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A Novel Approach for Visualising the Liquid Droplet Transfer Mechanism From a Surface to a Finger Pad Using Optical Coherence Tomography

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ABSTRACT

Viruses and microbes can be transferred from one surface to another via liquid droplets that result from, for example, sneezing. The exact mechanism of transfer from a surface to a finger-pad, however, has not been well studied. This novel work investigated how droplets are picked-up and how much liquid remains on each surface after contact is broken during a 'touching event' using optical coherence tomography (OCT) images. These showed that the droplet was pulled towards the finger-pad as it approached and formed an 'hour-glass' shape as the finger-pad moved away from the surface before splitting between surfaces as contact was broken. Despite the spread of liquid during the contact, after the touch, droplets reformed. Three-dimensional images of the droplets before and after the touch were used to determine the change in volume. For the droplets tested (0.40–1.85 mm^3), the results consistently showed a transfer of 77%–94% of the volume to the finger pad, suggesting that within this volume range, the transfer mechanism remains stable for this specific liquid-surfaces interaction. This study demonstrates the potential of OCT for studying liquid droplet transfer. This is important in designing surfaces for reduced liquid transfer and for improving models of droplet behaviour.

1 | Introduction

The role of water or moisture in the tribology of the finger pad is complex. Unlike materials in conventional tribology, human plantar skin is able to absorb or release water. Many researchers have investigated the role of moisture in finger pad friction [1–4]. It is generally found that friction of the finger pad will increase when the skin is slightly moist, as the liquid is absorbed increasing the compliance of the skin and therefore increasing the surface contact area. However, if there is too much water, then it might lubricate the contact as not all the liquid can be absorbed. The amount of water absorbed is also affected by the temperature of the skin [5]. This leads to an interesting question as to how liquid is transferred between the finger pad and a counter-surface during a touching event. Knowledge of this process could help, for example, in designing surfaces to enhance frictional control. Another reason for having a more detailed understanding of this transfer mechanism that has emerged more recently and is related to the transfer of viruses via surface touch events [6]. Recent work has focused on investigations into how the virus was transferred during the COVID-19 pandemic [7]. As people sneeze or cough, liquid in droplet form and is ejected from the body. Small liquid droplets stay air-borne for an extended period whereas larger liquid droplets will be deposited on nearby surfaces. Various studies [6–10] have extensively investigated virus transmission through contact. The amount of transfer with different surfaces and environmental conditions was assessed, for example by using biomarkers [11], but none studied the transfer mechanism of the virus carrier, in this case liquid droplets. Understanding what happens with droplets is important as water plays a vital role in enhancing the delivery of chemical or drugs via percutaneous penetration [5]. Hydrated skin could cause an increase in the absorption rate of substances in the stratum corneum (top layer of the epidermis) to 10 times compared with dehydrated skin [12].

Optical Coherence Tomography (OCT) has been previously used to study the morphological changes of a finger pad skin (see e.g., [13–17]). In addition, one previous study [18] also used OCT to image liquid droplets to track the flow patterns within the droplet as it evaporated. It was realised, therefore, that this may provide an approach for studying finger pad/droplet interactions. Therefore, this study aimed to study how a small liquid droplet behaves as the finger pad approaches a contact surface and interacts with it, using OCT.

2 | Methodology

2.1 | Test Subject and Liquid Droplet Preparation

The test subject was a 30-year-old Chinese ethnicity male with no history of skin disease. The tests were performed on the index finger in its natural state without any pre-treatment. The environmental conditions during the tests were 22°C and 45%–50% relative humidity. The protocol of the study was approved by The University of Sheffield ethics committee (041069). Experiments were performed on the left index finger

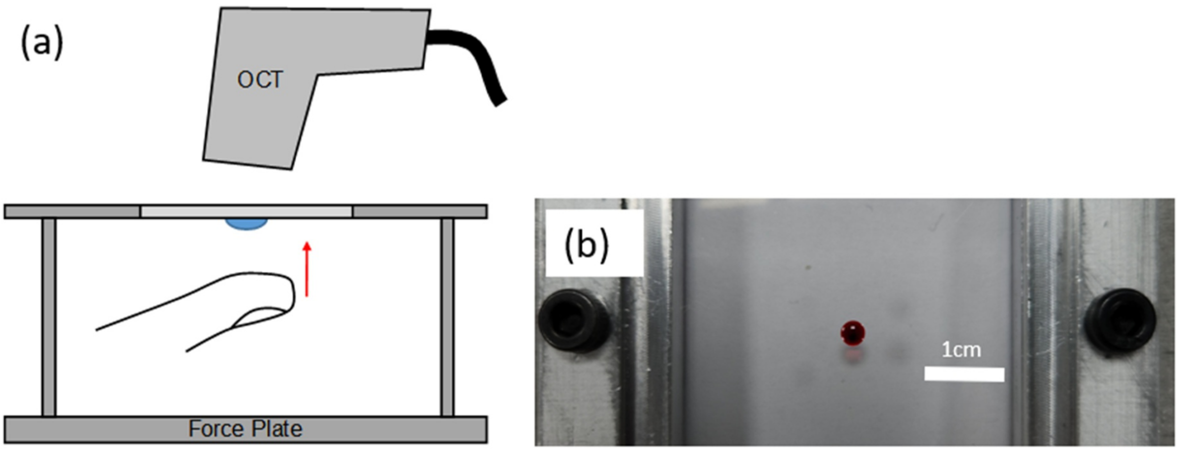

FIGURE 1 | (a) Imaging rig and (b) the condition of the liquid droplet as applied on the transparent plate.

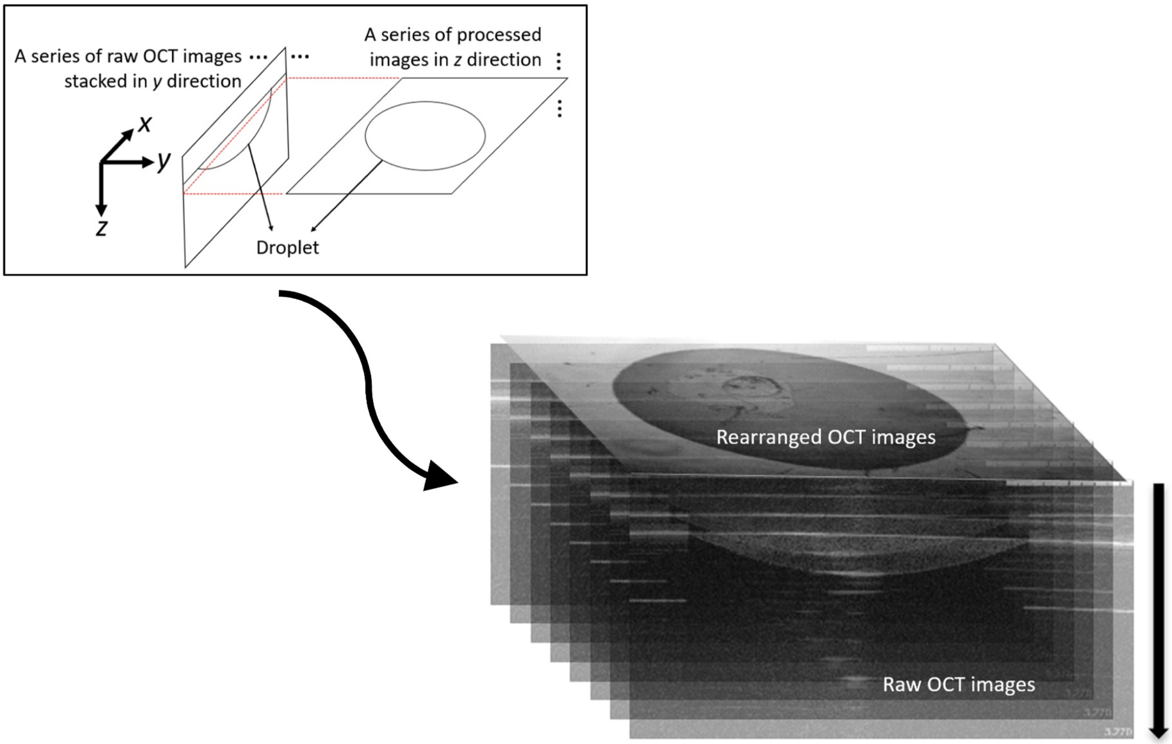

FIGURE 2 | Stacked raw OCT images and rearranged image.

of the subject. To ensure a consistent surface state free of surface contaminants, the finger was cleaned using a mild soap and water solution and patted dry with a lint free tissue. The subject then remained within the laboratory environment for 10 min prior to the start of the test to allow the skin to acclimatise and reach a stable, natural hydration state. To prevent cross contamination or residual effects from previous droplets, the cleansing and acclimatisation protocol was strictly repeated between each individual test, ensuring that each observation began from a consistent baseline.

As OCT relies on light reflection to visualise the liquid, test trials were performed initially on multiple liquid types (clean tap water, liquid food colouring of various pigments, water with flour and honey) to determine the most suitable liquid formulation for OCT visualisation. Clean tap water and honey were dropped because these liquids were invisible in the OCT images. Flour water made the liquid droplet visible in the OCT image, but the flour in the liquid droplet would fall to the bottom of the liquid droplet after approximately 15 min. Food colouring proved to be the most suitable sample in this project because its contents allowed the liquid droplet to be projected onto an image near perfectly without many changes in the OCT image for a long period of time (6 h). The ingredients of the red food colouring used were vegetable glycerol, water, carmine, curcumin, propylene glycol, emulsifier and acidity regulators.

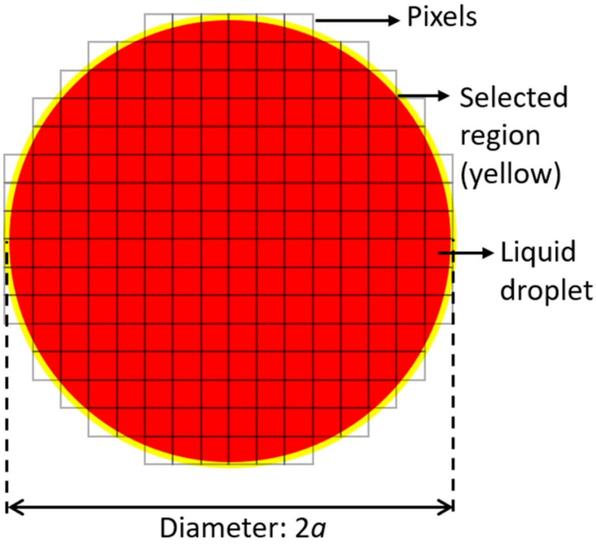

FIGURE 3 | Pixel calculation (view from above the droplet).

A syringe with a large tip was used to apply the liquid droplet on a transparent plate (0.5 mm thickness) as shown in Figure 1b. The amount of liquid applied in this test ranges from 0.40 to 1.85 mm^3. A micropipette could not be used because the dispensing of the food colouring was difficult due to its high viscosity. As such, it was difficult to exactly control the volume of each liquid droplet. Instead, this work focused on measuring the liquid volume change post-application and contact with a finger pad.

2.2 | Optical Coherence Tomography (OCT) and Imaging Rig

OCT is a non-invasive imaging technique and has been previously used to image skin and contact interaction with different counterface surfaces [13, 19]. A clinically approved Vivosight OCT system (Michelson Diagnostics, Kent) has a Fourier domain with a 20 kHz swept source laser at 1300 nm centre wavelength, 7.5 μm lateral and 5 μm axial resolution. The resolution of the raw images is 895 × 483 pixels. The assembly (OCT and imaging rig in Figure 1a) used is the same as that used in the study by Lee et al. [20]. The imaging rig used has a three axial force plate (AMTI) that measures up to a 40 N load.

2.3 | Static Touch Test

There were two types of tests carried out for assessing static touch effects on a droplet. The first test focused on capturing the liquid transfer mechanism. The OCT was used to capture stills at the same spot over time during the touch event. The second test focused on measuring the droplet size on the transparent plate before and after a touch contact to assess of the amount of liquid transferred from surface to finger pad. A 3-dimensional imaging technique was employed to scan the liquid droplet before and after each test. This technique captured 500 images at 0.01 mm intervals, resulting in 5 mm wide scanning region. This test compared the size of the liquid droplets at loads of 0.5, 1.0, 3.0 and 5.0 N applied by the finger pad. The finger pad was brought into contact slowly with the liquid droplet and held for 5 s before it was removed from the contact area. A conventional digital camera (resolution of 6120 × 8160 pixels) was also used to capture the liquid droplet before and after tests to compare with the size measured using OCT.

2.4 | Data Analysis of the OCT Images

After obtaining the raw OCT images of the liquid droplet, they can be stacked in y direction to give a 3-dimensional view, as

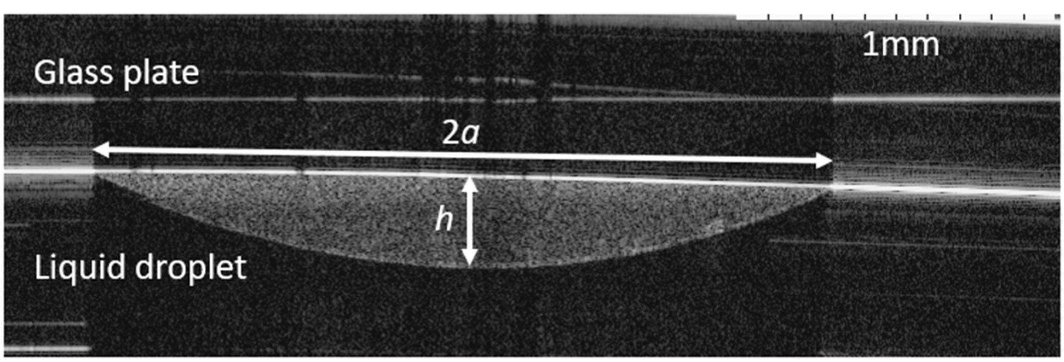

FIGURE 4 | The raw OCT image of the liquid droplet.

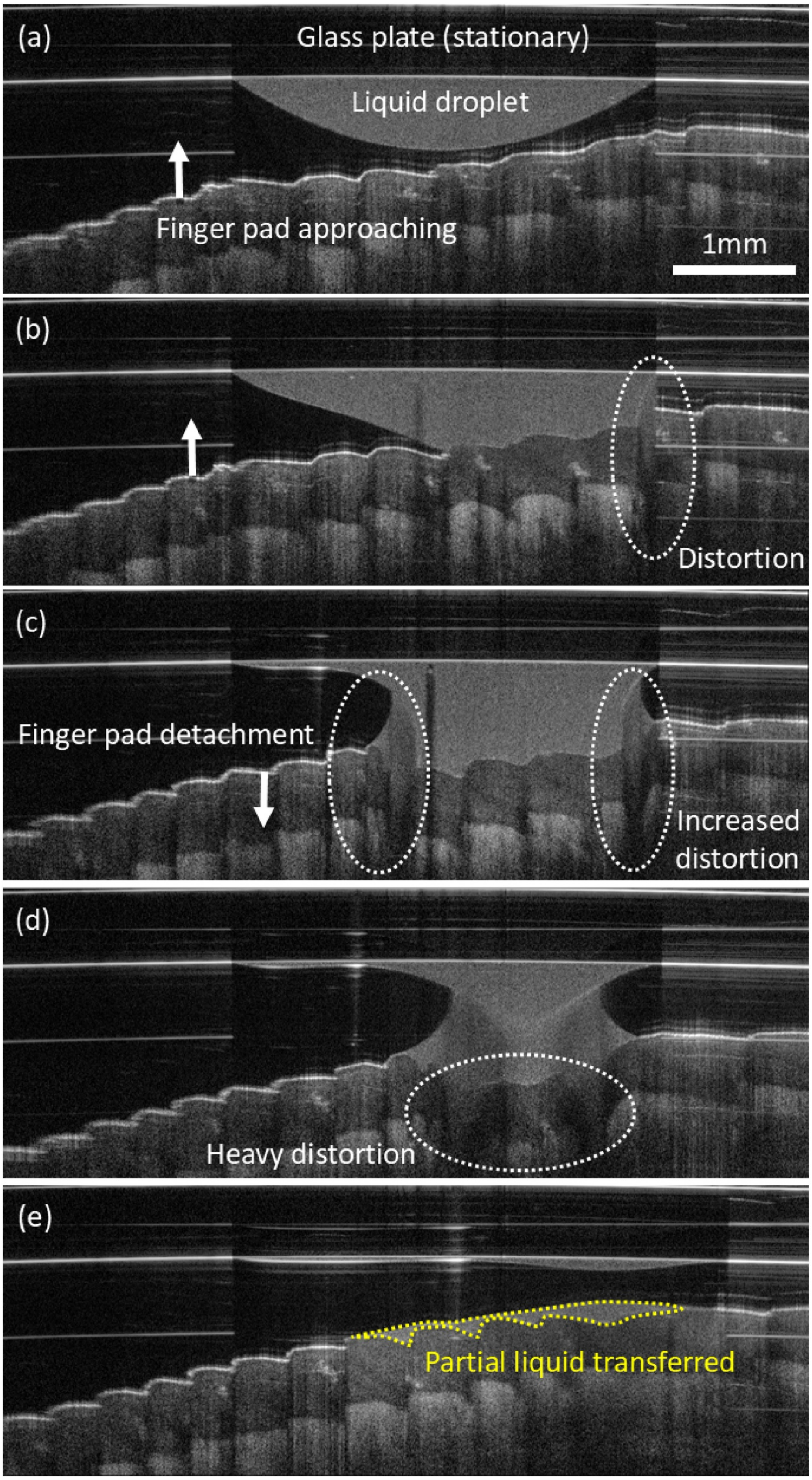

FIGURE 5 | (a–e) Chronological order of liquid droplet interacting with the finger pad.

shown in Figure 2. This allowed the image processing software (ImageJ) to produce new images from different views, for example in the z direction, as also shown in Figure 2. Then, the processed images were used to determine the size of the liquid droplet. This was achieved by calculating the number of pixels in a selected region. For instance, Figure 3 shows the liquid droplet and the pixels in the selected region looking from above. Knowing the number of pixels in the selected region and the resolution of the image gives the exact size and area of coverage of the liquid droplet.

The yellow areas outlined in Figure 3a have been drawn to estimate the area covered by the applied liquid droplet. The volume of the liquid can be estimated by using the volume formula for a spherical cap (1). The base radius of the cap, a, can be measured from the base area calculated in Figure 3a whereas the height of the liquid, h, can be measured from the OCT image as shown in Figure 4. The OCT image selected must have the largest h value from scans across the droplet.

$$V_{\text{Liquid droplet}} = \frac{1}{6}\pi h\left(3a^2 + h^2\right) \tag{1}$$

3 | Results

3.1 | Liquid Transfer Mechanism

Figure 5a–e shows images extracted from those taken over time during a finger pad touch contact. They show how a portion of the liquid was transferred to finger pad from the plate in a few stages. As the finger pad was approaching the liquid droplet (Figure 5a), the liquid was attracted to the finger pad. As soon as the finger pad contacted the liquid. The liquid appears to be ‘pulled’ (or drawn) towards the point of initial contact (Figure 5b). This is possibly due to the hydrophilic properties of the finger pad. The outer layer of plantar skin is made up of keratinised cell and keratin is hydrophilic [21]. The finger pad was then moving away after contacting the liquid for a few seconds. As the finger pad was moved away from the plate (Figure 5c,d), the liquid seemed to form a ‘string’ and when this was broken, part of the droplet stayed with the finger pad while the rest remained on the plate. It is interesting to see how, although the ‘string’ is quite narrow the liquid spreads back out when it is broken on both the surface of the plate and the finger pad. It was observed that there were distortions at the edge of the image of the liquid in Figure 5b,d. The distortion worsened when the liquid was breaking apart (Figure 5d). This in turn led to the partial mixture of liquid and air in the travel path of the light photons in OCT, causing them to scatter as they travelled.

3.2 | Liquid Droplets Before and After Contact

By using a 3-dimensional imaging technique to capture the liquid droplet, OCT images could be ‘stacked’ to form a new image that allowed the liquid droplet to be viewed at different angles. Figure 6a shows the size of the liquid droplet before a test. After the contact event, it was evident that the liquid droplet size was reduced, as shown in Figure 6b, and there was some liquid droplet (ranges from 0.02 to 0.21 mm^3) residue spread around the liquid drop (post-test). The OCT images also

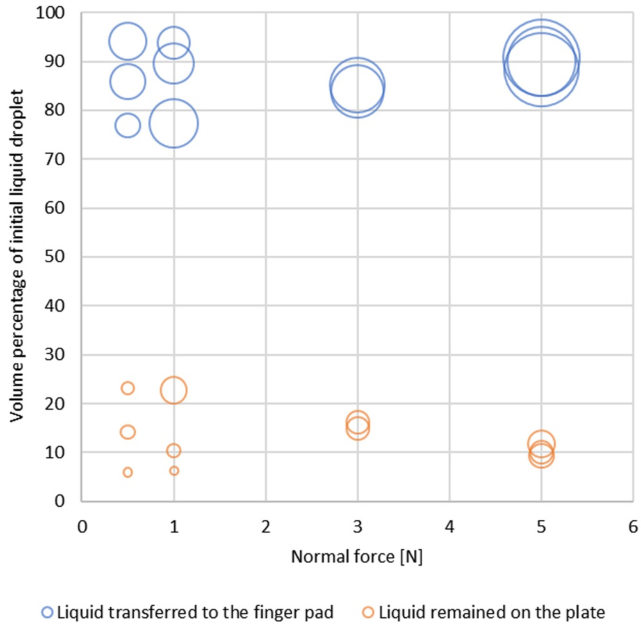

FIGURE 7 | The volume percentage distribution of the liquid between the finger pad and the plate after the finger pad touched the liquid droplet determined from analysis of OCT images. The size of the bubble represents the actual amount of the liquid transferred or remained.

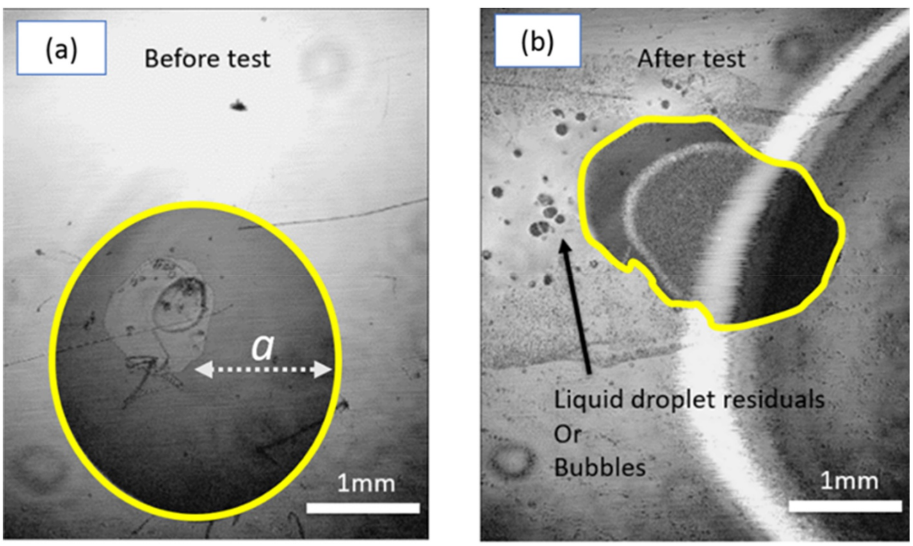

FIGURE 6 | OCT images of the liquid droplet: (a) before a test and (b) after a test.

showed that a liquid droplet will always reform (under the conditions used in these tests) on the plate after the finger pad touch despite the change in size or shape during the contact.

The distribution of the liquid volume between the finger pad and the plate after the touch is shown in Figure 7. Despite the wide range of initial volume of the liquid droplet applied ($0.40\ mm^3 < V_{initial\ liquid\ droplet} < 1.85\ mm^3$), the amount of liquid remaining on the plate was consistently low ($0.02\ mm^3 < V_{liquid\ remained} < 0.21\ mm^3$).

3.3 | Comparison Between Imaging Techniques in Measuring the Base Area of the Spherical Cap

Additional images of the liquid droplet were taken using a conventional digital camera with a resolution of 6120 × 8160 pixels. The images were taken from the top of the liquid droplet, showing its base area instead of the height of the liquid droplet. The base area of the liquid droplet can then be measured from these images similarly in Section 2.4. The root mean square error was found to be = 0.49 mm^2, which shows the liquid droplet sizes extracted from the OCT images are credible.

4 | Discussion

4.1 | General Observations and Liquid Transfer Mechanisms

No previous studies have documented how a liquid droplet on a surface physically interacts with a finger pad during a 'touch event'. This was made more complex due to the limited options available in terms of imaging equipment to capture the interaction. In addition to developing the novel use of OCT to observe the liquid droplet interaction with the finger pad, the observations made of the liquid droplet interaction in this work can help in giving a better understanding of the liquid transfer mechanism. The observations are summarised in Figure 8 with more detailed given below.

Firstly, most of the liquid was transferred to the finger pad, leaving only 6%–23% of the liquid droplet on the glass plate after the 'touch event', as shown in Figure 9b. Most of the liquid droplet was transferred to the finger pad due to the relative position of the liquid droplet and the gravity (see Figure 8b). Therefore, the bulk of the liquid droplet shifted towards the finger pad when the finger pad moved away after touching the liquid, as shown in Figure 10b.

Secondly, the liquid droplet always returned to being a droplet after the 'touch event', as shown in Figure 11f for the glass plate and the finger pad respectively. The forming of the liquid droplet is dictated by the cohesion (attraction between the molecules of the same substance) and adhesion (attraction between the molecules of two different substances) of the liquid. As the finger pad was moving away from the plate in Figure 8e,f, the adhesive force was in action as the liquid droplet was sticking to both the glass plate and the finger pad whereas the cohesive force was holding the liquid droplet together without breaking apart. As the adhesive force of the liquid was stronger than the cohesive force, the liquid droplet curved inwards before breaking apart. The cohesive force then pulled the remaining 'available' liquid (after breaking apart) to form liquid droplets on both the surfaces. However, some liquid could not return to form a new liquid droplet due to the capillary forces (the force generated as liquid flowing through narrow spaces) as some liquid stuck between the finger pad ridges (see Figure 11e).

Thirdly, the reformed liquid droplet could shift from its original position, because the droplet tended to reform at the point where the finger pad last detached from the plate. The finger pad often moved very slightly through the tests. This made documenting the liquid droplet interaction more difficult because the liquid may shift outside of the OCT capturing range in real time. This phenomenon showed the difference in adhesive force between the glass plate and finger pad when in contact with the liquid droplet. The adhesive force between the finger pad and the liquid was higher than that of glass plate. Therefore, the liquid droplet tended to move where the finger pad went.

Based on the observations above, it can be concluded that the adhesion of the liquid plays a significant role in the liquid transfer mechanism. The liquid droplet needed to stick on other surface to transfer a certain amount of liquid from the droplet.

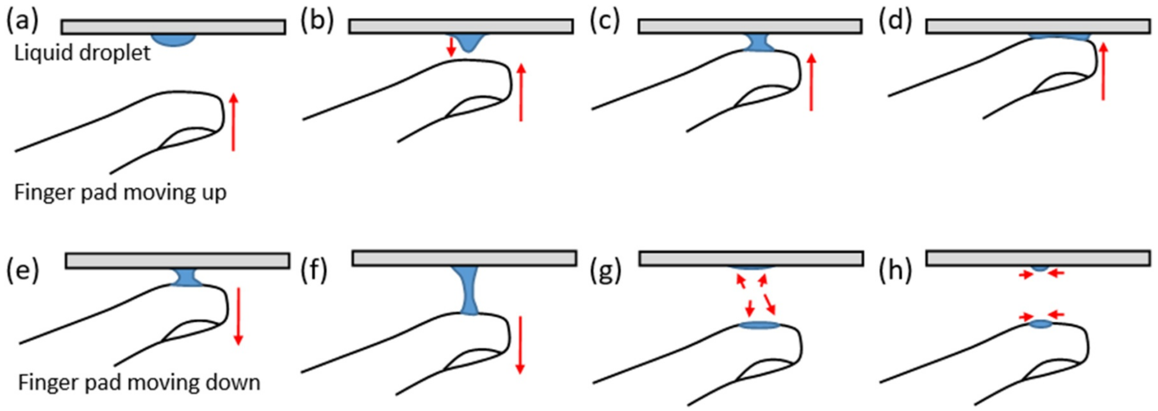

FIGURE 8 | The evolution of the transfer mechanism of the liquid droplet (stages (a–h) illustrate the droplet behaviour as the finger approaches, contacts and is then retracted from the surface and how the liquid splits between the finger and counterface).

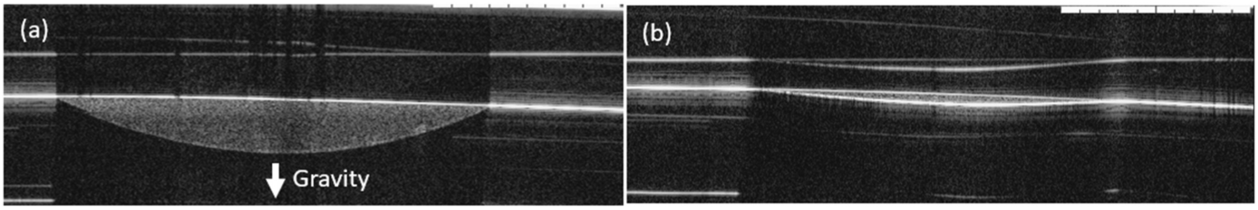

FIGURE 9 | The raw OCT image of liquid droplet on the glass plate: (a) before and (b) after a test at 1N.

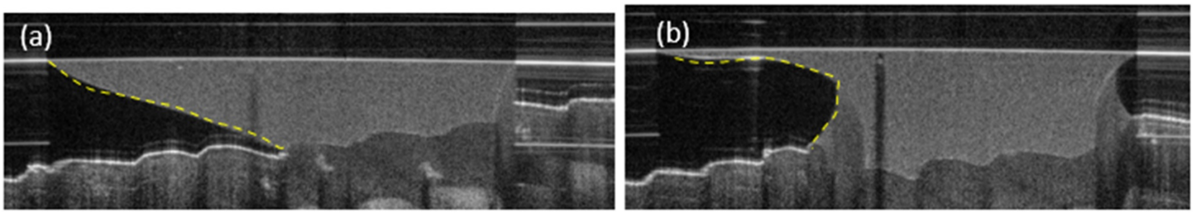

FIGURE 10 | The curvature of the liquid droplet when (a) the finger pad initially approached the liquid droplet and (b) moving away after touching.

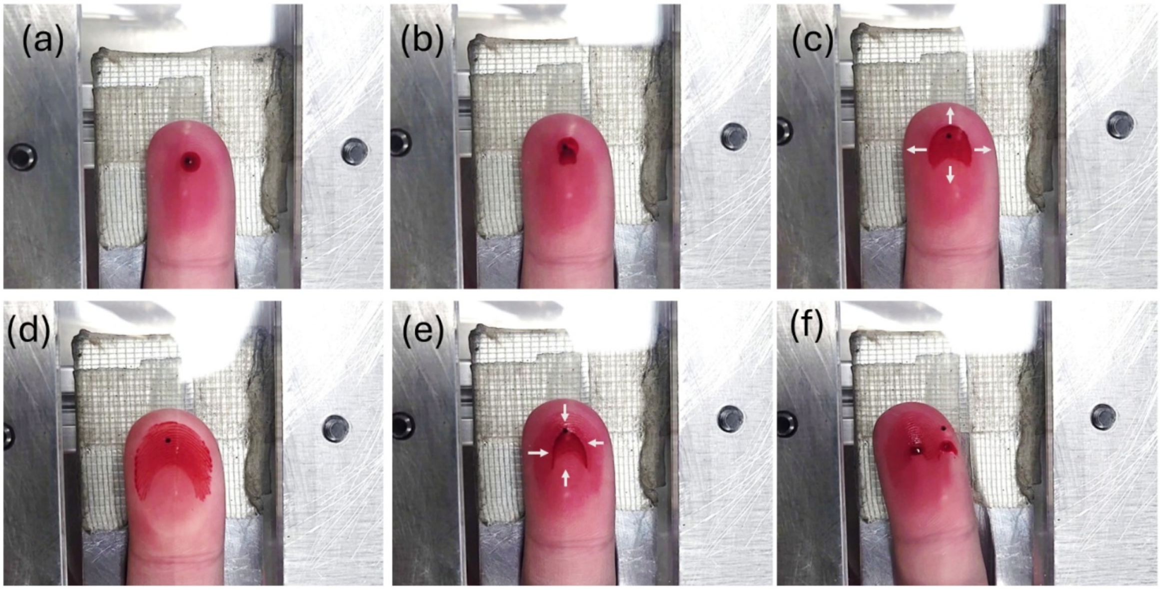

FIGURE 11 | Sequential stages of liquid droplet interaction with the finger pad: (a) Initial state prior to contact with the liquid droplet deposited on the glass plate; (b) incipient contact between the finger pad and the liquid bridge, prior to skin-plate contact; (c) expansion and sequestration of the liquid within the finger pad ridges as the finger pad made contact with the plate; (d) interface state at targeted normal contact force; (e) evolution of the liquid bridge as it pulled inwards during the initial stages of detachment, and (f) post separation state following full removal of the finger pad, showing the liquid transferred and the residual liquid remaining on the glass plate.

However, the adhesive level of the surface with the liquid, the cohesion, the gravity, the capillary force (only limited to finger pad) and the relative position of the liquid droplet will dictate the percentage amount of liquid transferred from one surface to another.

5 | Conclusions

This study explored the feasibility of using OCT to visualise the liquid transfer mechanism between finger pad and counter-surface. This technique shows the change in liquid shape and size in real-time while interacting with the finger pad. When the finger pad attempted to pull away from the counter surface after touching, the liquid seemingly pulled towards the finger pad surface due to a combination of adhesion and cohesion of the liquid and formed an inward curved 'hour-glass' shape as both surfaces were attempting to attract the liquid via adhesion. The liquid droplet was then separated into two smaller droplets, one of which was transferred to the finger pad and the other remained on the glass counter-surface. The OCT images generated 3-dimensional shapes for the liquid droplet which enabled the base area size of the liquid droplet and the volume to be determined before and after the 'touch event'. Although the initial area size of the liquid droplet was poorly controlled, the volume of the liquid droplet could still be estimated based on the OCT images taken. As such, it could determine that approximately 77%–94% of the liquid droplet was transferred from the glass plate to the finger pad due to various factors like the adhesion, the cohesion, the capillary action and the relative position of the liquid droplet to the gravity pull. In summary, OCT proves to be very useful in observing and studying the behaviour change in liquid droplet in the interaction of two materials.

While this study successfully establishes the feasibility of the OCT-based measurement framework, it is acknowledged that parameters such as substrate wettability and liquid viscosity fundamentally govern the volumetric transfer percentage. Preliminary evaluations of various media, including tap water, honey and flour-water suspensions, revealed significant limitations for the OCT imaging, ranging from excessive optical transparency to particle sedimentation. Ultimately, aqueous food colouring proved to be most suitable medium, providing the necessary optical scattering to optimise image contrast. Consequently, future research should prioritise the development of a suite of optically optimised fluids with tunable rheological properties. Such advancements will enable broader mapping of the interplay between fluid dynamics and contact mechanics, extending the utility of this sensing modality across diverse material systems.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

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