USING PHOTOGRAMMETRY TO QUANTIFY VITILIGO LESIONS ON HUMAN PATIENTS.

An Honors Thesis

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ABSTRACT

Individuals diagnosed with Vitiligo are left with few treatment options or answers regarding the prognosis of their disease. The natural course of the disease is unpredictable and can spread to any area of skin on the human body. Unfortunately, researchers and physicians have not reached a consensus on how outcomes of Vitiligo treatments should be measured or assessed. Photogrammetry offers the advantageous ability to capture 360 degrees of a human subject in a uniform fashion. Through the creation of a 3D model and the use of computerized measurements, areas of affected tissue on a human model may be accurately quantified. This study looks at how photogrammetry and computerized measurements may be used to quantify the areas of skin lesions on human patients with Vitiligo. Accurate and precise calculations produced from this method can pave the way for a standardized approach to gaining quantitative data on this disease and the efficacy of treatments.

BACKGROUND

Vitiligo

Vitiligo is depigmentation of the skin, and it presently affects nearly 1% of the world's population (Ezzedine et al., 2017). This disease can appear at any age, and has been found to naturally grow and recede on its own, leaving patients with abnormal patches of skin discoloration. The discoloration is due to the loss of function of melanin-forming cells, which are found in skin and hair (Alghamdi et al., 2012). These cells, known as melanocytes, are responsible for skin pigmentation, as they are producers and distributors of melanin (Ezzedine et al., 2017).

A cure for Vitiligo does not currently exist, but there are treatments available. However, these treatments do not present with ideal circumstances because they do not cure the underlying cause of the pathology (Rashighi & Harris, 2017). Only one treatment for Vitiligo is currently approved by the United States Food and Drug Administration (FDA), and other experimental treatments in use today have side effects and tend to be time consuming for the patient (Manga & Orlow, 2016). Additionally, with each treatment, as for any medical treatment, there is no guarantee of its success. Overall, this disease is not fatal or life-threatening, but there is a social stigma that accompanies the abnormal physical appearance of Vitiligo. Due to this demoralizing stigma, impacted individuals often develop depression or other psychological stresses (Parsad et al., 2003).

This study worked to accurately quantify the area of skin lesions on patients with Vitiligo through the use of digital imaging techniques in the medical field. These skin lesions, which can be categorized as white macules and patches, develop as a result of dysfunctional melanocytes (Ezzedine et al., 2017). The primary goal of this research is to create a method which can be used universally to measure the area of depigmented patches on the skin of various patients. These measurements will allow for physicians to better monitor their patients' Vitiligo, as the disease is capable of spontaneously growing and receding all over the body (Kim et al., 2017). Furthermore, these measurements allow for increased data collection, leading to more informed medical decisions regarding the efficacy of treatment due to the accuracy and consistency of the values produced.

We applied three dimensional photogrammetry techniques to quantify the area of skin lesions in vitiligo patients with the ultimate goal being a usable camera rig suitable for repeated use to quantify the rate of disease progression. This research specifically focuses on quantifying individual patches of Vitiligo on the skin of those impacted with the disorder. A photogrammetry rig was temporarily implemented to conduct trials with human patients of the Vitiligo Clinic and Research Center at the University of Massachusetts Medical School in Worcester, MA (IRB ID: H-14848). These patients all had visible patches of vitiligo on their bodies.

This study has taken place under the supervision of University of Massachusetts at Amherst Professor, Dr. Duncan Irschick, and University of Massachusetts Medical School Assistant Professor and Director of the Vitiligo Clinic and Research Center, Dr. John Harris. Assistance was also provided by Dr. Zainab Abbas of the University of Massachusetts Medical School.

Photogrammetry

Photogrammetry uses a compilation of 2D images to construct a 3D model of a still object (Baltsavias, 1999). These 2D images must capture the object of focus at every angle needed in the 3D model portrayal. Each image must also present with consistent lighting and resolution. 3D models developed with photogrammetry methods are extremely accurate and can be used to make precise measurements (Randalls et al., 2010). From start to finish, the 3D models maintain the authenticity and visual-spatial arrangement of the object captured in the original digital photographs (Petriceks et al., 2018). Thus, this method presents with the benefits of high accuracy and conservation of dimensions.

Significance

This study is significant to the field of dermatology because photogrammetry methods can be applied to various skin disorders and conditions. Therefore, the creation of the photogrammetry method developed through this study could pave the way for future applications of digital imaging for dermatological patients. For example, a 3D model of a patient with moles or skin growths can be analyzed with similar quantification methods as a patient with Vitiligo. Over time, a collection of photogrammetry scans can be obtained of a patient, in order to track the growth or recession of a skin disorder. This data can assist in patient monitoring and advancing the treatment or diagnosis of a patient’s health condition by providing accurate measurements of skin discoloration or abnormalities.

SUMMARY OF WORK OF PREVIOUS RESEARCHERS

Potential benefits of using photogrammetry to measure Vitiligo in human patients.

BACKGROUND

Individuals diagnosed with Vitiligo do not have a guarantee of success with their treatment options and there is no cure for the disease. Additionally, the natural course of the disease is unpredictable and, overall, a mystery (Alghamdi et al., 2012). Unfortunately, researchers and physicians have not reached a consensus on how outcomes of Vitiligo treatments should be measured or assessed (Eleftheriadou et al., 2012). This literature review will assess the potential benefits and drawbacks of using photogrammetry to quantify outcomes in Vitiligo patients.

Vitiligo

Vitiligo is depigmentation of the skin resulting from an attack of the autoimmune system on melanocytes. This disease presently affects 1% of the general population and can occur at any age (Rashighi & Harris, 2017). Vitiligo naturally grows and recedes on its own, leaving patients with abnormal patches of skin discoloration and no indication of the future for this randomized disfigurement. Unfortunately, a cure for Vitiligo does not currently exist, and despite the availability of treatments, none present with ideal circumstances (Gawkrodger et al., 2010). Only one treatment for Vitiligo is currently approved by the US Food and Drug Administration (FDA), and other experimental treatments in use today have side effects and tend to be time consuming for the patient (Manga & Orlow, 2016). Additionally, with each treatment, there is no guarantee of its success. Furthermore, a standardized method of evaluation does not exist for

Vitiligo, so many findings are subjective, rather than objective (Alghamdi et al., 2012). Overall, this disease is not fatal or life-threatening, but there is a social stigma that accompanies the physical appearance of Vitiligo. Due to this, impacted individuals often develop depression or other psychological stresses (Manga & Orlow, 2016). Since Vitiligo is the most common depigmenting disorder acquired by the general population, it is imperative that steps are taken to better understand the disease so that treatments and therapies can be created and improved (Alghamdi et al., 2012).

Photogrammetry

Photogrammetry is a non-invasive technique which uses a compilation of 2D images to construct a 3D model of a still object (Furlanetto et al., 2016). These 2D images must capture the object of focus at every angle desired to be included in the 3D model, and each image must present with consistent lighting and resolution. The models are created through the use of mathematical data representative of the spatial relationships between the object and its surroundings (Baltsavias, 1999). Additionally, landmark identification is used to ensure the accuracy of biometric measurements (Han et al., 2010). Therefore, the 3D models maintain the authenticity and visual-spatial arrangement of the object captured in the original digital photographs from start to finish (Petriceks et al., 2018). Thus, this method presents with the benefits of high accuracy and conservation of dimensions.

SUMMARIZED RESULTS

In 2017, a study was performed to compare methods of area measurement on Vitiligo patients (Hayashi et al., 2017). This study used a three-dimensional imaging analysis and a manual measurement that took place directly on the patient. The manual measurement relied upon the border-tracing method, which involved tracing and measuring each depigmented region individually. This study used the VECTRA© H1 device for the three-dimensional imaging analysis, which applies the methodology of photogrammetry.

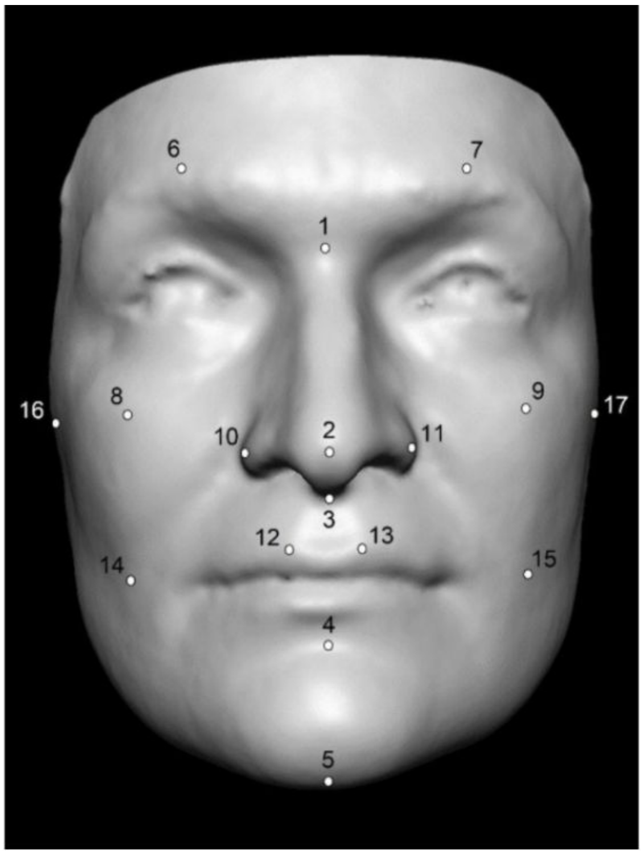

Figure 1. A 3D facial surface reconstructed with 136 linear distances calculated from 17 landmarks serving as coordinate positions.
(Hayashi et al., 2017)

The VECTRA© H1 device uses a landmark-based linear distance approach to construct accurate, highly-detailed 3D models that are virtually built to scale (Figure 1). This device and the photogrammetrical approach, in general, allow for researchers and physicians to stray away from more invasive, direct measurements that involve rulers and calipers. The VECTRA© H1 device also diminishes the potential for human error that accompanies anthropometric approaches. This decrease in error results because photogrammetry produces the same measurements, even when the individual obtaining the measurements differs. Meanwhile, anthropometric measurements often differ amongst the measurement-taking individuals (Camison et al., 2018).

The variability in anthropometric measurements is considered detrimental when applied in Vitiligo clinics and trials because there is no standard methodology in practice for determining the efficacy of Vitiligo treatments. Without the use of photogrammetric methods, physicians are simply looking at Vitiligo with the bare eye or through digital photos to monitor any growth or recession of the patient's disease (Nugroho et al., 2007). Photogrammetry techniques offer the benefit of combining these two methods of observation and adding the advantage of visualizing the growth or recession of the lesions on a three dimensional model (Petriceks et al., 2018). Computerized detection and measurement softwares used with photogrammetry also have increased efficacy rates of identification and measurement for depigmented skin lesions (Hayashi et al., 2017). These results mirror those seen in the 2015 study by Kohli et al., which addresses the quantification of body surface area (BSA) affected by Vitiligo.

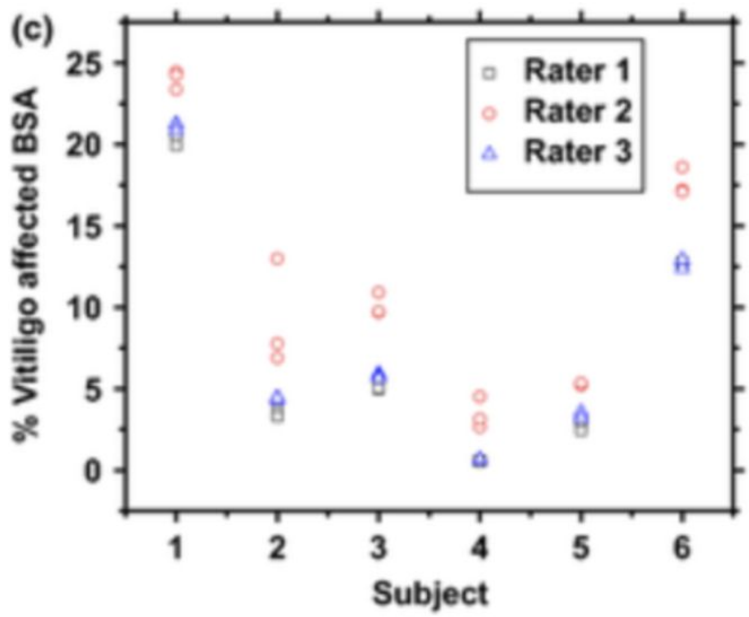

Figure 2. Three individual raters' measurements of different body surfaces affected by Vitiligo. (Kohli et al., 2015)

In the preceding study, three individual raters took three different Vitiligo-affected body surface area measurements (Figure 2). Significant discrepancies were found between each individual's measurements shown in figure 2. These measurements were taken directly, without the use of photogrammetry or computerized software.

CONCLUSION

Photogrammetry is a useful method for assessing skin lesions due to Vitiligo (Hayashi et al., 2017). Overall, the three-dimensional imaging analyses performed in the study by Hayashi et al. were found to procure more consistent results than their manual measurement. This 3D photogrammetry method obtains measurements of the patients' depigmented regions that are superior to the measurements from the manual measuring method (Kohli et al., 2015). The manual method relies upon the human eye which is subject to human error. Meanwhile, the computerized software used in the photogrammetry method is programmed with the ability to distinguish borders, such as those which exist between the depigmented skin of vitiligo lesions and the normal skin tone. This specific ability of the software is thus specifically useful in quantifying areas of depigmented lesions (Hayashi et al., 2017). Therefore, photogrammetry offers a higher level of data reliability than direct measurements (Kohli et al., 2015).

The lack of reliability of direct body surface area measurements is due to human error and, in comparison, measurements taken with the use of photogrammetry and computerized softwares are far more consistent (Kohli et al., 2015). Photogrammetry also allows for a faster identification and measurement of Vitiligo-affected skin areas through the use of computerized detection and measurement software. This is also a potentially homogenous method which can be implemented by dermatologists in all of their clinics and trials that take into account the area covered by patches of Vitiligo. Photogrammetry represents a method which can obtain concrete qualitative results and a permanent record of all visualized lesions (Alghamdi et al., 2012).

METHODS

Participants

Patients from the Vitiligo Clinic and Research Center at the University of Massachusetts Medical Center in Worcester, MA were recruited for this study based on the presence of visible vitiligo patches on or above the torso region. One or more lesions were necessary for selection. Larger lesions with high contrast to the patient's natural skin tone were preferred in a subject due to larger patches of vitiligo being simpler for the computerized area quantification. For eligibility, each participant was required to sign a waiver. This waiver allowed us to photograph each participant's body and use the obtained images to construct 3D models on the computers in the Irschick Lab at the University of Massachusetts at Amherst. Proper consents and supervision were also arranged prior to subject documentation per University of Massachusetts standards and protocols. Additionally, prior to each photogrammetry trial, Dr. John Harris and/or his associates obtained the subject's complete medical history including, but not limited to, disease history and prior treatments. In order to maintain anonymity, each participant of this study was assigned a random identification number. These identification numbers were used in place of the patients' names when labeling digital files and data to satisfy HIPAA compliance. These methods also had IRB approval (IRB ID: H-14848).

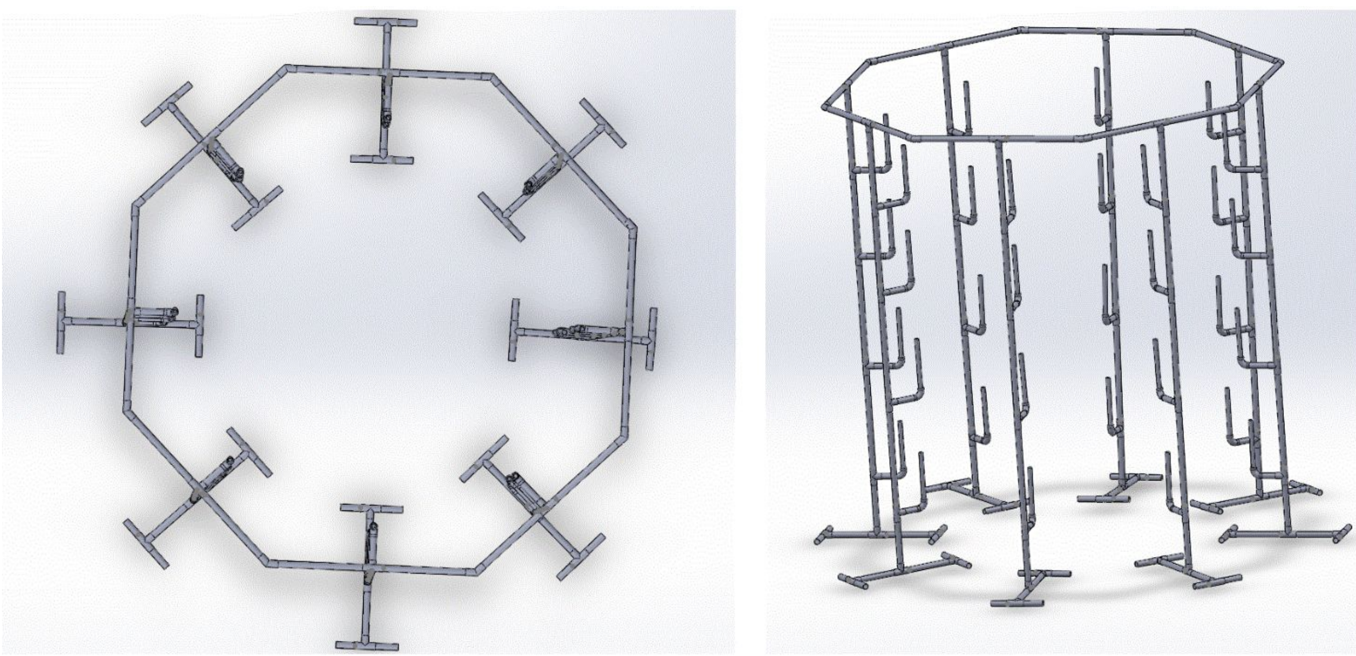

Figure 3. Digital blueprints for the PVC pipe structure of the camera rig used.

Figure 4. Fully constructed 360° photogrammetry rig equipped with 26 Canon G16 DSLRs and LED lighting.
Left panel: Half-body mannequin used for trials.
Right panel: G16 cameras mounted on rig and equipped with wireless trigger sensors.

Materials

Using a camera rig constructed from PVC pipe, patients were photographed with 26 Canon Powershot G16 digital cameras (Figure 3). The camera rig was lit with four standing LED light bulbs and eight LED light strips. The light strips were attached to the middle camera mount of each post. This position was chosen for the light strips to prevent shadows on the patient and to provide optimal lighting for the cervical and cephalic regions. Additionally, white cloth was attached to all sides of the camera rig to provide more consistent lighting, improved patient privacy, and elimination of nonessential background images (Figure 4). Eliminating the background noise of the images was important for the creation of the 3D models because this led to clearer distinguishing points for Reality Capture™ to work with.

Reality Capture is a program that uses the photogrammetry method to construct virtual 3D models from photographs. This program was chosen for 3D model construction in this study because of its efficiency and ability to construct detailed models from JPEG and RAW files. The 3D model created in this software was then exported to Blender™ (Blender Foundation) as an OBJ file. Blender is an open-access software that was used to edit and scale the 3D model to accurately portray the subject. Additionally, Blender has a measurement tool within its "object" mode which was used for quantification in this study.

Photogrammetry Rig Specifications

In this study, 26 Canon PowerShot G16 cameras were used. These cameras fit within the desired budget, were compatible with wireless triggers, and compact. The compact sizing made them easy to transport in Pelican cases between the University of Massachusetts at Amherst and the University of Massachusetts Medical Center in Worcester. Additionally, these digital cameras shoot at a resolution of 12.10 megapixels and are capable of capturing both RAW and JPEG files (Canon G16 Review). These files are helpful in obtaining high-quality 3D models due to their high level of detail. The ability to capture RAW and JPEG files was extremely vital to the final 3D model construction because the quality of the 3D models is dependent upon the file sizes and digital cameras used to capture the initial photographs. Additionally, the sum cost of these digital cameras makes photogrammetry relatively inexpensive in comparison to other imaging techniques used in the medical field. Additionally, the methods of this study are non-invasive and require no physical contact with the patient's body (Furlanetto et al., 2016). The cameras in use and the patient being photographed must be stationary throughout the imaging, but the images are captured rapidly. Consequently, the patient risk involved in this study is minimal, and can be considered comparable to posing for a regular photograph.

Construction of a camera rig capable of capturing 360 degrees is required to most effectively document the progression of the disease in human patients of the Vitiligo Clinic and Research Center. This rig, the first implemented in any hospital, must be equipped to capture consistent photographs of human subjects of all sizes. Each patient is impacted by Vitiligo in different social, psychological, and physical ways. Therefore, it is significant to be able to record all presented depigmented patches, despite their location on the human body. The more dimensions of depigmentation that are measured, the more valuable the data becomes to physicians and researchers since much is unknown about Vitiligo and each new dataset can assist in future Vitiligo studies.

Procedure

Prior to beginning this research study, the following two *Collaborative Institutional Training Initiative* (CITI) training courses were completed for the qualification to work with live human subjects:

1. Human Research - Group 1 Biomedical Research Investigators and Key Personnel (ID 1475)
2. Human Research - Group 2 Social and Behavioral Research Investigators and Key Personnel (ID 1476)

Initial tests of the photogrammetry protocol with the use of a Canon G16 camera, tripod, wireless trigger, rotating stool, and a mannequin representing a human torso were performed to familiarize researchers with the procedure. This procedure involved placing a patterned, half-body mannequin (Figure 4) on the stool and using the wireless trigger to capture 20 images of the subject as the stool was manually rotated. These images were taken in sequence at equally spaced intervals and captured 360 degrees of the mannequin. All photos were loaded into Reality Capture for construction of a 3D model, with the goal of obtaining familiarity with the program and the use of OBJ files.

Once the feasibility of the method was demonstrated, construction began on a camera rig suitable for documenting the lesions of patients at the Vitiligo Clinic and Research Center. Once the rig was completed, it was to be used during two trials at the University of Massachusetts Medical Center.

Prior to photography of each subject, a complete medical history was obtained by the subject's physician, including, but not limited to, disease history and prior treatments. The patients were individually positioned in the camera rig such that their ventral side was photographed and documented. It was imperative that the patient's body was minimally covered, so that the maximum amount of skin was captured in the photos. White drapes were wrapped around the photogrammetry rig for additional patient privacy (Figure 4). Proper consents and supervision were arranged prior to subject documentation per University of Massachusetts Medical Center standards and protocols.

Figure 5. 270° photogrammetry rig equipped with 21 Canon G16s and LED lighting at the Vitiligo Clinic and Research Center in Worcester, MA.

The goal of these first trials was to successfully construct models spanning 270 degrees, enough to fully capture the human face. 270 degrees was chosen as the first goal so that techniques could be perfected before moving towards the ultimate goal of capturing 360 degrees with 26 cameras. For these trials, rather than moving the camera and relying on the subject matter to stay still, 21 cameras were used (Figure 5). These 21 cameras were synced to a single wireless trigger so that 270 degrees of the subject could be captured in one take. This eliminated the potential for error due to the subject moving in between takes.

In order to simultaneously photograph the body at multiple angles, the cameras were all connected to a single wireless trigger to capture photos, at the same instant. Multiple photos were needed to ensure that there was enough data to create a 3D model of each patient using the software Reality Capture. Additionally, the same images were repeatedly captured several times to ensure accuracy and precision. This allowed for the photographer to ensure that each camera was functioning. It also eliminated the potential error that would result from blurry photos due to unexpected movement from the subject.

After the photogrammetry trial at the vitiligo clinic, the photos were uploaded to a secure external hard drive in the Irschick Lab in Amherst, MA, and downloaded into Reality Capture for 3D model construction. Each 3D model created was then evaluated for clarity and accuracy. If the model was deemed adequate (no gaps in data, clear contrast in coloring, sharp imaging), then its OBJ file was imported into Blender for quantification of the patient's patches of Vitiligo. After this first trial's strengths and weaknesses were identified, adjustments and enhancements were made to improve any faulty areas of the camera rig and photogrammetry procedure. For example, the structural soundness was reinsured and the gaps lacking photographic data were filled.

Next, a 360 degree camera rig built of PVC pipes and equipped with 26 Canon G16 cameras and LED lighting was constructed (Figure 4). Trials were run at the University of Massachusetts at Amherst prior to the transport of the rig to the University of Massachusetts Medical Center's vitiligo clinic in Worcester, MA. This rig was used to run patient trials at the vitiligo clinic and obtain measurements of the vitiligo lesions on these patients' 3D models. Throughout the trials, the lighting and camera placements were continuously modified based on the trial results.

The photogrammetry trial began with the selection of participants. Participants were selected if they possessed at least one visible patch of vitiligo. The larger the patch was, the simpler the quantification of the patch would be in the future. Following selection, the trial participants were asked to sign a waiver, allowing for their participation in the study. Proper consents and supervision were arranged prior to subject documentation per standards and protocols of the University of Massachusetts at Amherst and the University of Massachusetts Memorial Medical Center.

At the start of each trial, the participant was instructed to sit up straight with both hands on his/her thighs, on a stool placed in the center of the camera rig. It was imperative that the patient's body was minimally covered, so that the maximum amount of skin could be captured in the photographs.

To simultaneously photograph the body at multiple angles, the cameras were all connected to a single wireless trigger. Photographs capturing multiple angles were needed to guarantee enough data to create a 3D model of the patient, which is why 26 cameras were used. Using the trigger, the same imaging was repeated at a minimum of two times per patient, in order to ensure accuracy and precision. All cameras were checked in between each photo trial, to ensure that all were functioning and photographing as desired. The subject was sometimes instructed to alter their positioning for different trials to best capture their skin lesions.

All photos were then securely uploaded onto an external hard-drive at the University of Massachusetts at Amherst. If any photos appeared inconsistent with the others of the dataset, they were edited in Adobe Photoshop CC2019 to have the appropriate lighting and coloring. If a file could not be edited without losing the integrity of the initial photograph, then it was omitted from the model construction. The high number of cameras used in each trial allowed for an erroneous photograph to be omitted without damaging the integrity of the dataset. After sifting through all the photos for a given subject, their 3D model was then created in Reality Capture. Within Reality Capture, the model was then evaluated for clarity and accuracy. If the model was deemed adequate (no gaps in data, clear contrast in coloring, sharp imaging), it was then imported into Blender as an OBJ file. Within Blender, the measurement tool in Object Mode was used to quantify the size of the patient's Vitiligo skin lesions. It was significant that the model was calibrated to the patient's actual size in Blender. For this calibration, the model was scaled to fit the pre-measured values of the circular stool on which the patient was positioned. The stool was chosen as a good calibration for the model because its size and location did not change, regardless of the trial's subject. Therefore, the stool provided a measurement reference standard, so the lesions could be measured consistently with the use of this known value.

Ideally, researchers would continue to capture images of patients over the course of the following months. Throughout this research study, these images were to be continuously used to create new 3D models for patch quantification. The data detailing the Vitiligo patch measurements were then going to be recorded and analyzed in conjunction with the treatments that may or may not be presently used by the patients. Each patient model was to be compared to prior models of the same patient. If a patient repeatedly sat for photogrammetry studies over the course of this research, all of their past and present models were to be virtually analyzed together, so that any growth or recession of the Vitiligo regions could be quantified.

Figure 6. Half-body mannequin used for trials.
Left panel: Dorsal side of mannequin with a white paper circle and a black foam rectangle attached for quantification purposes.
Right panel: Ventral side of mannequin with a bubble wrap rectangle and a white paper rectangle attached for quantification purposes.

Data Collection & Analysis

Access to patients became limited during this study, which led the main data collection to occur with the use of a half-body mannequin in the Irschick Lab at the University of Massachusetts at Amherst (Figure 4, left panel). Various materials were attached to the mannequin to simulate abnormal skin lesions on a patient. In this trial, foam, paper, and bubble wrap were used. The variety of attachments was used to also test whether this method could be used for other dermatological disorders, tumors, or moles. On the ventral side of the mannequin, a bubble wrap rectangle and a white paper rectangle of known dimensions were attached. On the dorsal side of the mannequin, a black foam rectangle and white paper circle of known dimensions were attached (Figure 6).

This mannequin was placed on a stool in the center of the photogrammetry rig. This trial was meant to mirror the methods used at the Vitiligo Clinic and Research Center to capture the human participants. Therefore, LED lighting and 26 Canon G16s were used. Two trials were conducted and all photos were then uploaded to a computer in the Irschick Lab at University of Massachusetts at Amherst for 3D model construction in Reality Capture. This model was then exported to Blender as an OBJ file.

In Blender, excess data points were removed and the model was scaled to its actual size based on the measurements of the stool that the mannequin was placed on. The simulated lesions were then measured in Object Mode within Blender.

RESULTS

Model Construction and Material Quantification

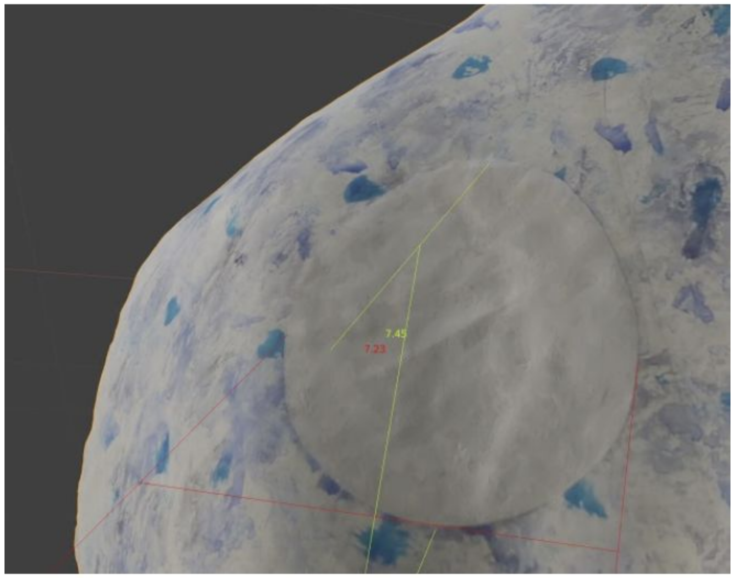

Figure 7. Measurements taken in Blender of the white paper circle on the dorsal side of the mannequin used in the photogrammetry trials.

The full 3D model construction of the half body mannequin is shown in figure 6. Measurements of the materials attached to the mannequin were taken on both the physical mannequin and the digital 3D model. The 3D model measurements were taken in Blender and the physical mannequin measurements were taken with a ruler. The numbers obtained from these quantifications were identical. For example, the white paper circle attached to the mannequin's upper left thoracic region was measured on both the physical mannequin and the 3D model in Blender to be 7.45 cm vertically and 7.23 cm horizontally. There were no discrepancies in the measurement methods. Therefore, the photogrammetry techniques used in this study are capable of producing accurate 3D models of humans which can be used to take precise measurements on the surface of the human body.

DISCUSSION

The purpose of this study was to develop a method for quantifying skin lesions on a human patient with the use of photogrammetry. The ultimate goal was to prove that this concept was feasible and effective in a medical setting. Overall, the methods used in this study were able to accurately capture 360 degrees of images of human patients with vitiligo and produce 3D models without gaps or inaccuracies in the produced figures. Additionally, when scaled to reflect the subject’s actual sizing, then the model could be used to produce accurate quantifications of the subject’s skin lesions.

Despite these accomplishments, there were limitations to the study. The trial was unable to accommodate as many human subjects as the initial plan hoped for due to time and spatial limitations. This trial was held at the University of Massachusetts Medical Center, while the research team was based at University of Massachusetts at Amherst. Therefore, the time frame during which patients could be seen made it difficult to use the photogrammetry rig on many patients within the available trips to Worcester, MA. Only one patient could be photographed at a time, and prior to each patient’s trial, the cameras needed to be adjusted to account for their body frame size. This was a time consuming process that limited the number of subjects that could be captured in a single day. These trial days were also limited, as the Vitiligo clinic was only open one day each week. If this study is repeated in the future, more subjects should be captured to gain additional data.

An additional limitation of this study was due to the materials used in the photogrammetry rig. PVC pipe and zipties were used for construction to stay within a low budget. These materials are inexpensive, but they did not maintain balance and they could not be easily collapsed and reassembled. This made transport of the rig between University of Massachusetts at Amherst and the University of Massachusetts Medical Center very difficult and time consuming. In a future study, it would be useful for the rig to be constructed from custom-cut pieces of plastic or metal that securely fit together and contain weighted bases for maintaining balance. A rig built from more secure materials would also improve the reproducibility and efficiency of the trials.

A future rig should also be adaptable to size variations. Our rig was able to accommodate both adults and children through adjustments to the heights and angles of the cameras mounted on the PVC pipe. When the cameras were adjusted, the standing LED lights could also be manipulated to light the subject in a personalized manner. However, the lighting and cameras could not accommodate for individuals who exhibited vitiligo lesions with low contrast to their skin. These lesions were not easily identified in the 3D model construction and, therefore, their measurements could not be accurately taken. A future experiment could account for this deficiency through trial and error with different lighting equipment, such as xenon or UV lighting.

With developments to this study, these methods could be used throughout the medical field in the future. For example, all dermatological patients could use this photogrammetry quantification system to document their skin abnormalities over time. This would be useful in obtaining a tangible record of the growth or recession of visible disorders, and could potentially create a new source of data on various maladies.

Ultimately, this study had to conclude prematurely due to the global COVID-19 pandemic, but the amount of data collected was significant enough to support conclusions regarding this method's efficacy in modeling human patient skin lesions. This method is controlled and highly regulated, thus providing the ability to monitor a subject's skin condition over time. Under ideal circumstances, more data could have been collected from the human 3D models that were constructed. Also, supplementary trials could have been run with the photogrammetry rig. There were plans to experiment with the use of xenon lighting, additional cameras, and more diverse materials on the mannequin used. However, these unexplored plans can be implicated in future studies of photogrammetry. These future studies can allow other areas of dermatology to be explored with photogrammetry, as each subject will present with different attributes that are in need of being captured.

A more substantial grant and a longer timeframe would allow for further developments in this study. There currently is not a software for quantifying areas using a computerized color map. Development of this software would allow for additional applications of the photogrammetry methods used in this study. Also, a larger room would support a more sizable rig. The extra space in a larger room could accommodate a better reinforced camera rig, as well as a computer desktop setup. This computer setup would be linked to cameras that wirelessly upload images to the photogrammetry software as they are taken. This technology costs more money, but would increase efficiency of each patient's trial. This time saving technology as well as a longer timeframe of the study, would allow for more patients to be captured throughout the duration of this research. The improved efficiency would also be useful in capturing patients when time is of the essence. The methods of this study, along with these refinements, can have further applications as a diagnostic tool for various dermatological disorders and abnormalities.

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