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Evaluation on an Optical Scanning Device for Skin Profile Measurement

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Synopsis

This paper describes experimental evaluations of an optical scanning device for skin surface recovery using multiple light source photometric stereo method. The portable optical device based on the principle of six-light photometric stereo was developed and subjected to evaluation and advancement through clinical trials for the purpose of monitoring skin conditions. As the device can provide objective topographic data for the description of the skin surface condition, the evaluation processes are mainly applied on skin *in vitro* and *in vivo* and compared with a commercial product, PRIMOS, which has been so far considered as a standard device used for skin surface measurement. The results of the experiment show that the topography measured by the device is significantly closer to that of the ground truth. Meanwhile, the new optical scanning device demonstrates better performance in measuring skin surface *in vivo*, superior to that of the PRIMOS.

INTRODUCTION

SKIN TOPOGRAPHY MEASUREMENT *IN VITRO* AND *IN VIVO*

As one of the largest organs of human body, it is important to be aware of changes in the condition of the skin surface as an important indicator of human health. However, the skin surface *in vivo* has proved difficult to monitor and record because of its complex characteristics. For example, it is complex in structure, elastic in behavior, and easily shrunk or stretched when subjected to extreme changes in the external environment. It is also optically complex in terms of its light transferring properties. As such, few instruments are available to measure such an object accurately (1).

Skin replicas were used as a simple and repeatable approach to record the microstructures of the skin without affecting skin function and structure. Essentially a negative skin replica can be easily obtained by smearing a silicon rubber material mixed with a catalyst over the skin surface. This is left for several minutes before being taken off. Fine details in the form of the furrows and peaks of the skin relief can be reproduced exactly when this process is carefully undertaken. After the replica has been produced, measurement of skin

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topography can be achieved by applying either a contacting stylus or some sort of optical systems to the surface of the replica (2). These traditional measurement techniques applied to static silicone replicas of the skin have proved very useful in recording skin topography with satisfactory accuracy for use in analyzing skin microstructure and anisotropy.

Although skin replicas have been used as a successful means to investigate the topography of the skin, there are a number of drawbacks associated with this kind of *in vitro* replication technique. First, the silicon replica can reproduce the structure of the skin, but fails to copy the color information of the skin which is also most important in skin disease diagnosis. Second, it takes a relatively long time to collect the data, which makes it unsuitable for real applications with short time requirements, as may be the case when collecting data in a primary care scenario. Third, considerable operator skill is required to successfully copy the skin using the replica method. To obtain a qualified replica, the sample should be taken on clean and dry skin under given specified temperature and humidity on standardized positions of the body and with correct specified mixture ratio of catalyst and paste. Finally, highly sensitive and/or damaged skin may not be durable to contact with the polymer replica materials directly.

Clearly an appropriate direct observation of the skin surface is clinically desirable, particularly given the aforementioned disadvantages of an indirect replica-based method. In a clinical setting, the most frequently used methods are direct manual observations with the naked eye together with the use of photography. Although these methods have been used for a long time, they tend to suffer from low accuracy and subjective judgment. Hence, more scientific techniques are required to be integrated in the inspection of the skin surface *in vivo*. Various types of video microscope have been developed to scan the skin surface, but few of them can be used with minimal patient inconvenience while in a clinical setting (3). The PRIMOS device uses a structured light source technique and has been commercialized with released specifications for the measurement of skin *in vivo*. The 3D data of the skin from this device are recovered by using a phase-shifting principle from a series of images with stripe lights projected onto the skin. It has been considered in dermatology as an ideal tool for the investigation and documentation of skin microstructure and wrinkles (4). The temporal phase shift–based PRIMOS method is one of the most frequently used methods; however its working principle, where the object is recovered using a serial projection of parallel black/white stripes, makes this technique unsuitable for the recovery of heavily colored skin surface. Meanwhile, the resolution of this technique has been limited. Some experiments have pointed to an inability to record fine scale features as the fringe may not be able to reach deep valley features on living skin (5). In addition, the PRIMOS is a bulky device and does not lend itself to handheld use. It is almost impossible to use it for *in vivo* measurement of those skin lesions distributed arbitrarily around the body.

A NEW SKIN PROFILE MEASUREMENT DEVICE: SKIN ANALYZER

Photometric stereo is an optical approach to recover the surface shape of an object using several images taken from the same view point but under different lighting directions and has been extensively used in industrial applications, especially for inspection of large-scale products such as tile, stones, and metal components. Because of the relative unrestricted availability of space in the design and construction of these optical systems,

the illuminates can be appropriately arranged around the objects without significant difficulty to satisfy the assumption of achieving a point light source or a parallel, collimated form of illumination (6). It is clearly impractical to handle a bulky device in a clinical setting. Hence, an ergonomically and aesthetically pleasing handheld device called Skin Analyzer has been designed and manufactured with the aim of estimating the topography of skin surface (7). Several pilot clinical studies have been undertaken by using this device to investigate the potential of applying the new device to obtain a description of the surface of human skin as additional information for monitoring local skin conditions (8).

As Figure 1 shows, the Skin Analyzer device is finished in black and embedded with six surface-mounted light-emitting diodes (LEDs) and a compact digital Charge-Coupled Device camera. The internal structure of the device is configured to achieve the optimized results for the position of the illuminates relative to the camera system.

The Skin Analyzer has dimensions of 65 * 65 * 130 mm and weighs less than 1 kg. It can be easily assembled and operated using custom-build software. Because of the lightweight design, the Skin Analyzer can be held in a single hand without touching the skin. This ensures the measurements have good repeatability and stability because any external distortion is largely excluded from the skin surface during data capture. The following evaluations on the device whose manufacturing details are described in (9) are carried out on both skin replica *in vitro* and skin lesion *in vivo* by comparing with the reference data acquired by the PRIMOS.

EXPERIMENTAL EVALUATION ON SKIN PROFILE RECOVERY

THE COMPARISON DATA FORMAT

The Skin Analyzer provides surface gradient information directly based on the principle of photometric stereo. The gradient data are the results of partial differentiation of the

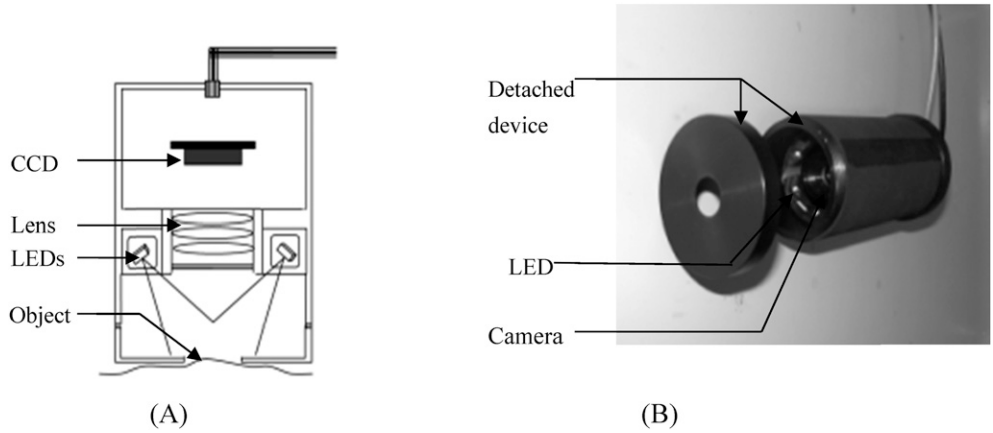


Figure 1. Schematic (A) and developed (B) handheld skin lesion imaging system – known as the "Skin Analyzer" composed of a small IEEE1394 digital camera (AVT Marlin, F-046C) and a high-resolution compact lens (Schneider, 1.4/23 mm + extension tube), surrounded by six surface-mounted high power chip-type LEDs (NSCW455, NICHIA, Tokushima, Japan) positioned equidistantly in angle on a circle of radius 8 cm that is centered on the camera's optical axis and lies in a plane orthogonal to this axis in line with the front of the first optical element of the lens.

surface profile and can be easily converted into a surface normal format. An object description expressed in the gradient domain can offer advantage in terms of surface orientation independence and thus can facilitate object recognition tasks (10). However, this format is not intuitive when compared with a description method based on 3D profile data. To obtain a 3D description of the skin surface, the gradient must be further integrated to produce a height-map format. This is found to be difficult and sensitive to noise as the surface gradient recovered by photometric stereo can only characterize the surface locally (11). Errors in the reconstruction process are unavoidably accumulated when an integration process is carried out. If the outliers in the recovered surface gradients caused by specularities and shadows are significant, the results from reconstruction may deviate far from the original shape of the object. To deal with these problems, there has emerged a large body of work aimed at integrating the surface shape from noisy gradient data accurately (12).

To make the data extracted using the photometric stereo technique comparable with that of the pure 3D data output from the PRIMOS device, we transform the 3D data from the PRIMOS into a gradient representation format using a procedure of partial differentiation, which will not introduce any error because of the local calculation. In addition, the surface profile is reconstructed on a relatively small specified area in order that the accumulated errors can be minimized. The evaluation procedure on the acquired topography data is carried out using three test objects, i.e., a painted ball bearing, replica of skin, and *live* skin.

THE EXPERIMENTAL SUBJECTS

Ball bearing. A ball bearing with diameter of 10 mm in Figure 2 is chosen as a reference because it is manufactured with high precision, i.e., tolerance of diameter and sphericity is ±0.002 inches. In addition, the spherical shape of the ball bearing contains a full range of gradient values, which makes the ball an ideal object to test most surface recovery

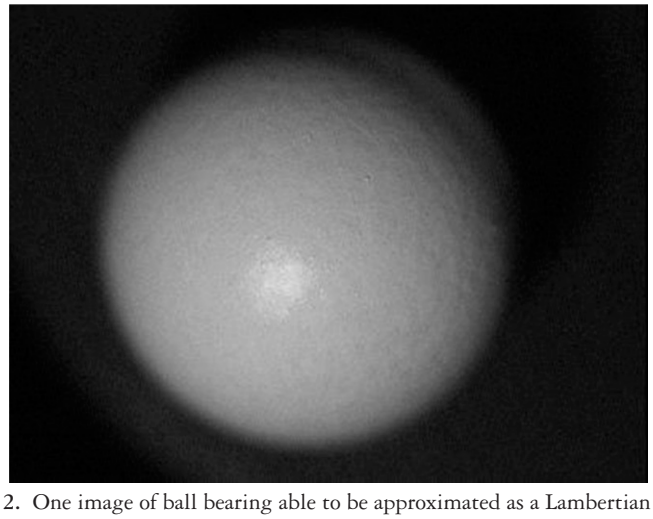


Figure 2. One image of ball bearing able to be approximated as a Lambertian surface.

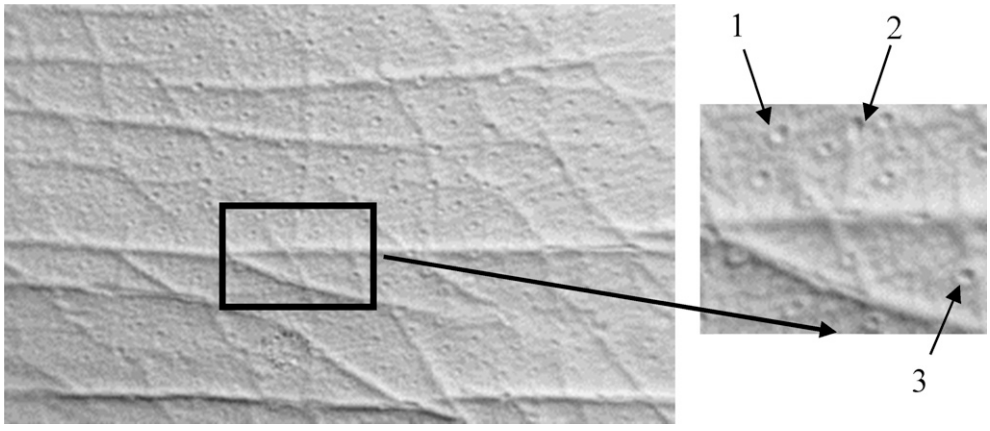


Figure 3. Replica made from the dorsal side of a volunteer's hand and one region selected for the convenience of comparison.

methods. A matt paint uniformly sprayed onto the ball surface eliminates the effect of mirror reflection from the metal component and makes the surface nearly Lambertian.

Replica of skin. The replica shown in Figure 3 is taken from normal skin on the back of a hand. The reconstruction is only carried out on an area defined by the window with a size of 140×100 pixels (*or a physical size of* 3.28×2.34 *mm*) to avoid the effect of accumulated errors associated with the integration process.

Skin in vivo. Normal skin on the dorsal side of a volunteer's hand is acquired by both the Skin Analyzer and the PRIMOS device. Markers shown in Figure 4 are drawn for rough alignment during acquisition of data by using the two different devices.

RESULTS AND DISCUSSION

Figures 5A and B are plots of recovered and calculated surface vectors composed of the gradient components in x and y directions. The length of the arrow represents the relative

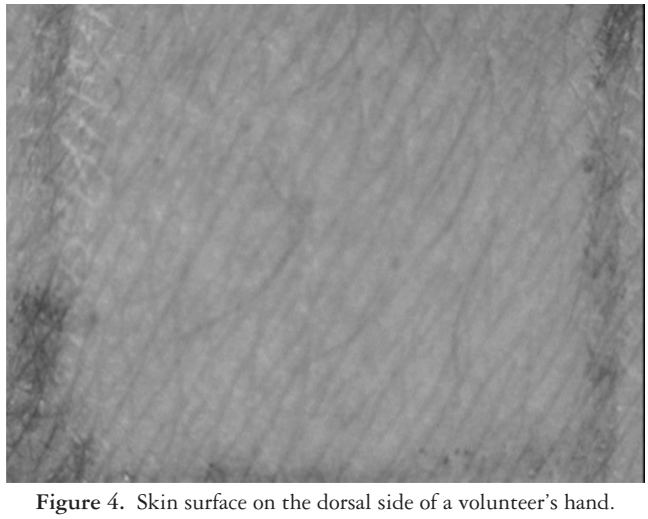


Figure 4. Skin surface on the dorsal side of a volunteer's hand.

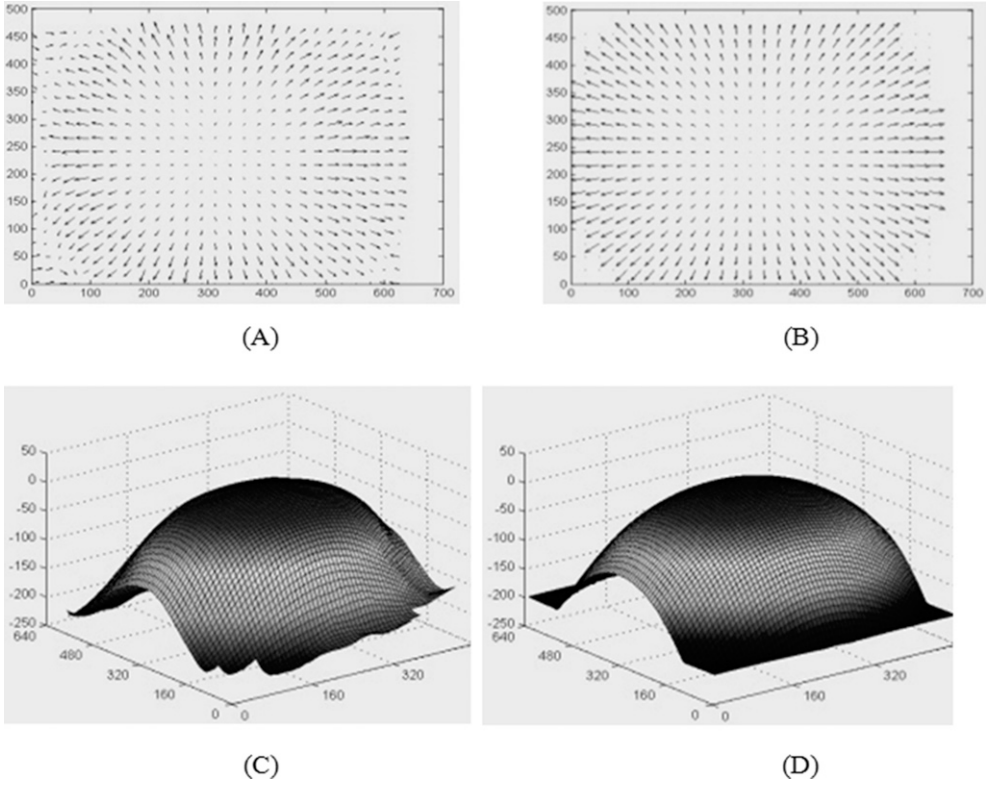


Figure 5. Needle maps and reconstructed results of the ball bearing from the Skin Analyzer and theoretic results calculated from an ideal sphere model.

amplitude of the vectors. It is found that most of the semisphere can be recovered correctly using the photometric stereo technique. Figures 5C and D are 3D profile of the ball bearing reconstructed from photometric stereo (left) and theoretically calculated with the known diameter (right).

The least squares mean diameter fitted from the reconstructed data gives the results of 10.2 mm diameter. Although deviation from the ground truth has been observed, the result is quite close to that of the ground truth. In fact, the error associated with the result may be caused by the integration approach which inherently accumulates the error from noise or digitization.

Figure 6A–D are needle maps of the whole replica and specified smaller area in Figure 3. The two images on the left are the gradient data from the Skin Analyzer and the two on the right are the results extracted from the data acquired by the PRIMOS. It can be found that the Skin Analyzer demonstrates higher sensitivity as there are more vectors with long amplitude. However, several evident vectors (within three circles) with large amplitude presented in Figure 6B appear to be outliers which may result from problematically transforming from the 3D profile to gradient. In Figure 6D, a line of vectors (on the edge which can be observed in Figure 3) stand out dramatically in the downward direction, whereas the vectors shown in Figure 6C change their values relatively smoothly.

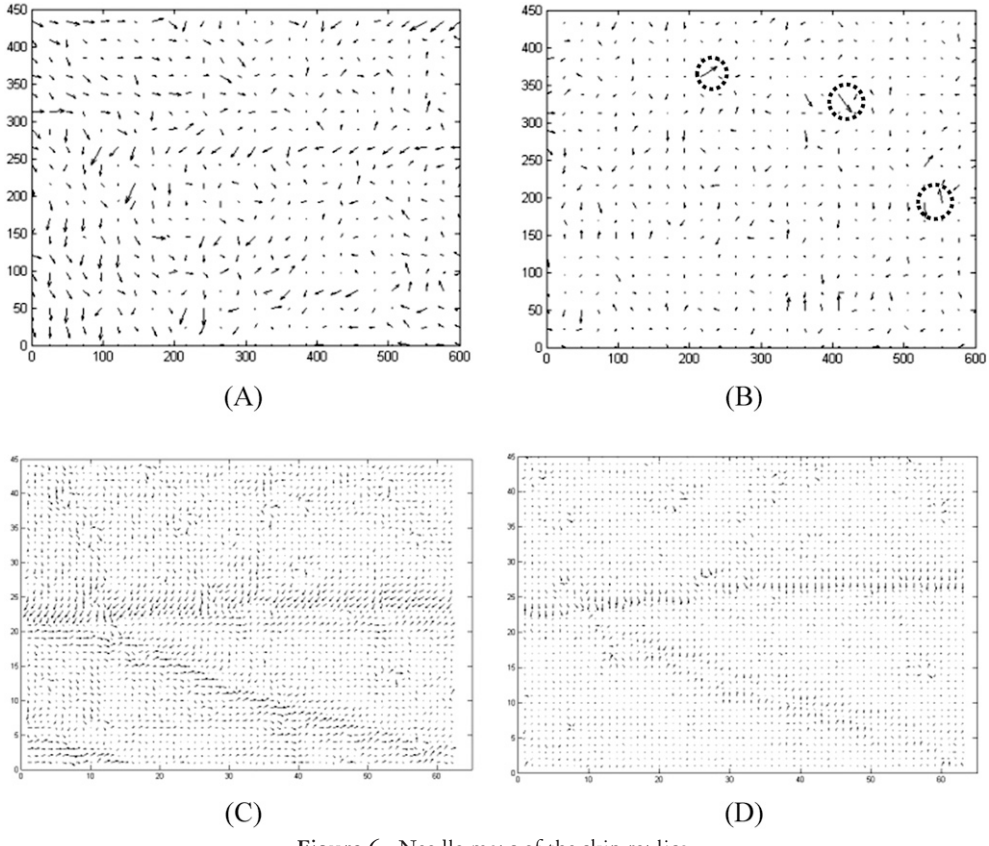


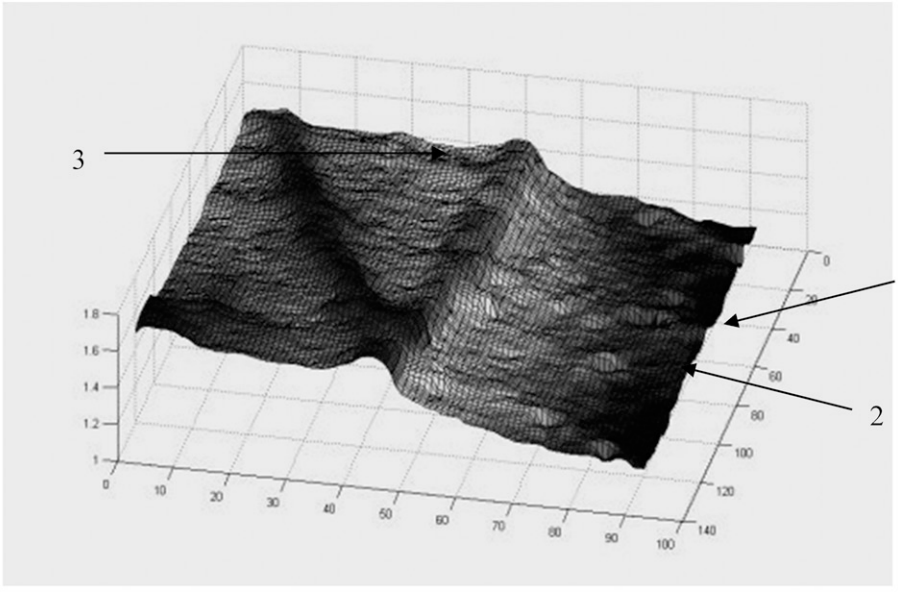
Figure 6. Needle maps of the skin replica.

The Skin Analyzer also keeps the profile changing smoothly. Such a phenomenon can be observed from the reconstructed profile maps in Figure 7, i.e., some small deeper holes (1, 2, 3) appear roughly recovered using the PRIMOS. This may be explained by a failure in the recovery of features with sharp edges due to the obstruction of projection light illuminated from one direction only. The Skin Analyzer is able to take advantage of the multiple light sources to remove the presence of shadow and specularities. From the profile maps, the edges and holes reconstructed using the photometric stereo technique appear more reliable and credible than those recovered from the PRIMOS.

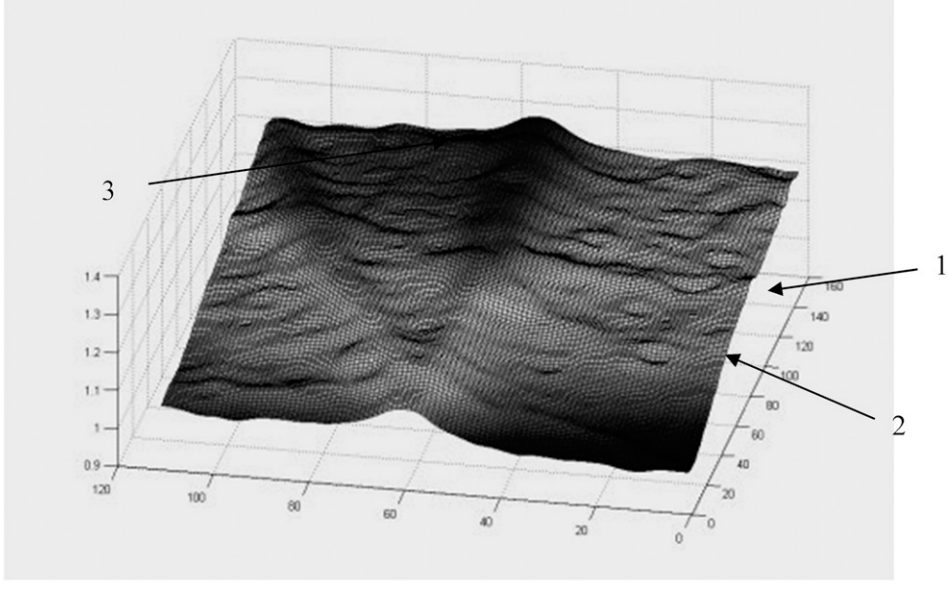
Figure 8 shows images rendered with a virtual light using the gradient data from both the Skin Analyzer (A) and the PRIMOS (B). It can be found that the Skin Analyzer can recover the skin, but PRIMOS failed to detect the details of live skin. The data collected by the PRIMOS on *in vivo* skin tend to be even less credible as the PRIMOS needs a long acquisition time and cannot compensate for object (usually human being) movement.

CONCLUSION

From the experimental evaluation presented in this article, it is proven that the Skin Analyzer device based on the photometric stereo technique may be more suitable than



(A) 3D data taken from PRIMOS and plotted through Matlab



(B) 3D reconstructed result from surface gradient data taken from photometric stereo

Figure 7. Comparison of skin replica 3D data taken from the PRIMOS and Skin Analyzer.

either manual assessment or the existing PRIMOS device for skin topography investigation tasks. Especially, it can deliver both the reflectance and profile information which can be obtained by few techniques so far. As the Skin Analyzer uses multiple light sources,

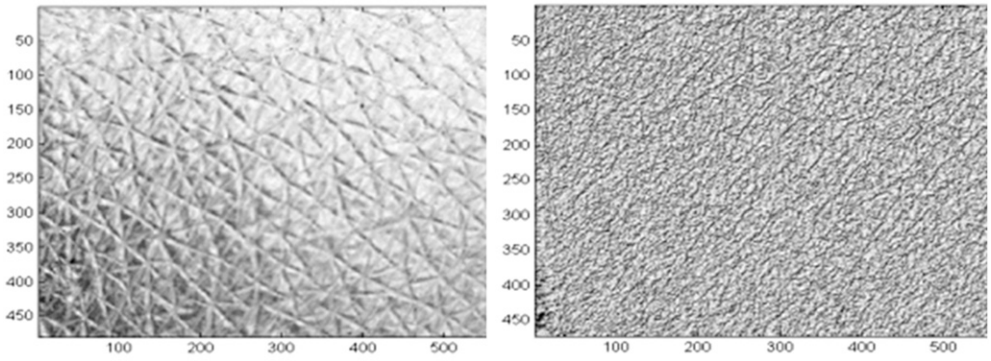


Figure 8. Rendered images of skin *in vivo* from the data captured from the Skin Analyzer and PRIMOS devices.

either normal or critical skin surfaces can be correctly recovered. Even though the PRIMOS has been considered as a field standard for skin data recovery, in some cases, lack of credibility due to the basic recovery principle employed is observed.

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