into the fruit flesh; (III) Probe diameter; (IV , V) Schematic diagram of the fruit firmness tester (GY-4) detecting the firmness of an apple;

The fruit flesh firmness was measured using a digital fruit firmness tester (GY-4, San liang Technology Co. Ltd., Guangzhou, China) equipped with a 3.17 mm diameter stainless steel probe. The probe penetrates the fruit flesh vertically at an acceleration of 5 mm/s until a penetration depth of 10 mm is reached, and the firmness value displayed by the instrument at this moment is recorded. The average firmness value of six equally spaced measurement points is used as the reference hardness. Simultaneously, the firmness is calculated using the formula: Firmness= F/A , where F is the measured value from the fruit firmness tester (GY-4), and A is the probe area, measured as $A = \pi r^2 = 0.0791 \text{ cm}^2$, with r being the probe diameter. The

converted apple firmness unit at this point is kg/cm^2 .

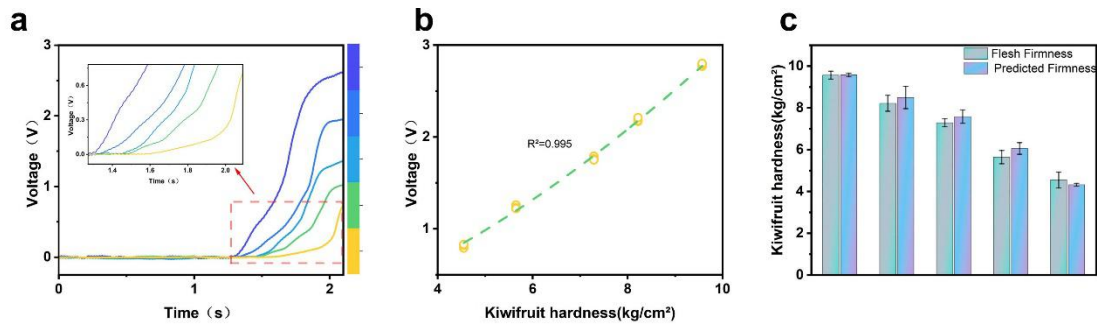


Figure. S26 : Firmness testing of kiwifruits at different maturity stages. (a) Time-response graph of the normal force signals generated by the 3ASD-TET under different harvesting cycles. (b) Relationship between firmness and normal force signals. (c) Comparison of the kiwifruit firmness testing results at different harvesting stages, with measurements taken using our tactile sensor and a fruit firmness tester.

The application range of the 3ASD-TET has been extended to complete firmness testing of kiwifruits at different maturity stages, with the results shown in Figure S16. The results indicate that under the same gripping force control, as the soft tactile sensors grasps kiwifruits at different stages, the response speed of the normal force voltage signal generated by the 3ASD-TET increases over time (Figure S16a), and the generated voltage gradually increases. This suggests that we can assess the maturity of kiwifruits at different growth stages based on the output signals of the 3ASD-TET in the normal direction. We performed a hardness-voltage fitting by comparing the actual firmness measured by the GY-4 with the voltage signals obtained from the 3ASD-TET, as shown in Figure S16(b). Additionally, the soft tactile sensors grasped kiwifruits at different stages with the same gripping force, and the tests were repeated more than three times to obtain an average value. The quality of the fitting was evaluated by calculating the coefficient of determination (R^2), which was found to be 0.995. Subsequently, we measured the kiwifruits at each maturity stage using a fruit firmness tester and compared the results with the measured firmness values, as shown in Figure S16(c).

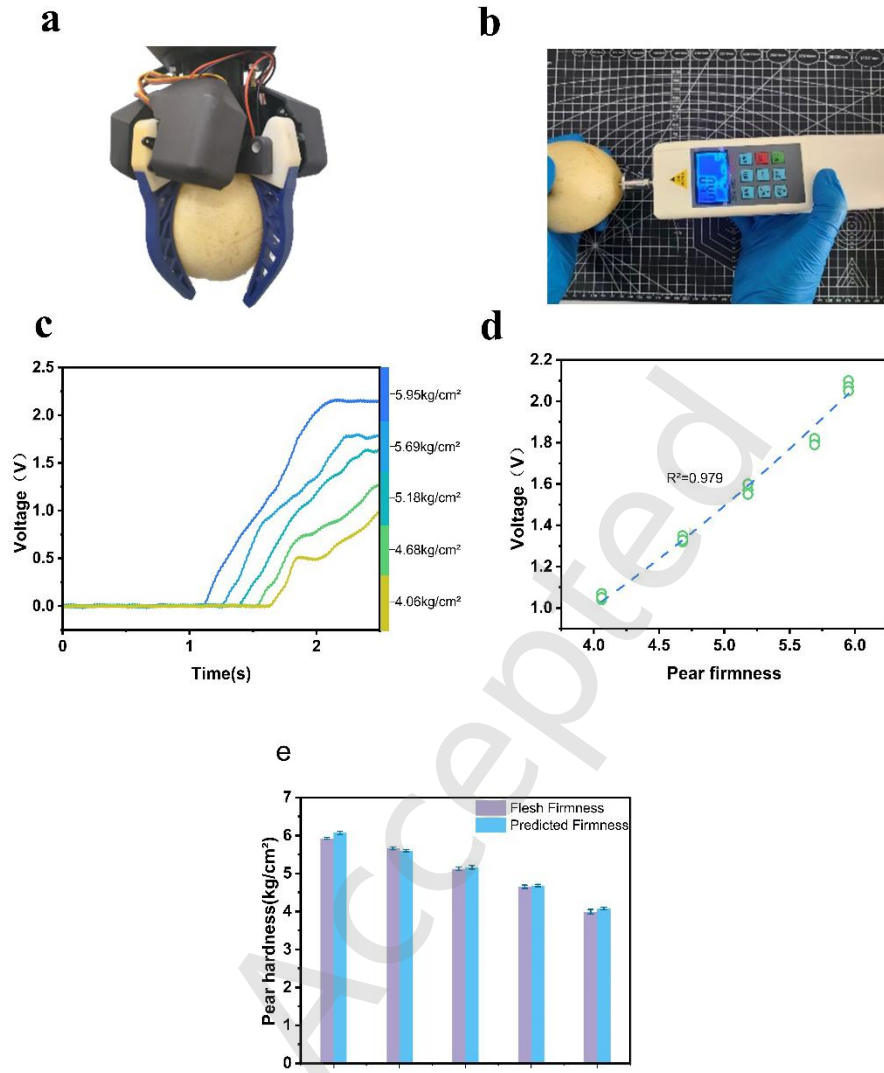
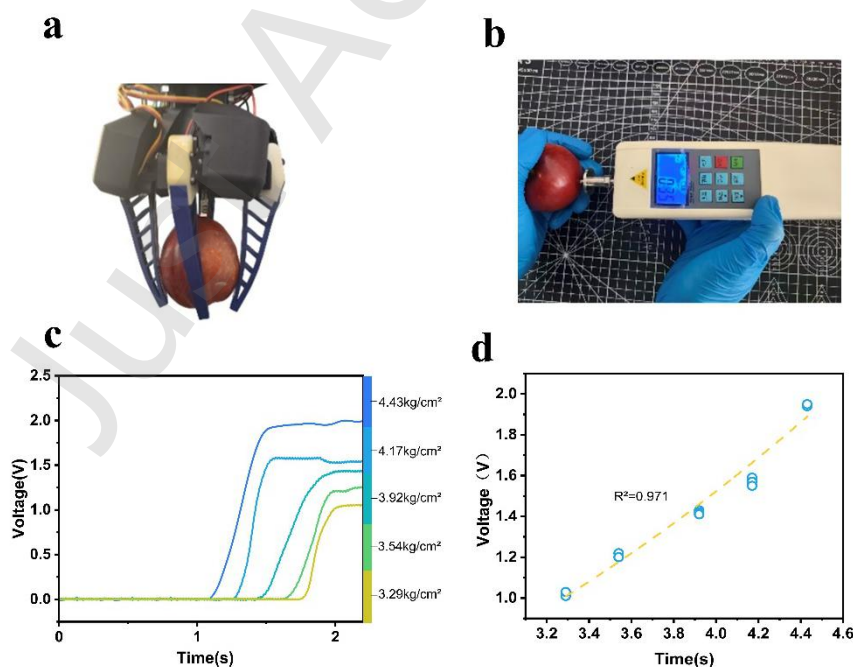


Figure. S27: Firmness testing of pears at different maturity stages.(a) Schematic of the soft robotic gripper measuring the firmness of a pear.(b) Schematic of the fruit firmness tester measuring the firmness of a pear.(c) Time response of the normal force signals generated by the 3ASD-TET at different harvesting stages.(d) Relationship between firmness and the normal force signals. (e) Comparison of pear hardness test results at different harvesting stages, measured using our tactile sensor and a fruit hardness tester.

The application scope of the 3ASD-TET has been further extended to complete firmness testing of pears at different maturity stages. As shown in Figure 26(c), under the same controlled gripping force, when the soft tactile sensor grasped pears at different stages, the response rate of the normal force voltage signal generated by the 3ASD-TET gradually increased over time, and the generated voltage also gradually increased. This indicates that the maturity of pears at different growth stages can be evaluated according to the output signal of the 3ASD-TET in the normal direction. We further fitted the actual firmness values

measured by the GY-4 fruit firmness tester with the voltage signals measured by the 3ASD-TET to establish the firmness–voltage relationship. In addition, the soft robotic gripper grasped pears at different stages under the same gripping force, and each test was repeated at least three times, with the average value taken for analysis. The goodness of fit was evaluated by calculating the coefficient of determination (R^2), and the result was 0.979 (Figure S26(d)).

To further quantitatively evaluate the prediction accuracy of the hardness detection results, we statistically compared the actual hardness values measured using a GY-4 fruit hardness tester with the predicted hardness values obtained based on the output signals of the 3ASD-TET, and presented the results as the mean $\pm$ standard deviation. As shown in Figure S27e, the predicted hardness values of pears were highly consistent with the corresponding actually measured hardness values, with only slight deviations among different maturity stages. These results further indicate that the 3ASD-TET can accurately distinguish the hardness differences of different fruits at different maturity stages and provide reliable quantitative support for fruit hardness evaluation.



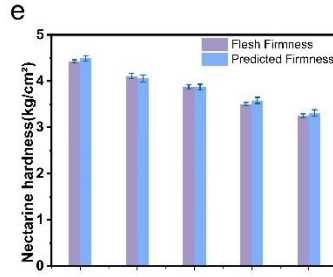


Figure. S28: Firmness testing of nectarines at different maturity stages.(a) Schematic of the soft robotic gripper measuring the firmness of a nectarine.(b) Schematic of the fruit firmness tester measuring the firmness of a nectarine.(c) Time response of the normal force signals generated by the 3ASD-TET at different harvesting stages.(d) Relationship between firmness and the normal force signals. (e) Comparison of nectarine hardness test results at different harvesting stages, measured using our tactile sensor and a fruit hardness tester.

The application scope of the 3ASD-TET has been further extended to complete firmness testing of nectarines at different maturity stages. As shown in Figure 27(c), under the same controlled gripping force, when the soft tactile sensor grasped nectarines at different stages, the response rate of the normal force voltage signal generated by the 3ASD-TET gradually increased over time, and the generated voltage also gradually increased. This indicates that the maturity of nectarines at different growth stages can be evaluated according to the output signal of the 3ASD-TET in the normal direction. We further fitted the actual firmness values measured by the GY-4 fruit firmness tester with the voltage signals measured by the 3ASD-TET to establish the firmness–voltage relationship. In addition, the soft robotic gripper grasped nectarines at different stages under the same gripping force, and each test was repeated at least three times, with the average value taken for analysis. The goodness of fit was evaluated by calculating the coefficient of determination (R^2), and the result was 0.971 (Figure 27(d)).

To further quantitatively evaluate the prediction accuracy of the hardness detection results, we statistically compared the actual hardness values measured using a GY-4 fruit hardness tester with the predicted hardness values obtained based on the output signals of the 3ASD-TET, and presented the results as the mean $\pm$ standard deviation. As shown in Figure S28e, the predicted hardness values of nectarines were highly consistent with the corresponding actually measured hardness values, with only slight deviations among different maturity stages. These results further indicate that the 3ASD-TET can accurately distinguish the hardness differences of different fruits at different maturity stages and provide reliable quantitative support for fruit hardness evaluation.

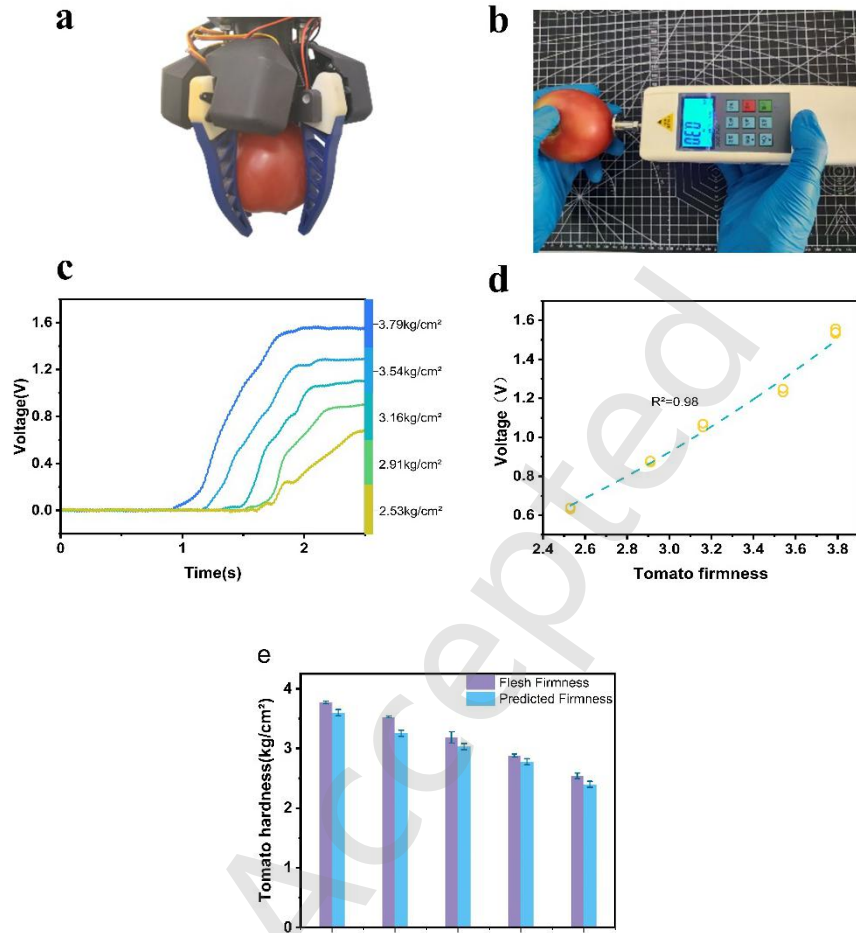


Figure. S29: Firmness testing of tomatoes at different maturity stages.(a) Schematic of the soft robotic gripper measuring the firmness of a tomato.(b) Schematic of the fruit firmness tester measuring the firmness of a tomato.(c) Time response of the normal force signals generated by the 3ASD-TET at different harvesting stages.(d) Relationship between firmness and the normal force signals. (e) Comparison of tomato hardness test results at different harvesting stages, measured using our tactile sensor and a fruit hardness tester.

The application scope of the 3ASD-TET has been further extended to complete firmness testing of tomatoes at different maturity stages. As shown in Figure 28(c), under the same controlled gripping force, when the soft tactile sensor grasped tomatoes at different stages, the response rate of the normal force voltage signal generated by the 3ASD-TET gradually increased over time, and the generated voltage also gradually increased. This indicates that the maturity of tomatoes at different growth stages can be evaluated according to the output signal of the 3ASD-TET in the normal direction. We further fitted the actual

firmness values measured by the GY-4 fruit firmness tester with the voltage signals measured by the 3ASD-TET to establish the firmness–voltage relationship. In addition, the soft robotic gripper grasped tomatoes at different stages under the same gripping force, and each test was repeated at least three times, with the average value taken for analysis. The goodness of fit was evaluated by calculating the coefficient of determination R^2 , and the result was 0.980 (Figure 28(d)).

To further quantitatively evaluate the prediction accuracy of the hardness detection results, we statistically compared the actual hardness values measured using a GY-4 fruit hardness tester with the predicted hardness values obtained based on the output signals of the 3ASD-TET, and presented the results as the mean $\pm$ standard deviation. As shown in Figure S29e, the predicted hardness values of tomatoes were highly consistent with the corresponding actually measured hardness values, with only slight deviations among different maturity stages. These results further indicate that the 3ASD-TET can accurately distinguish the hardness differences of different fruits at different maturity stages and provide reliable quantitative support for fruit hardness evaluation.

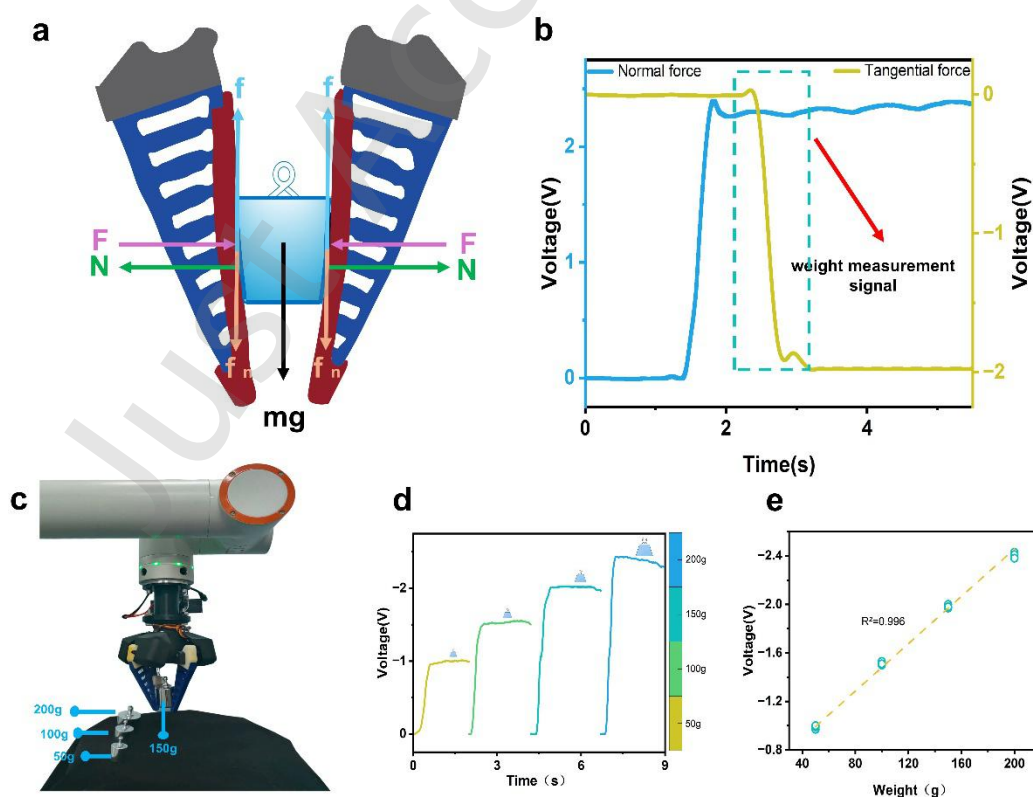


Figure. S30 :(a) Experiment of the soft tactile sensors integrated with the 3ASD-TET for force balance while

grasping weights of different masses; (b) Characteristics of the tangential force signal when the weight is in force balance; (c) Experiment with weights of different masses; (d) Characteristics of the tangential force signal under force balance with weights of different masses; (e) Fitting curve of the relationship between weight and tangential force signal;

The results show that when the weight is not grasped, the output voltage of the 3ASD-TET is zero, meaning both the normal and tangential forces are zero. When the soft tactile sensors begins to grasp the weight, the blue line representing the normal force gradually increases until it reaches the set value, while the yellow line representing the tangential force remains zero. This indicates that only the normal gripping force exists, with no tangential force. This is because, during the grasping process, the soft fingers only exert a force in the vertical direction, i.e., the normal force, on the surface of the weight. At this point, there is no trend of relative motion between the weight and the 3ASD-TET, meaning no tangential force exists.

The soft tactile sensors holding the weight grasps the weight on the platform with the palm facing vertically downward. The weight is then lifted upwards, at which point the blue line remains unchanged, while the yellow line gradually decreases from its initial position and stabilizes. This indicates that the normal force remains stable, while the tangential force undergoes significant changes. This is because once the soft tactile sensors reaches the set gripping force, it no longer continues to apply additional gripping force, so the normal force remains unchanged. After the palm of the soft tactile sensors becomes vertical to the ground, the weight is influenced by gravity, resulting in a tendency for downward movement. Due to the suction cup structure of the 3ASD-TET, the weight stabilizes after a period of downward movement. This means that the weight has reached a state of force equilibrium.

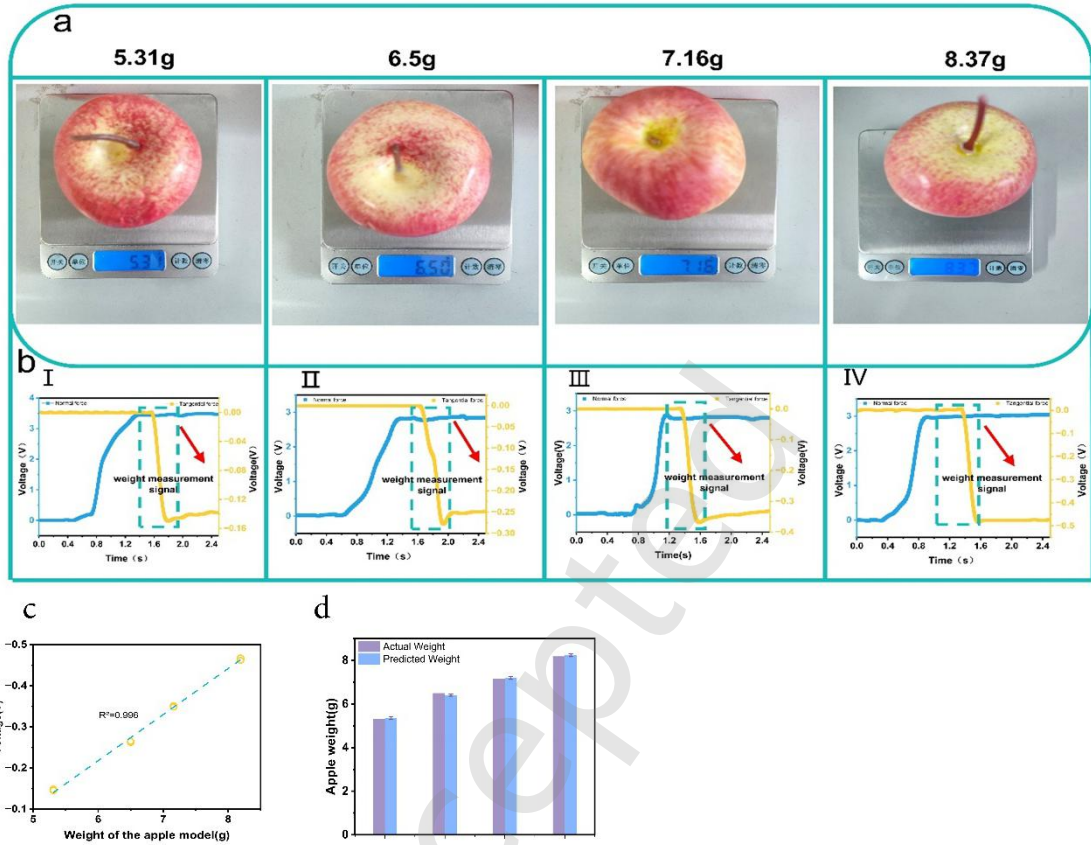


Figure. S31: (a) Weight measurement results of different small-weight objects.(b) Normal force and Tangential force signals generated by different small weights:(I) normal force and Tangential force signals generated when releasing a 5.31 g weight;(II) normal force and Tangential force signals generated when releasing a 6.5 g weight;(III) normal force and Tangential force signals generated when releasing a 7.16 g weight;(IV) normal force and Tangential force signals generated when releasing an 8.37 g weight.(c) Fitting curve of the relationship between small-weight apple models and the Tangential force signal.(d) Comparison between the actual and predicted values of apples with different weights.

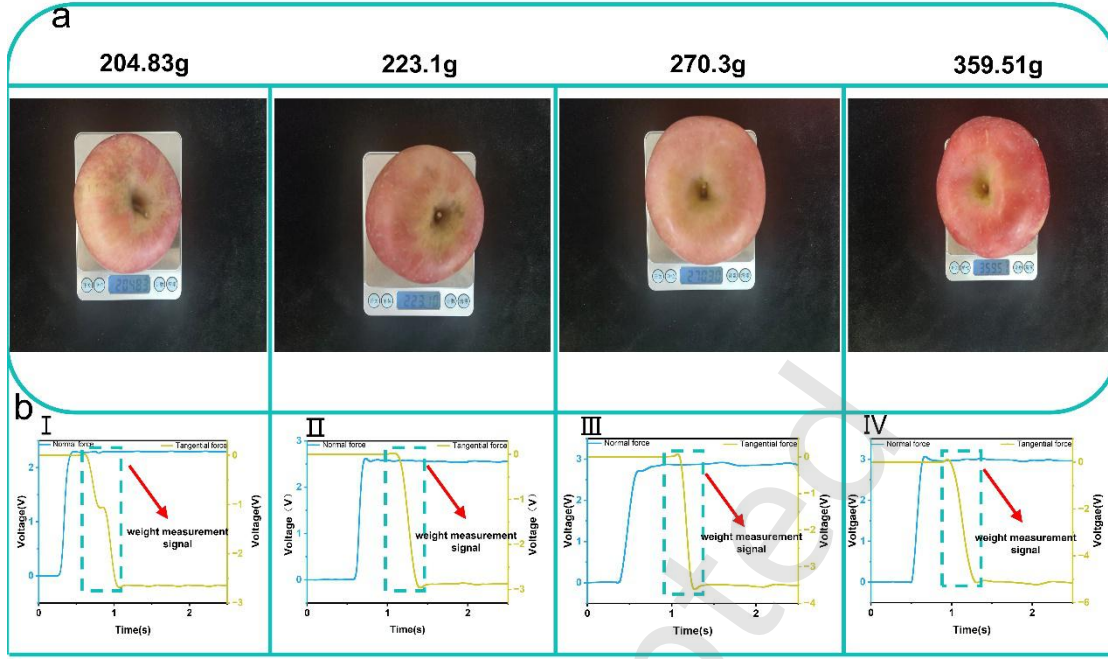


Figure. S32 : (a) Weight measurement results for different masses; (b) Normal force and tangential force signals generated by different weights; I) Normal and tangential force signals generated during the release of a 204.83g weight; II) Normal and tangential force signals generated during the release of a 223.1g weight; III) Normal and tangential force signals generated during the release of a 270.3g weight; IV) Normal and tangential force signals generated during the release of a 359.51g weight;

For apples of different weights, the output voltages of the normal and tangential forces from the 3ASD-TET are shown in Figure 18(b). In the figure, the blue line represents the normal force, and the yellow line represents the tangential force.

It can be observed that when the apple is not grasped, the output voltage of the 3ASD-TET is zero, meaning both the normal and tangential forces are zero. When the soft tactile sensors begins to grasp the apple, the blue line representing the normal force gradually rises until it reaches the set value, while the yellow line representing the tangential force remains at zero. This indicates that only the normal gripping force exists, with no tangential force. This is because, during the grasping process, the flexible fingers exert only a force in the vertical direction, the normal force, on the surface of the weight. At this point, there is no trend of relative motion between the weight and the 3ASD-TET, meaning no tangential force exists. When the soft tactile sensors grasps the apple at the equator with the palm facing vertically downward, the blue line remains unchanged, while the yellow line gradually decreases from its initial position and stabilizes. This

indicates that the normal force remains stable, while the tangential force undergoes significant changes. This is because once the soft tactile sensors reaches the set gripping force, it no longer continues to apply additional gripping force, so the normal force remains unchanged. After the palm of the soft tactile sensors becomes vertical to the ground, apples of different weights generate different amounts of gravitational force, causing the apple to have a tendency to move downward. Due to the suction cup structure of the 3ASD-TET, the apple stabilizes after a period of downward movement. At this point, the apple reaches a state of force equilibrium.

Overview		Digital I/O	
Product	USB-6009	Bidirectional Channels	12
Product Series	Multifunction DAQ	Input-Only Channels	0
Bus Type	USB	Output-Only Channels	0
Part Number	779026-01	Timing	Software
Operating System / Target	Linux, Mac OS, Pocket PC, Windows	Logic Level	TTL
DAQ Product Family	B Series	Input Current	Sinking current, sourcing current
Measurement Type	Voltage	Output Current	Sinking current, sourcing current
Isolation Type	None	Programmable Input Filters	No
RoHS Compliance	Yes	Supports Programmable Pull-up Resistors?	No
USB Power	Bus-powered	Single-Channel Current Drive Capability	8.5 mA
Analog Input		Total Current Drive Capability	102 mA
Number of Channels	4, 8	Watchdog Timer	No
Single-Ended Channels	8	Supports Handshaking I/O?	No
Differential Channels	4	Supports Pattern I/O?	No
Resolution	14 bits	Maximum Input Range	0 V to 5 V
Sample Rate	48 kS/s	Maximum Output Range	0 V to 5 V
Throughput (All Channels)	48 kS/s	Counter / Timer	
Maximum Analog Input Voltage	10 V	Number of Counters / Timers	1
Maximum Voltage Range	-10 V to 10 V	Buffered Operation	No
Accuracy at Maximum Voltage Range	7.73 mV	Pulse Glitch Removal	No

Minimum Voltage Range	-1 V to 1 V	GPS Synchronization	No
Accuracy at Minimum Voltage Range	1.53 mV	Maximum Range	0 V to 5 V
Number of Ranges	8	Maximum Signal Frequency	5 MHz
Simultaneous Sampling	No	Pulse Generation	No
Onboard Memory	512 B	Resolution	32 bits
Analog Output		Timebase Stability	50 ppm
Number of Channels	2	Logic Level	TTL
Resolution	12 bits	Physical Specifications	
Maximum Analog Output Voltage	5 V	Length	8.51 cm
Maximum Voltage Range	0 V to 5 V	Width	8.18 cm
Accuracy at Maximum Voltage Range	7 mV	Height	2.31 cm
Minimum Voltage Range	0 V to 5 V	I/O Connector	Screw terminal
Accuracy at Minimum Voltage Range	7 mV	Motion / Vision / Synchronization	
Update Rate / Frequency Range	150 S/s	Trigger	Digital
Single-Channel Current Drive Capability	5 mA	Synchronization Bus (RTSI)	No
Total Current Drive Capability	10 mA		

Figure. S33: Power supply mode, operating current, and power consumption parameters of the NI USB-6009 data acquisition unit.

According to the technical specifications of the NI USB-6009, the device is powered by a USB bus, with a supply voltage range of 4.10–5.25 VDC, a typical operating current of 80 mA, and a maximum operating current of 500 mA. In addition, the data acquisition card provides 8 single-ended analog input channels or 4 differential analog input channels, with a differential input resolution of 14 bit and a maximum aggregate analog input sampling rate of 48 kS/s, which can meet the requirements for multichannel voltage signal acquisition in this study. Therefore, under the standard 5 V USB power supply condition, the typical power consumption of the data acquisition card can be calculated as:

$$P_{\text{typical}} = U \times I = 5V \times 0.08A = 0.40W \quad (1)$$

That is, the typical power consumption is approximately:

$$P_{\text{typical}}=400\text{mW} \quad (2)$$

Under the maximum operating current condition, the maximum power consumption is:

$$P_{\text{max}}=5\text{V}\times0.5\text{A}=2.5\text{W} \quad (3)$$

That is, the maximum power consumption is approximately:

$$P_{\text{max}}=2500\text{mW} \quad (4)$$

In this experimental system, the 3ASD-TET itself does not require an external power supply, and the external energy consumption mainly comes from the signal acquisition unit. If the power consumption of the host computer is not considered, the typical power consumption of the signal acquisition unit is approximately 400 mW. When a 10000 mAh USB power bank is used for power supply, and the internal cell voltage of the power bank is assumed to be 3.7 V with a power conversion efficiency of 85%, the available energy can be estimated as:

$$E=3.7\text{V}\times10\text{Ah}\times0.85=31.45\text{Wh} \quad (5)$$

Therefore, under typical power consumption conditions, the continuous operating time of the system can be estimated as:

$$t_{\text{typical}}=\frac{31.45}{0.40}\approx78.6\text{h} \quad (6)$$

Under the maximum power consumption condition, the continuous operating time of the system can be estimated as:

$$t_{\text{max}}=\frac{31.45}{2.5}\approx12.6\text{h} \quad (7)$$

Therefore, under typical power consumption conditions, the system can operate continuously for approximately 78.6 h, while under the maximum load condition, it can operate continuously for approximately 12.6 h.

Table 1. Comparison of the 3ASD-TET with resistive, piezoelectric, and capacitive tactile sensors

Year	Normal force detection range	Tangential force detection range	Response time	Flexibility	Cycling stability	Reference
2022	0–0.6 N	0–0.8 N	60 ms	√	NA	Ref. ³
2022	0.009–4.3 N	0.009–4.3N	frequency bandwidth 5–600 Hz	√	2.16×10^6 cycles under 4.3 N and 400 Hz;	Ref. ⁴
2024	1–11 N	1–11 N	NA	√	NA	Ref. ⁵
2024	0–5 N	0–5 N	Response: 80 ms; recovery: 160 ms	√	High repeatability reported; repeatability	Ref. ⁶
2023	0.5–4 N	0.5–4 N	NA	√	NA	Ref. ⁷
2026	0–20N	0–20N	Normal Response/ recovery: 125 ms; Tangential Response/ recovery: 100 ms;	√	10000 cycles	This work

Table 2. Comparison of the 3ASD-TET with current triboelectric-based flexible multi-axis force sensors

Year	Research focus	Materials	Size	Application scenario	Reference
2024	Three-dimensional bionic underwater triboelectric palm-like tactile sensor for vertical force and shear force feedback	CPP polymer shielding layer/ hydrogel /silicone gel/liquid metal/silicone support.	114mm×90mm	Underwater robotic grippers, force feedback control, object hardness and shape recognition, underwater grasping	Ref. ⁸
2018	TENG-based self-powered six-axis tactile sensor for detecting normal and shear forces	PDMS/ PTFE/ Al/ Galinstan	50mm×32mm	Six-degree-of-freedom attitude detection, 3D spatial control, human-machine interaction, robot control, wireless systems and biomedical systems	Ref. ⁹
2022	Fingerprint-inspired flexible triboelectric tactile sensor using contact-separation and stretching modes for multifunctional tactile sensing	EGaIn/ Ecoflex 00-30 , Smooth-On/PTFE	15mm×20mm	Flexible electronic skin, robotic tactile sensing, wearable tactile perception, human-machine interaction	Ref. ¹⁰
2023	Four single-electrode TENG unit array for decoupling normal load and shear load	PDMS/ MXene/ BASE-SCD1/ Silver	NA	Robotic tactile feedback, automatic pipetting in biological laboratories, reduction of droplet residue	Ref. ¹¹
2024	Hydrogel-integrated TENG for vertical pressure, transverse friction, and multidirectional force detection	γ -PGA/ AA/ MBAA/ I2959/ PDMS/ copper foils	NA	Robotic hand electronic skin, wrist pulse, speech recognition, writing, step counting, respiratory monitoring, human-machine interaction	Ref. ¹²

Year	Research focus	Materials	Size	Application scenario	Reference
2026	An octopus-sucker inspired triboelectric self-decoupling three-axis force sensing Simultaneous detection of normal and tangential forces	Ecoflex/PVC/ Cu/PTFE	15mm×6mm	Agricultural picking, low-damage harvesting, fruit maturity evaluation, and weight grading	This work

Table 3 Comparison of performance parameters between the 3ASD-TET and existing triboelectric-based flexible multi-axis force sensors

Year	Sensor range	Sensitivity	Decoupling/ recognition metric	Self-powered capability	Stability	Application scenario	Reference
2021	Pressure range: 3–45 kPa	144.8 mV kPa ⁻¹ in the low -pressure region; 0.024 V kPa ⁻¹ in the high-pressure region	Multidimensional force discrimination based on the output-voltage difference between symmetric electrode regions	√	NA	Electronic skin, multidimensional tactile perception, robotic tactile sensing	Ref.8
2022	External load: 1–5 N	Voltage sensitivity: 0.14057 V N ⁻¹ ; current sensitivity: 0.58082 nA N ⁻¹	Linear fitting R ² = 0.98609; external force prediction error <1.78% at 4 N and 9.40% at 3 N	√	2800 cycles	Underwater vehicle tactile perception, underwater manipulator force feedback, pipeline nondestructive evaluation, autonomous underwater grasping nondestructive evaluation, autonomous underwater grasping	Ref.9

Year	Sensor range	Sensitivity	Decoupling/ recognition metric	Self-powered capability	Stability	Application scenario	Reference
2022	Normal force: 1–15N; pressure range: 5.1–7 6.5 kPa; shear force: 0.05–0.4 N	2.97 mV kPa ⁻¹	Linear fitting $R^2 = 0.977$ 3; shear force detection l imit: 255 Pa / 50 mN; f orce direction recognized by signal location and voltage amplitude	√	>10000 cycles	Multidimensional tactile sen sing, force direction percep tion, human–machine intera ction, electronic skin, soft r obotic sensing	Ref.10
2024	Pressure range: 0–70 mmHg	2.61 ± 0.02 mV mmHg ⁻¹	Pressure direction and de gree recognized by differ entiating signal location and output voltage magni tude	√	NA	Real-time remote pressure s ensing, human–machine int erface, biomedical monitori ng, multidirectional pressur e sensing	Ref.12
2026	Normal force: 0–20 N; tange ntial force: 0–2 0 N	Normal and tangential force responses demonstrated	Device-to-device error < 2% for normal force and <3% for tangential forc e; simultaneous normal/ta ngential force detection	√	10000 cycles	Agricultural picking, low-da mage harvesting, fruit matu rity evaluation, slip-related feedback and weight gradin g	This work

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