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Biocompatible Hydrogel Ostomy Adhesive

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Abstract

Ostomies are digestive and excretory surgeries where waste is redirected to the outside of the abdomen, requiring a bag to catch excretion. Current methods use adhesives to create adhesion for 24-hour usage of the ostomy bag. However, current adhesives are weak and unstable, and often lead to leakages of ostomy effluents resulting in various clinical complications including irritant dermatitis and infection. Due to these challenges, no commercially-available product provides strong enough adhesion nor mechanical softness to prevent skin damage from ostomy leaks. In this work, we introduce a hydrogel ostomy adhesive (HOA) made from a tough double-network hydrogel based on polyacrylamide and sodium alginate that strongly adheres onto the skin for over 24 hours and prevents leaks by maintaining fluid-tight sealing against regular bodily movements. The adhesion of HOA to abdominal skin is achieved by the topological adhesion formed by a biopolymer chitosan solution. The HOA's robust adhesion of an ostomy bag is demonstrated on *ex vivo* porcine skin and *in vivo* human skin and is compared to existing commercially-available ostomy bag adhesives.

Keywords: Hydrogel, Ostomy, Tissue Adhesive, Chitosan, Surgical Stomas, Contact Dermatitis, Bandages

1 Introduction

With 700,000 affected annually (Grant et al., 2013), ostomies are lifesaving redirective surgeries for those who have defective waste systems (e.g., urinary and digestive) caused by acute diverticulitis, colorectal cancer, trauma, or inflammatory bowel disease (Burch, 2005; Dabirian et al., 2010). As result of these surgical interventions, the stoma (i.e., an artificial opening) is created through the abdomen wall from the bladder, ileum, or colon. To collect the stoma effluent, most use a one-piece closed ostomy bag that is often adhered around the stoma and disposed daily (Voergaard et al., 2007). Current ostomy bags have two main limitations that lead to leakage: (1) face plates that are ineffective interfaces due to their overly stiff composition and (2) weak adhesion resulting in short wear time and difficult application. While various commercially-available adhesive pastes and glues have been introduced to reinforce adhesion of ostomy bag to abdominal skin, existing adhesives for ostomy bags still lack the ability to form strong and stable adhesion, often resulting in premature failures and leakages. Such leaked digestive effluent can damage surrounding skin tissues, creating painful swelling and dermatitis (Cressey et al., 2017; Pieper, 1996; Richbourg et al., 2007). Regrettably, as many as 34% of ostomy patients commonly develop chemical irritation of the skin as result of leakages (Leong et al., 1994).

Commercially-available ostomy bag faceplates are composed of two parts: the adhesive layer and a tin flexible polymeric film. The adhesive layer is a blend of polyiso-butylene, pectin, gelatin, and sodium carboxymethylcellulose while the thin polymeric film is made from polyethylene. Owing to various problems from ostomy bags alone and its application to skin, ostomy patients commonly use a variety of methods for improved adhesion of ostomy bag and prevention of leakages. Diverse forms and materials of ostomy bag adhesives have been developed including adhesive pastes (Burch, 2011) and pectin-based powders (Boyles, 2010). In this work, three commonly used pastes and powders were used as comparisons. Karaya Gum powder comes in the form of a dry slightly brown powder that is applied on both commercially-available ostomy adhesive and skin and is composed of a polysaccharide exudate. Stomahesive has a consistency of a thick brown hydrocolloid paste that acts as both an adhesive and a buffer from leaks, providing contour to irregularly shaped stomas. Ostobond is a white viscous solution of liquid latex, *N*-hexane, and zinc oxide that is coated on the skin and adhesive. (See Fig. S2 for additional information and pictures of the adhesives).

However, these existing products show relatively weak adhesion strength with limited efficacy to prevent leakages from ostomy bags. Several strategies utilize the injection of porcine or bovine collagen or synthetic hydrogels into the skin to create improved conformal adhesion of ostomy bags have been proposed (Arai & Okubo, 1999; Smith et al., 2007; Weidmann et al., 2014), these methods still require complicated application procedures or surgery.

To address these challenges of close-fitting, stable, easy to apply sealed ostomy bags, this work introduces a hydrogel ostomy adhesive (HOA) capable of forming biocompatible, soft, and durable adhesion and sealing of ostomy bags to skin that are uncomplicated to change. This work sought to achieve three specific aims: (1) test mechanical softness, strength, and biocompatibility of the HOA with the skin, (2) test robust adhesion strength and toughness between the HOA and skin compared to the three commonly used pastes and powder adhesives mentioned above, and (3) test endurance of the HOA attached to the skin. The HOA consists of a polyacrylamide-alginate tough hydrogel ring that allows for robust adhesion of ostomy bag to resist regular skin motions and weight from the bag. The HOA matches the mechanical properties of human tissues like the skin to minimize tissue damage or discomfort from mismatch in mechanical properties (Yuk, Lu, et al., 2019). The HOA forms robust yet stretchable adhesion to skin surface based on a chitosan tough adhesive that can form robust interfacial adhesion via diffusion of biopolymer chains and resultant topological adhesion (J. Li et al., 2017; Yang et al., 2018).

Hydrogels were chosen for the HOA because they have been shown to be safe in the medical field with highly favorable biocompatibility, tissue-like mechanical properties, and high water content (Deligkaris et al., 2010; Grolman et al., 2019). While conventional hydrogels have been limited to weak mechanical strength (e.g., gelatin, agar), this work utilizes a recently developed hydrogel with high strength and fracture toughness (Sun et al., 2012). These recently developed hydrogels have enabled a broad range of new biomedical applications including drug-delivery wound dressings (Balakrishnan et al., 2005; Kokabi et al., 2007; Liang et al., 2019; Q. Liu et al., 2018) and tissue adhesives (Liu et al., 2012; Rahimnejad & Zhong, 2017; Ryu et al., 2011; J. Li et al., 2017; Yang et al., 2018; Yuk, Varela, et al., 2019). In particular, this work takes advantage of recent advances in particular methods of robust wet adhesion of tough hydrogels (J. Li et al., 2017; Yang et al., 2018; Yuk, Varela, et al., 2019). The capability to establish robust adhesion on skin together with biocompatibility with human tissue, softness, high toughness, and stretchability render tough hydrogels as an ideal candidate for ostomy adhesives. The adhesion performance of the HOA is characterized based on various standard mechanical testing methods in comparison to various commercially-available ostomy bag adhesives. We further demonstrate the fluid-tight sealing of ostomy bags by the HOA under realistic loads and daily motion based on *ex vivo* porcine skin and *in vivo* human skin.

2 Results

Design of the hydrogel ostomy adhesive (HOA) and chitosan tissue adhesive. HOA placement on the ostomy is shown schematically in Figure 1. An 85 mm outer diameter and a 25-35 mm inner diameter ring has been laser cut from a 1 mm thick tough hydrogel. The inner diameter size depends on the size of the ostomy. The HOA consists of the first polyacrylamide network crosslinked by a covalent crosslinker (*N,N'*-methylenebis(acrylamide)) and the second alginate network crosslinked by calcium ions to form a highly stretchable and tough double-network hydrogel (Sun et al., 2012).

To achieve durable adhesion of the HOA, two types of chitosan-based adhesives were designed based on previously reported methods (J. Li et al., 2017; Yang et al., 2018). The first chitosan tissue adhesive consists of a bridging polymer solution of chitosan with 2-(*N*-morpholino)ethanesulfonic acid (MES) buffer at pH 4.5 applied onto the abdomen (See Materials and Methods for further information on the preparation of the HOA and the adhesives). For stronger adhesion, an alternative second chitosan tissue adhesive EDC-NHS was prepared using first chitosan solution, 1-ethyl-3-(-3-dimethylaminopropyl) carbodiimide hydrochloride (EDC), and *N*-hydroxysuccinimide (NHS). Both chitosan adhesives are applied between the hydrogel and skin. Because chitosan dissolves in acidic solutions with pH below 6.5 (Yang et al., 2019), the higher pH of the hydrogel (around 7) allows pH-induced crosslinking of chitosan between the hydrogel and the skin. The chitosan provides strong, and flexible topological adhesion between the HOA and the skin that can resist movement and mechanical wear. Furthermore, cationic characteristic of chitosan can provide antibiotic properties against bacteria, fungi, and parasites, allowing for sanitation and protection from infection of the ostomy (Blacklow et al., 2019; J. Li & Mooney, 2016). Removal of the adhesive from the skin is done by applying a slightly acidic solution of MES buffer (pH 4.5) to the edge of bonding to dissolve the chitosan polymer network (Yang et al., 2018). Note that the weakly acidic MES buffer with pH 4.5 is regarded as not skin-sensitizing (Daniel et al., 2018).

Mechanical properties of the HOA. The HOA has a Young's modulus of less than 10 kPa to match the moduli of skin (85 kPa) (McKee et al., 2011) in order to provide a flexible watertight seal. This mechanical softness of the HOA ensures conformal contact to the underlying skin surface compared to existing ostomy bag adhesives that are hard and inflexible. Figure 2 show that the HOA material can stretch up to 11 times its original length. The calculated Young's modulus (E) of the HOA is 7.12 ± 1.98 kPa. In contrast, commercially-available ostomy bag face plates can only be stretched around 7.75 times before fracture, with the calculated Young's modulus of 772.45 ± 17.20 kPa (p-value = 0.00014).

Adhesion and endurance performance of the HOA. An initial qualitative evaluation of HOA adhesion was done by applying the chitosan tissue adhesive solution on the solely HOA and human abdominal skin for 24 hours (Fig. 3a). While the HOA exhibits slight drying at the outer edges over time, the majority of HOA retains robust adhesion to the skin. After one full day (i.e., 24 hours), the HOA was still securely adhered to the abdomen. Longer adhesion times of over 24 hours were considered while developing the HOA but were not performed at this time. Instead, it was opted to clean and replace the bag after 24 hours to avoid the possibility of infection. Longer adhesion times could be explored in the future.

Quantitative results of the HOA's adhesion strength on *ex vivo* porcine skin (Fig. 3b) shows the HOA ring provides sufficient adhesion strength to withstand forces up to 4.9 N (i.e., 500 g of weight) (Fig. 3e). these results are above the average mass of typical ostomy bags capacity (~ 128 g) (Rose et al., 2015). After 6 hours of testing on the mock ostomy setup, the HOA retained its shape and strength (Fig. 3b). Even after 12 hours of adhesion to the porcine skin, the HOA still retains high stretchiness and strength (Fig. 3d). In contrast, the commercially-available ostomy bag adhesive shows weak adhesion and leakage (Fig. 3c).

We further perform standard mechanical interfacial toughness and shear strength tests to compare the HOA and commercially-available ostomy bag adhesives on porcine skin (Fig. 4 and Fig. S3). The commercially-available adhesives show low interfacial toughness (37.5 J/m^2 for Karaya Powder; 15.3 J/m^2 for Ostobond; 12.6 J/m^2 for Stomahesive) and shear strength (4.28 kPa for Karaya Powder; 5.18 kPa for Ostobond; 4.40 kPa for Stomahesive). The HOA adhered by EDC-NHS chitosan adhesive shows much higher interfacial toughness (58.5 J/m^2) and shear strength (9.82 kPa).

3 Discussion

This work introduces a hydrogel ostomy adhesive (HOA) as an alternative for ostomy patients that provides a promising solution to address the three proposed aims not achieved by existing ostomy bag adhesives. Mechanical properties of the HOA is shown to be closer that of the human skin through the comparison of Young's modulus, allowing for a soft, biocompatible, and elastic interface which allows for ease of motion. Data from adhesion tests reveals that the HOA adhered with the chitosan tissue adhesive EDC/NHS had interfacial toughness and shear strength values that exceeded those of commercial pastes, powders, and adhesives. A high shear strength from the tissue adhesive allows the HOA to stay adhered despite shear stress the ostomy bag applies on the adhesive. Strong adhesion can prevent the bag from coming loose during body movement. Lastly, through *in vivo* and *in vitro* testing of the HOA on human and porcine skin, the device showed remarkable endurance with wear times of up to 24 hours, increasing the lifespan of ostomy bags and reducing the potential leakage of effluent onto the body. Combining these three properties, the HOA offers an interface closely resembling skin for flexibility and comfort, a soft, stretchable and durable adhesion between skin and ostomy bag that holds 0.5 kg of ostomy effluent over at least a 24-hour duration to help prevent leakage of effluent. While this paper introduces a new product for consideration, clinical trials on various skin types while attaching an ostomy bag filled with liquid would need to be done before this product could ever be implemented. We present the introduction of the possibility of new materials.

The HOA could be improved by testing for longer duration times. Adding anti-drying features on the hydrogel like a thin polydimethylsiloxane (PDMS) layer could prevent water from evaporating out of the hydrogel (Yuk, Zhang, Parada, et al., 2016) and thus increase viability of the material. On top of the HOA's capability as robust adhesion agent for the ostomy bag in this work, the HOA has potential to be expanded with various other functionalities and methods. For example, drug delivery might be integrated into the surface of the HOA to administer medication such as hydrocortisone or other antihistamines that reduce inflammation after an accidental tear. A leak detection system might be another possible addition to the HOA where an alternating current could be passed through the gel, detecting bioimpedance changes to alert the patient of a potential leak. Furthermore, the HOA could potentially be modified to collect data on one's eating habits, by detecting and recording the various ions or vitamins from the patient's daily waste. We also envision that the robust integration of medical devices by the hydrogel adhesive demonstrated in this work may potentially be beneficial for other types of medical devices beyond ostomy bags.

Experimental Section

Materials.

All reagents were obtained from Sigma Aldrich unless noted otherwise and used without further purification. For the hydrogel monomers, acrylamide (AAm, A8887-100G, suitable for electrophoresis, 99%) and alginic acid sodium salt (sodium alginate, A1112-100G, low viscosity) were used. For the crosslinkers, *N,N'*-methylenebis(acrylamide) (MBAA, 146072-100G, 99%), *N,N,N',N'*-tetramethylethylenediamine (TEMED, T22500-100ML, ReagentPlus®, 99%), ammonium persulfate (APS, A3678-25G, 98%), and calcium sulfate ($CaSO_4$, 255548-100G, 98%) were used as a covalent crosslinker, accelerator, initiator, and ionic crosslinker respectively.

Chitosan (448869-50G, low molecular weight) and 2-(N-morpholino)ethanesulfonic acid (MES hydrate, M2933-25G) were used in formulating the chitosan tissue adhesive. The chitosan tissue adhesive EDC-NHS involved N-hydroxysuccinimide (NHS, 130672-5G, 98%) and N-(3-dimethylaminopropyl)-N'-ethylcarbodiimide hydrochloride (EDC, 03450-1G, 98%) as crosslinkers for the chitosan.

Glass panes and a silicone sheet (1.5 mm thick) were used as the mold for curing the hydrogel. Rain-X 2-in-1 Glass Cleaner + Rain Repellent was purchased at Target, which was used as a hydrophobic coating for the glass to decrease the adhesion of the hydrogel with the device. Hy-top® Assorted Food Coloring, which contained water, glycerine, FD&C Red #40, and FD&C Blue #1 was obtained at a local supermarket. Distilled water (dH_2O) was also obtained at a local supermarket.

Commercial ostomy adhesive solutions (Karaya Powder from Convatec®, Ostobond Skin Bonding Cement, and Convatec Stomahesive Paste) were obtained through Amazon and used as comparisons against the HOA. Current ostomy bags from Celecare were obtained from Amazon as well to facilitate mechanical test comparisons against the HOA.

For mechanical tests, a Dual-Range Force Sensor from Vernier measured the amount of force from shear, peel, and tensile tests. A vice from Irwin secured porcine skin and adhesives. To record all tests and experiments, all photos and videos were either taken on a Samsung S9 or a Nikon D500. Porcine belly skin was purchased at a local supermarket for in vitro testing of the hydrogel adhesive.

A mock simulation of ostomy-like conditions was created with plastic tubing and a plastic box bought from a local hardware store. A 3D printed mock stoma was designed in Fusion360 and then printed with PLA in order to simulate a stoma in the mock test. (Images of the setup are in Fig. S4)

Methods.

Creation of the HOA Device. The creation of the hydrogel follows modified procedures from Sun et al. 2012 and Lin et al. 2016 (Process of polymerization are in Fig. S5). 1.028 g of sodium alginate and 5.3575 g of AAm were dissolved in 50 mL of dH_2O for 24 hours until the sodium alginate was dissolved. About 10 μL of the blue or red food coloring was added in the solution for better visualization of the gel.

A glass mold was created by 2 glass panes 1 mm thick with a 1 mm thick rubber sheet. The glass panes were lubricated by a hydrophobic coating to prevent the hydrogel from sticking to the glass pane; in this case, Rain-X 2-in-1 Glass Cleaner + Rain Repellent was applied.

15 mL of the alginate/AAm solution was mixed with 600 μL of MBAA (0.2 g per 100 mL), 100 μL of APS (0.75 M), 400 μL of $CaSO_4$ (0.27 M), and 10 μL of TEMED. To prevent quick gelation of the alginate with the ionic crosslinker, the solution was quickly poured into the mold. Then, the gel was cured under UV light (365 nm) for 1 hour. After curing was complete, the gel was submerged in dH_2O for 10 minutes to release some of the excess crosslinker and the hydrogel from the glass plate. Aluminum foil was then wrapped around the glass plate and the hydrogel was then placed onto the aluminum foil to ease the cutting process. The gel was then vector cut to a pre-designed shape in a laser cutter (Epilog Zing 24, 40 W) at 70% speed and 45% power, forming the HOA.

For the test requiring adhesion to in vivo human skin, the HOA was left to sit in dH_2O overnight and then was sprayed with isopropyl alcohol for further rinsing. Otherwise, the HOA was quickly stored in Ziploc® Freezer Quart Bags (Images of assembling the HOA are included in Fig. S6).

Synthesis of the chitosan tissue adhesive. The tissue adhesive follows the same procedures from Li et al. 2017 and Yang et al. 2018 (Chitosan tissue adhesive EDC/NHS bonding mechanism is shown in Fig. S7). 0.476 g of MES hydrate was dissolved into 50.0 mL of dH_2O. pH was not monitored to prevent cross-contamination with the pH probes, but approximate pH was around 4.5 to 6 pH. 0.5 g of chitosan was then dissolved into the MES hydrate solution for 1 hour to completely mix. The solution was then covered and sat still for 24 hours to release the remaining air bubbles in the solution. The solution is slightly viscous and has a light-yellow tinge.

The tissue adhesive EDC/NHS was made creating a concentration of 12 mg/mL of NHS and EDC. In this case, 0.12 g of NHS was weighed and mixed in 5 mL of the chitosan / MES buffer solution as described previously. 0.12 g of EDC was mixed into another 5 mL of the chitosan / MES buffer solution to prevent NHS-EDC crosslinking before adhesive application. The solution was then covered and left to settle for 24 hours. The solution is viscous but clearer than the solution described before.

To apply the adhesive solution, a micropipette was used to transfer the solution to the porcine skin. As a small droplet was applied onto the skin, the solution was then spread evenly to insure adhesion on all the adhesive. (Images of assembling the chitosan tissue adhesive are included in Fig. S8).

Mechanical tests on the HOA. Mechanical tests were used to compare the strength of the material of current ostomy adhesive backings with that of the HOA. Stress-strain curves of the device alongside the other current products were measured by stretching the material until rupture occurs. A 10 mm x 50 mm strip was cut from ostomy adhesives and the HOA. 10 mm of each side was anchored (one side with a vice and the other with a binder clip). A Dual-Range Force Sensor by Vernier or a mechanical tester (2.5 kN load-cell, Zwick/Roell Z2.5, Fig. S3) was used for mechanical tests.

To compare the mechanical stiffness of the HOA, Young's modulus was used as the standard of comparison and was tested on porcine skin due to its similar mechanical properties and toughness like the human skin (J. Li et al., 2017). Young's modulus (E) is defined by the relation of stress by the amount of strain:

$$E = \frac{\sigma}{\epsilon} \quad \text{(Eq. 1)}$$

$$E = \frac{F/A}{\Delta L/L_o} \quad \text{(Eq. 2)}$$

To calculate Young’s modulus commercially-available ostomy bags and the HOA, the tensile test data was plotted in engineering strain (i.e., displacement divided by the original gauze length) vs engineering stress (i.e., tensile force divided by the original cross-sectional area of the sample) and the linear slope at 2 % engineering strain was taken as the Young’s modulus.

Adhesion tests of the tissue adhesive applied to the HOA. Current products on the market, such as Stomahesive, Ostobond, and Karaya gum powder were used as comparisons to the current device. Adhesion strength was determined through two tests. All tests were done on porcine skin. First, a lap shear test was used to determine shear strength. Shear strength was evaluated on each of the adhesives due to the ostomy bag's innate design, a bag with weight exerting a shear force on the adhesive to the skin.

20 mm x 50 mm strips of porcine skin and ostomy bag adhesive (from Celecare) were cut and adhesives were then applied onto 40 mm of the strip, leaving 10 mm for anchoring purposes (A binder clip

was clipped to the ostomy bag adhesive while the vice secured the porcine skin). The Dual-Range Force Sensor was then hooked onto the binder clip and was pulled to create a shear motion. (Video recorded displacement of the porcine skin and ostomy bag adhesives) (See Figure 4 for images of the setup)

To derive shear strength, the maximum force is found until fracture and is divided by the total initial area of bonding:

$$\text{Shear Strength} = \frac{F_{max}}{WL} \qquad \text{(Eq. 3)}$$

where W is the width of the adhesive area while L is the length of the adhesive area.

Then, a peel test was used to test the resistance to peel forces. Methods were similar to that of the shear strength test. Adhesion energy with peel tests was measured in terms of interfacial toughness with the units of kJ/m^2, while the shear test was measured in terms of shear with the units of kPa. (See Figure 4 for images of the setup)

Interfacial toughness can be defined as:

$$\Gamma = \Gamma_o + \Gamma_d \qquad \text{(Eq. 4)}$$

where Γ_o is equal to the chemically anchored interfacial toughness, Γ_d is equal to the interfacial toughness that is around the interface, and Γ is equal to the total interfacial toughness of adhesion. $F_{plateau}$ is found by determining the steady-state of the peel test. The peeling rate of 50 mm/min was used to measure interfacial toughness (Fig. S3). A simple calculation can then be done to find Γ through the equation after measuring the force plateau of the peel test:

$$\Gamma = \frac{F_{plateau}}{2W} \qquad \text{(Eq. 5)}$$

Additionally, as a qualitative measure of adhesion strength, the HOA was attached to porcine skin with the chitosan tissue adhesive and an 11 cm x 11 cm plastic plate or ostomy bags were attached to the HOA by cyanoacrylate glue (Loctite Super Glue). Once the plate was attached while in contact with the HOA, a 500 g mass was clipped onto the ledge of the plastic plate and was suspended for 20-30 minutes.

Device endurance tests. The endurance of the device was first measured in vitro. A mock setup simulated the environment of an ostomy. A tube is attached to a supply of tap water. The other end of the tube leads to a 3D printed stoma that allows for water leakage to simulate the process of excretion (Images of the setup are included in Fig. S4) Over the course of 12 hours, the HOA is left out adhered on porcine skin attached to the mock setup. A light stream of water is continuously run through the mockup and onto the HOA device. Every hour, an image was recorded to determine the endurance of the device in terms of hydration and drug delivery.

For the in vivo test, the HOA device onto the forearm or the right hypochondriac and right lumbar of the abdomen for 24 hours. The human subject was participated the experiment with consent (the author, W.P.) and the safety precautions were taken to ensure the experiment caused no pain, irritation, or damage to the human subject's skin based on the Material Safety Data Sheets (MSDS) of the HOA and chitosan adhesive. An image was then taken every 3 hours to record the status of the device.

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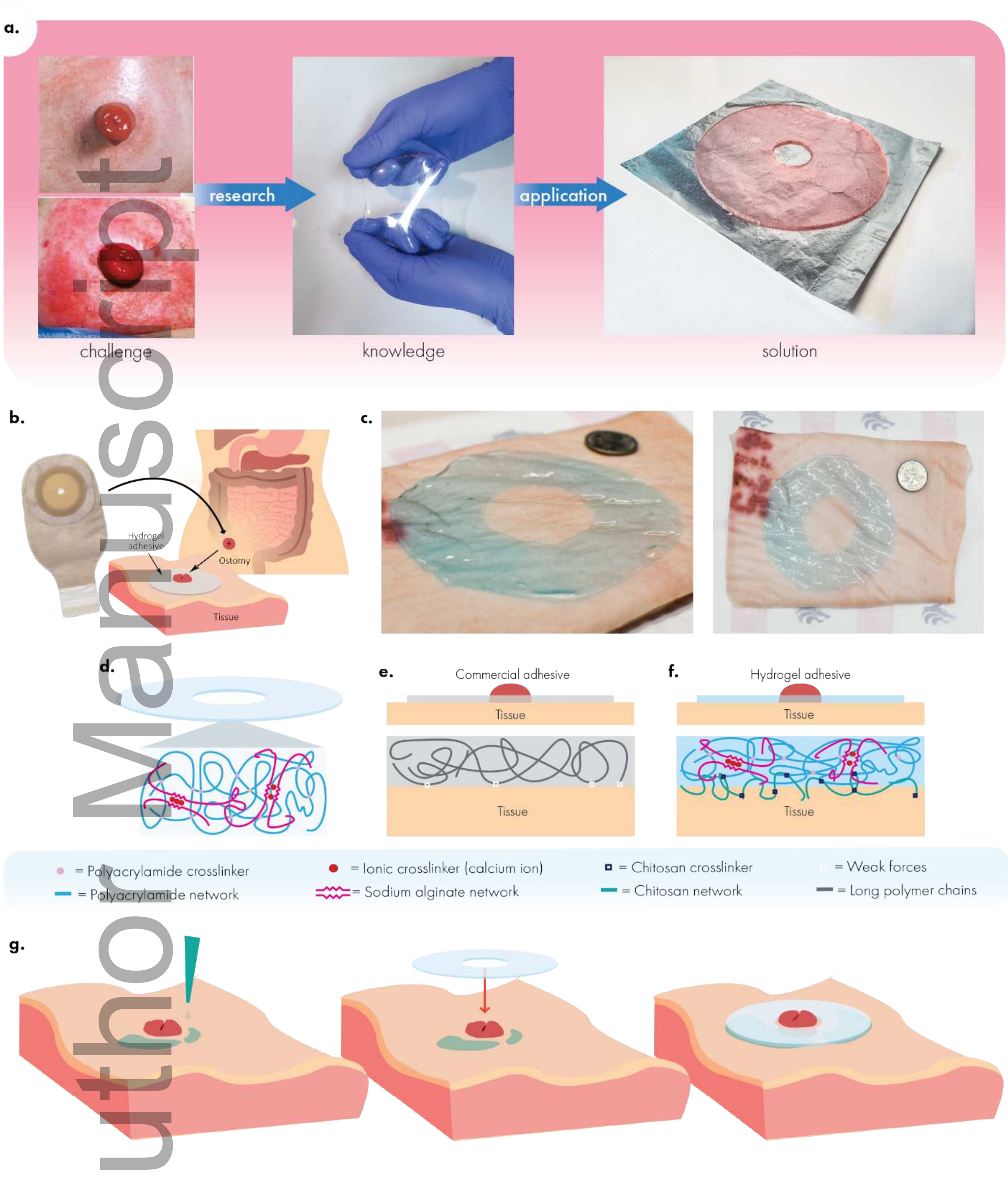


Figure 1 | Design and mechanism of the HOA. a. The top shows a normal stoma while the bottom shows a stoma with dermatitis caused by leakages (Photo credit: ConvaTec). The HOA along with the chitosan tissue adhesive can provide improved adhesion of ostomy bag to skin. **b.** The HOA is applied to the ascending colostomy. Devices, such as the ostomy bag as shown, can be applied to various other places such as transverse colostomy, jejunostomy, and left colostomy.

c. Images of the HOA on porcine skin for in vitro testing. **d.** The HOA consists of the double-network hydrogel of covalently-crosslinked polyacrylamide and ionically-crosslinked alginate networks. **e.** Commercially-available ostomy adhesives adhere to skin based on weak intermolecular forces such as Van Der Waal's forces to create temporary adhesion. **f.** The HOA adheres to skin based on topological adhesion between the skin and the hydrogel network by chitosan polymers. **g.** The application process of the HOA based on the chitosan adhesion solution.

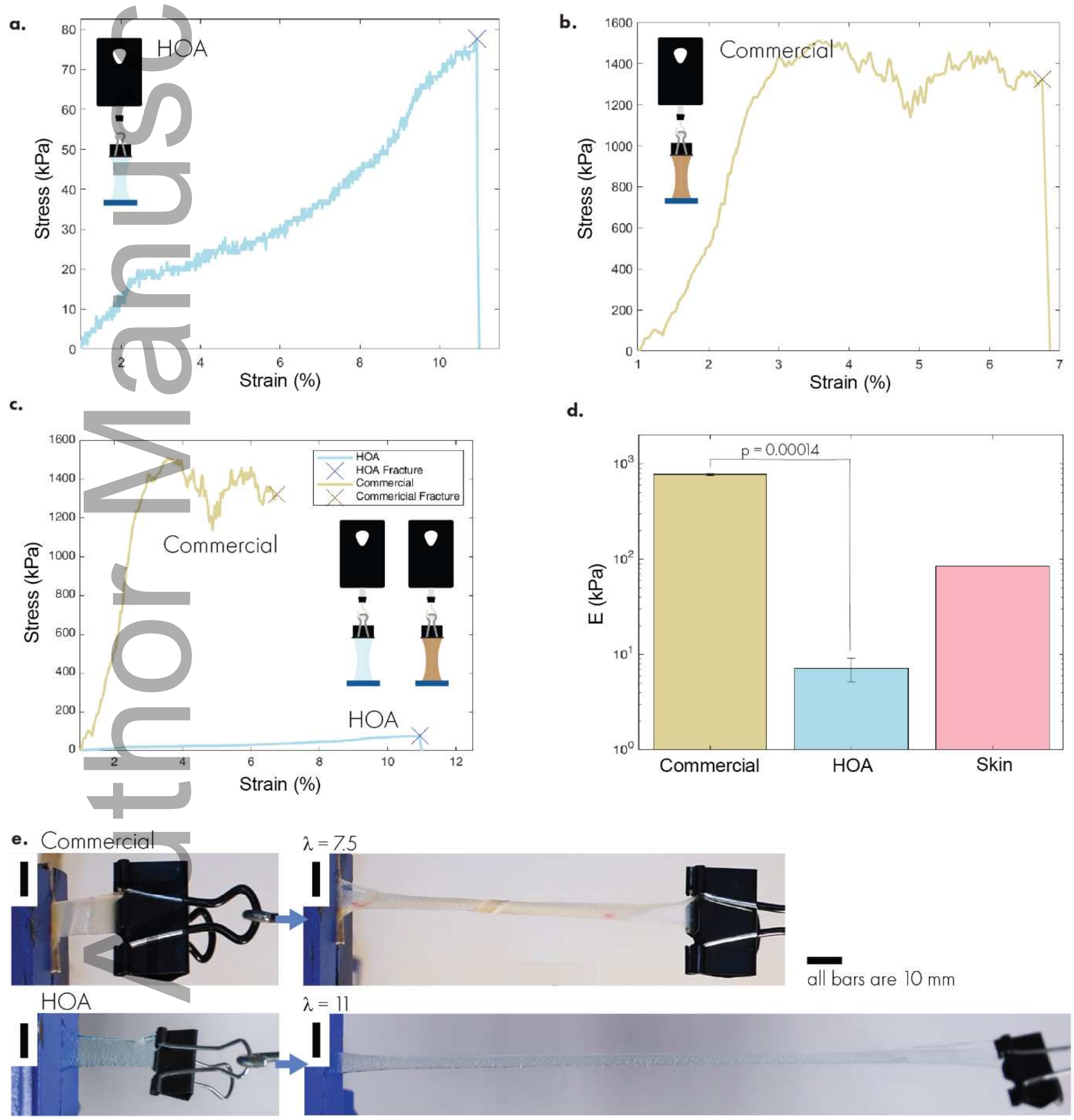


Figure 2 | Mechanical properties of the HOA. a. Engineering stress vs stretch curve of the HOA. **b.** Engineering stress vs stretch curve of a commercially-available ostomy bag material. **c.** Engineering stress vs stretch curves of the HOA and the commercially-available ostomy bag material shown together. **d.** Young's modulus of the HOA, commercially-available ostomy bag material, and human skin. **e.** Time-lapse images of the commercially-available ostomy bag adhesives (top) and the HOA (bottom) near the maximum stretch. The bars represent a length of 10 mm. The *p*-value is calculated by the Student t-test.

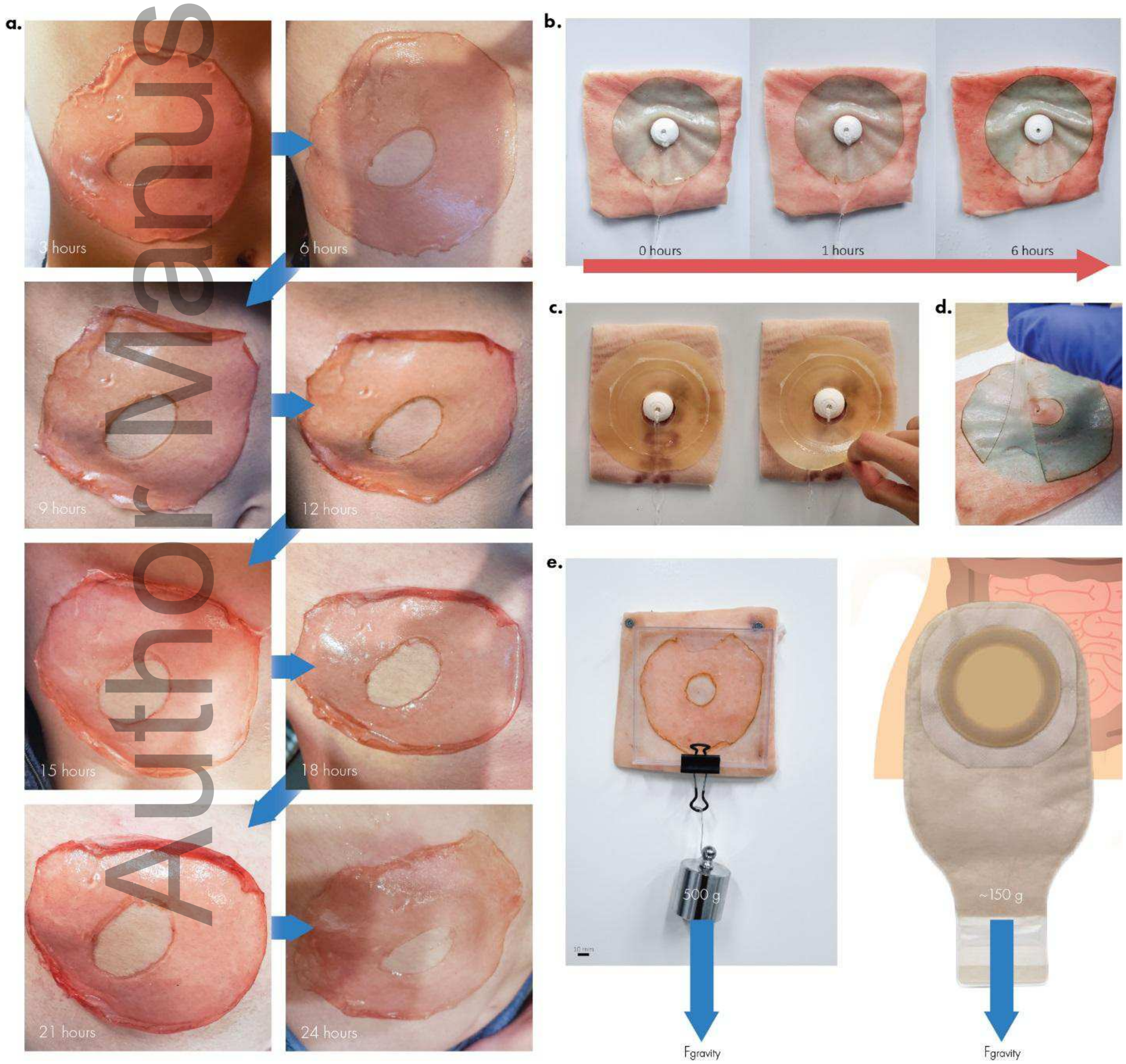


Figure 3 | Robust and durable adhesion of the HOA on skin. a. The HOA along with the chitosan tissue adhesive was applied onto the right hypochondriac and right lumbar of the abdomen skin. For every 3 hours, an image of the HOA was taken to monitor the adhesion and mechanical strength of the HOA. **b.** Time-lapse photos are shown of the HOA with adhered to chitosan tissue adhesive seconds after adhesion, 1 hour after adhesion, and 6 hours after adhesion on a mock ostomy tester based on porcine skin. **c.** The durability test of commercially-available ostomy bag adhesives shows weak bonding to the porcine skin when liquid flow as simulated. The adhesive can easily be peeled off and slip off the porcine skin. **d.** Even after 12 hours of adhesion with the HOA, strong adhesion was present between the HOA and the porcine skin along with high mechanical strength. **e.** The HOA was bonded to porcine skin for 12 hours and a plastic plate was adhered to the HOA to attach a 500 g weight (4.9 N of force).

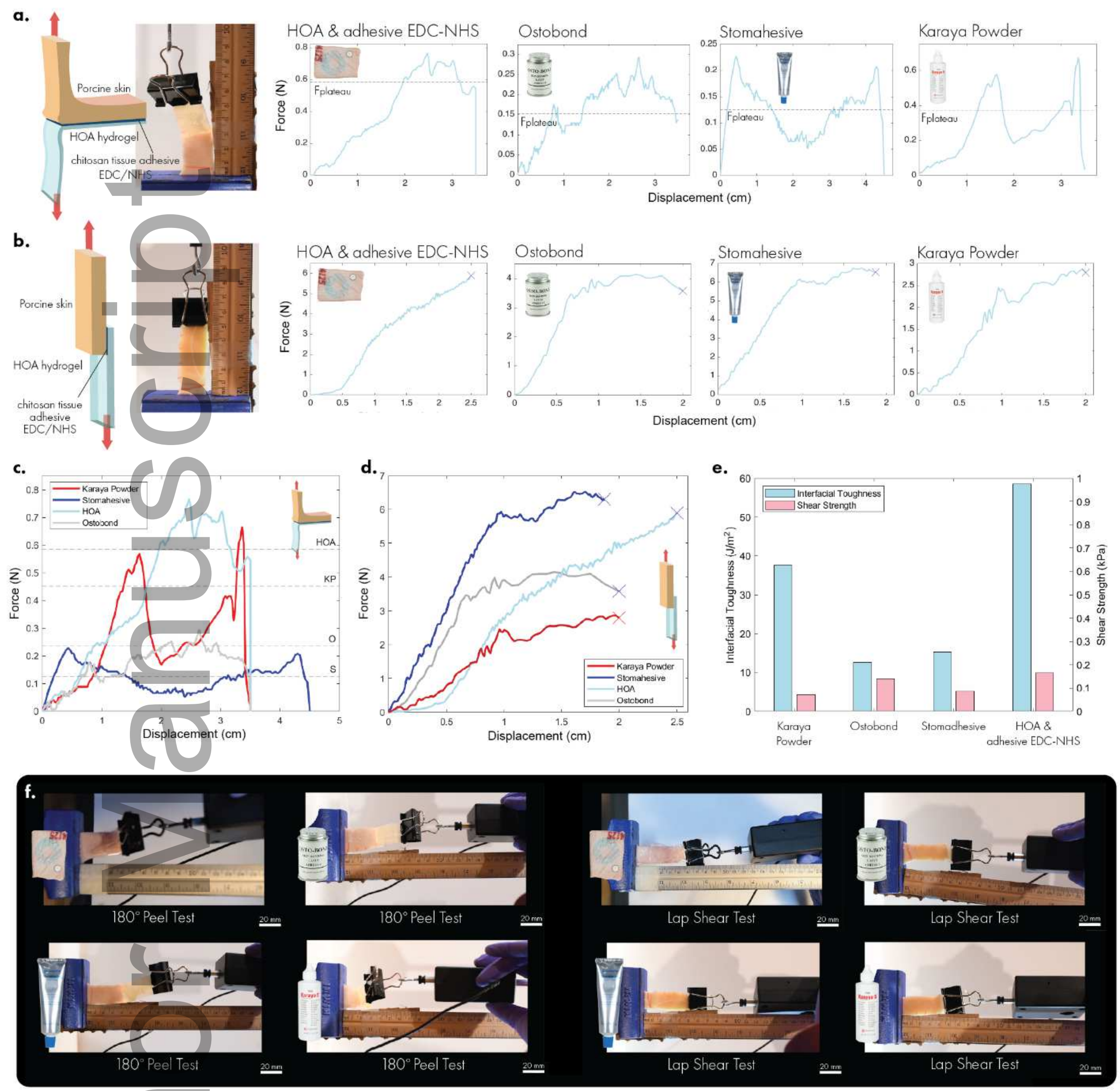
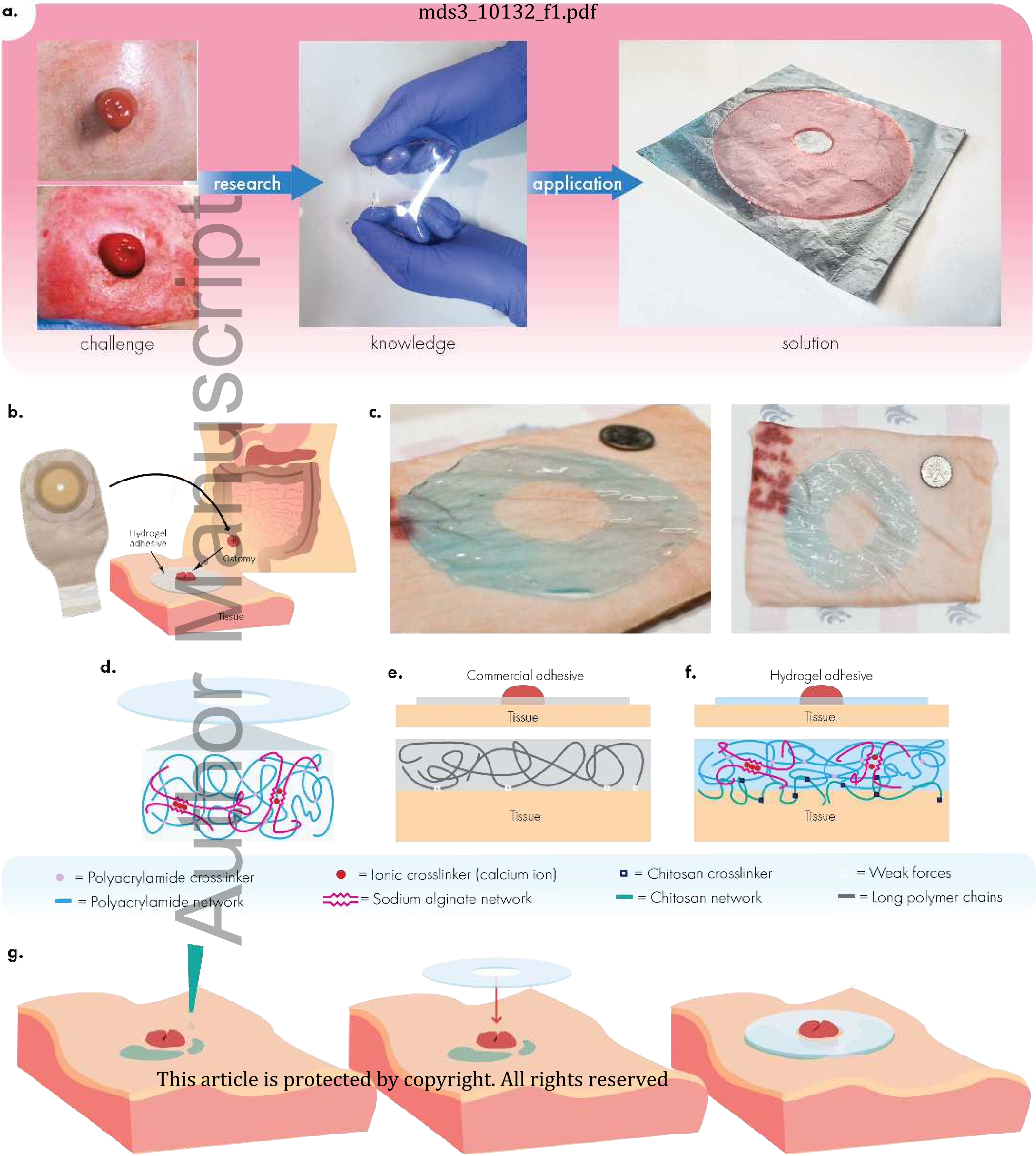
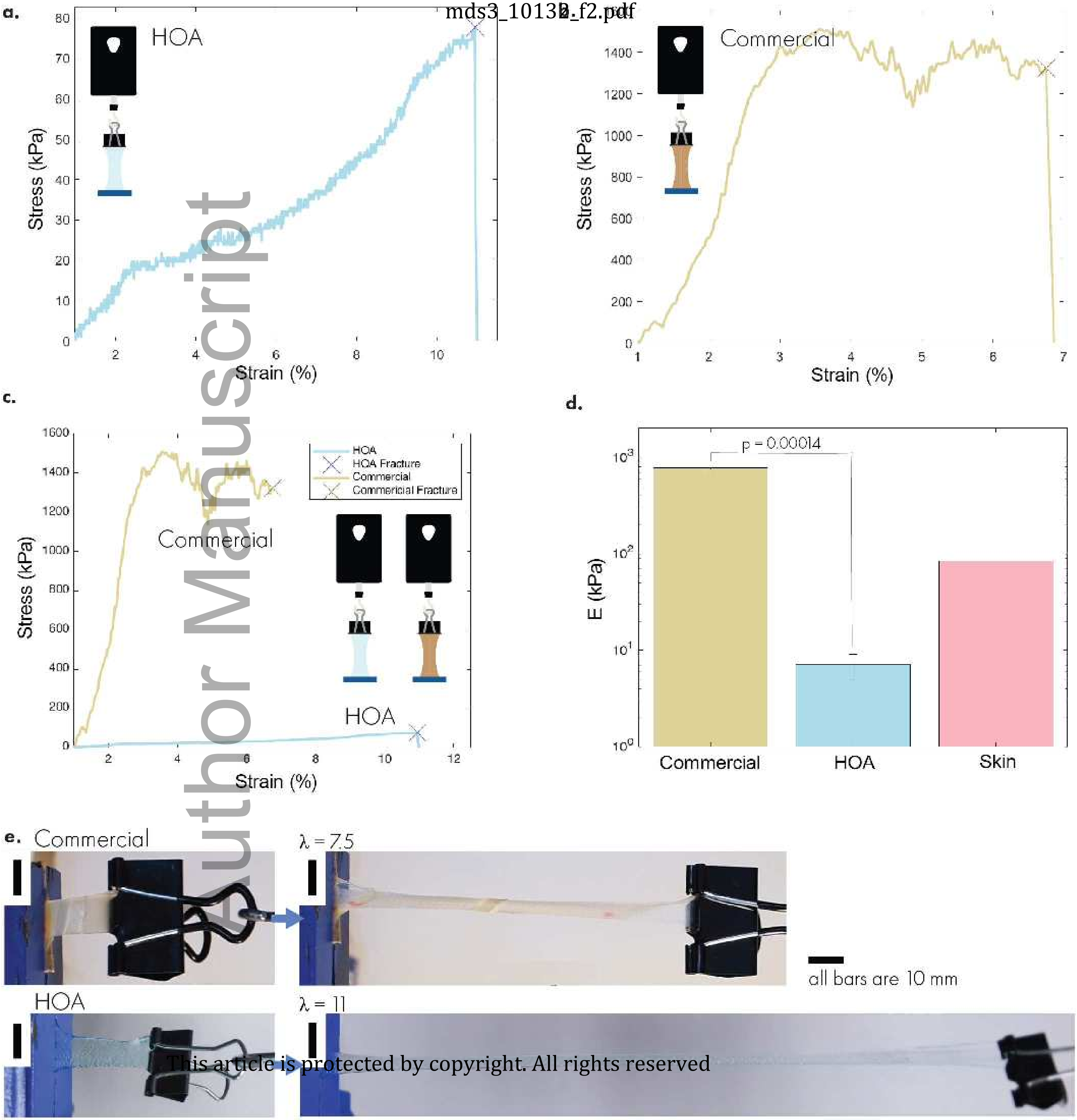


Figure 4 | Adhesion performance of the HOA. a. A 180^{o} degree peel test was to determine the interfacial toughness of each of the different solutions. (Top left is Karaya Powder, top right is Stomahesive, bottom left is Ostobond, and bottom right is the HOA). **b.** A lap-shear test was used to determine the shear strength of each of the different solutions (Top left is Karaya Powder, top right is Stomahesive, bottom left is Ostobond, and bottom right is the HOA). **c.** Representative testing curves for the 180^{o} degree peel tests. **d.** Representative testing curves for the lap-shear tests. **e.** Measured interfacial toughness and shear strength of the HOA and commercially-available ostomy bag adhesives **f.** Representative images of the adhesion performance tests for the HOA and commercially-available ostomy bag adhesives.


a.
research
application
challenge
knowledge
solution
b.
Hydrogel adhesive
Ostomy
Tissue
c.
d.
e.
Commercial adhesive
Tissue
Tissue
f.
Hydrogel adhesive
Tissue
Tissue
= Polyacrylamide crosslinker
= Polyacrylamide network
= Ionic crosslinker (calcium ion)
= Sodium alginate network
= Chitosan crosslinker
= Chitosan network
= Weak forces
= Long polymer chains
g.


a.
HOA
Stress (kPa)
Strain (%)
Commercial
Stress (kPa)
Strain (%)
c.
Commercial
HOA
HOA
HOA Fracture
Commercial
Commercial Fracture
Stress (kPa)
Strain (%)
d.
p = 0.00014
E (kPa)
Commercial
HOA
Skin
e.
Commercial
λ = 7.5
all bars are 10 mm
HOA
λ = 11

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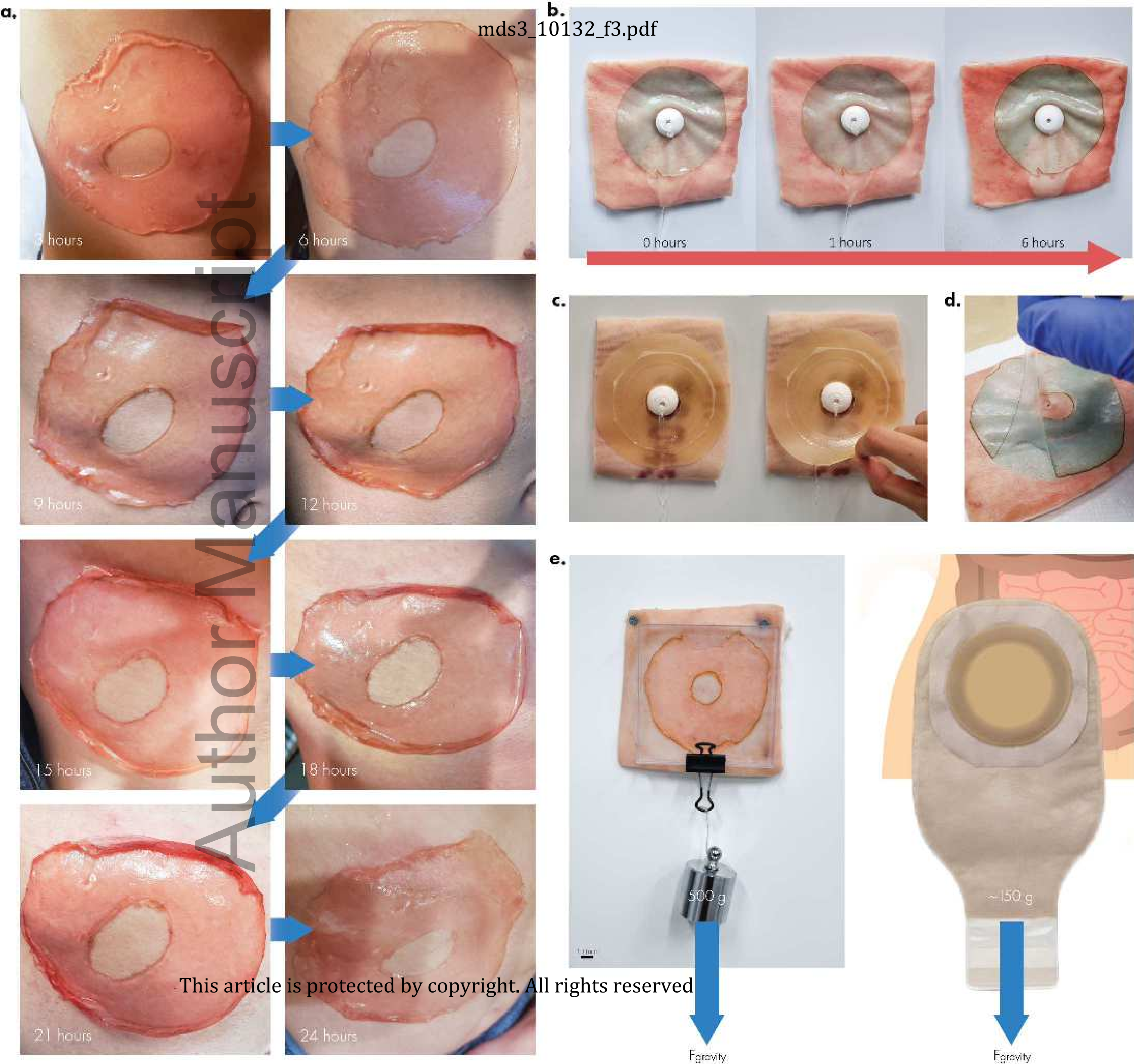

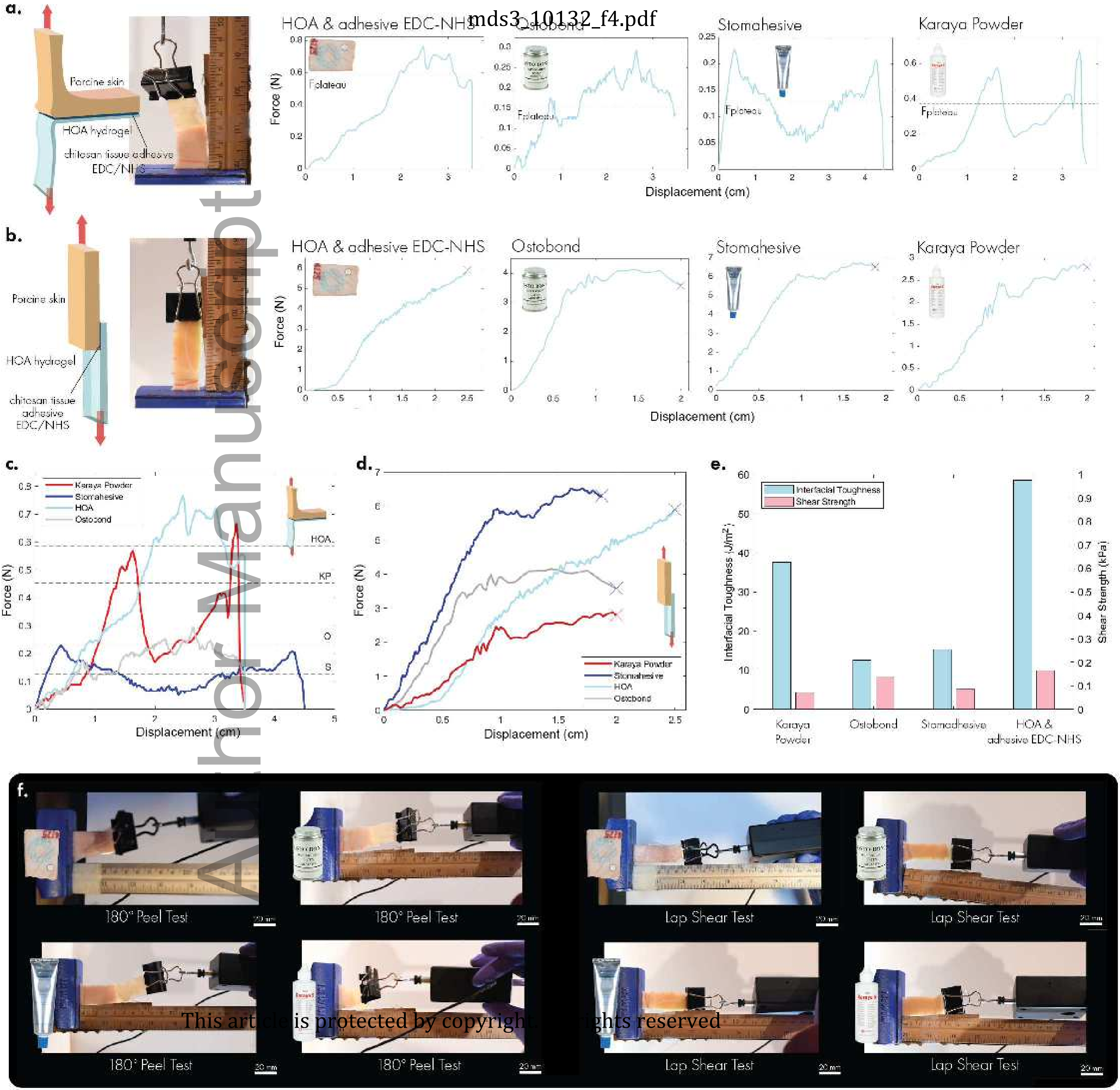
a.
Porcine skin
HOA hydrogel
chitosan tissue adhesive
EDC/NHS
HOA & adhesive EDC-NHS
Ostobond
Stomahesive
Karaya Powder
Fplateau
Force (N)
Displacement (cm)
b.
Porcine skin
HOA hydrogel
chitosan tissue
adhesive
EDC/NHS
HOA & adhesive EDC-NHS
Ostobond
Stomahesive
Karaya Powder
Force (N)
Displacement (cm)
c.
Karaya Powder
Stomahesive
HOA
Ostobond
HOA
KP
O
S
Force (N)
Displacement (cm)
d.
Karaya Powder
Stomahesive
HOA
Ostobond
Force (N)
Displacement (cm)
e.
Interfacial Toughness
Shear Strength
Interfacial Toughness (J/m²)
Shear Strength (kPa)
Karaya Powder
Ostobond
Stomadhesive
HOA & adhesive EDC-NHS
f.
180° Peel Test
180° Peel Test
Lap Shear Test
Lap Shear Test
180° Peel Test
180° Peel Test
Lap Shear Test
Lap Shear Test
20 mm