COMPARISON OF TWO DIFFERENT PHOTO PROTOCOLS AND INCREASING THE ACCURACY OF 3D MODELING OF SNOW SHOEPRINTS BY PHOTOGRAMMETRY.

by
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Dedication

This research project is dedicated first to God for the numerous blessings that He gave to my family and me, to my lovely husband, Luis and my little son Julian, who encouraged me to pursue my dream and finish this master. To my parents, Maria Elena and Antonio, who gave me their love and support throughout my life, and my sisters Erika and Camila, who always were there for me.

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Abstract

Sometimes a shoeprint can help in narrowing down the number of suspects in a crime scene, so having an efficient recovery method for them can be helpful (Andalo et al., 2012). Photogrammetry has been proposed as a simple and reliable method for shoeprint analysis in previous studies, however, its use in certain surfaces such as snow can be challenging, and it also requires following a strict protocol for picture taking (Larsen and col., 2020). The objectives of this study are to test the equivalency of an alternative picture-taking protocol proposed by Larsen et al. with the standard protocol proposed by the developers of Digtrace, a software that allows the 3D modeling of shoeprints; and to test the effectiveness of different techniques for improving the quality of shoeprint's photos taken in snow. In the first experiment, two shoeprints were created on sand and mud, and photographed using Larsen's and Digtrace's photo taking protocol. A series of 3D models were created in Digtrace, randomized, and cloud points extracted from them were compared using the CloudCompare software to assess differences in variability. In the second experiment five shoeprints were created in snow and several enhancing techniques (oblique light, red filter /black – white photo, red, and blue dyes) were used to increase the contrast of the photographs. The same comparison process from experiment was used to determine a reduction in the variability of cloud point distances with a control group. The results shown a higher accuracy from Larsen's protocol (mean distance 0.1025 mm) than Digtrace's protocol on mud surface, however on sand surface Digtrace's protocol revealed less error distance (0.0968 mm) than Larsen's protocol. The results from the second experiment shown that the use of blue and red dyes produced noticeable improvement of the reliability values. (mean error distance 0.0648 mm and 0.0734 mm). In contrast, oblique lights and red filters/black-white photos did not produce a significant improvement. This study shows that both Larsen's and Digtrace's protocols can be used

to build reliable shoeprint 3D models and that the accuracy of 3D snow shoeprints can be improved with a simple method such as the spraying of red or blue dyes.

Introduction

Overview

Shoeprints are usually found on crime scenes. They can be found even more frequently than fingerprints, providing a valuable tool for forensic investigations (Bodziak, W. J., 2000, Chapter 1). A shoeprint is created when a person takes a step and the outsole of the shoe has direct contact with the substrate, producing a detailing replication of the shoeprint. The recovery of the partial or complete shoeprint during the first hours in a crime scene investigation is essential since these impressions begin to degrade soon after they were created, especially the ones made on exteriors (Bodziak, W.J., 2017, Chapter 1). The current method for 3D or plastic shoeprint is casting, a time- consuming and intricated method which require highly trained and skilled personal to make a 3D detailed life size shoeprint modeling (Bodziak, W.J., 2017, Chapter 3).

A new low cost, friendly to use, and economic recovered method of plastic shoeprints has been studied as an alternative to conventional method which requires a scale, digital camera, and a computer with a photogrammetry software. Photogrammetry utilizes a series of sequentially photos from different views of the plastic shoeprint evidence to build a reliable detailed 3D model, which permits to make different measurements on the shoeprint, identify different outsole patterns and the compare them with other known and unknown 3D shoeprints models. However, because this method is new in the forensic field, there is not a standardized photographic protocol for shoeprint evidence which would ensure the build of a high-quality 3D shoeprint model (Petraco, N. and col., 2016). Snow shoeprints are the most challenging shoeprint evidence to cast and photograph due the homogenicity of the surface and the reflection of the snow. Different methods have been used to enhance the details of snow shoeprint photos, but no studies have been made enhance the photos to build a high-quality 3D shoeprint using photogrammetry (Pereira, L. 2015).

To address these problems , the following research questions were developed:

-Is Larsen's photographic photographic protocol equal or betther than the one recommended by DigTrace software for the building of a reliable 3D shoeprint model using photogrammetry?

- Do the use of different dyes, oblique lights or black-white photos improve the quality of a snow shoeprint photograph and therefore build a high qualitive and reliable 3D shoeprints with photogrammetry?

Importance

Many studies have been proposed for improving the recovery method of shoeprints, but most of them have been focused only on the use of different casting materials and not in use new methods to address the different limitations that casting can have. Nowadays photography is a common and important part in the documentation of a shoeprint evidence in a crime scene. Photogrammetry permits the use of these photos to build a reliable 3D models of shoeprints, but an appropriate photographic protocol that ensure the built of accurate and repeatable 3D shoeprint models have not been studied.

The comparison of different photographic protocols will permit the analysis of the accuracy and repeatability of the built 3D shoeprint models, which will allow to stablish the superiority of one from the other. This photographic protocol could be considered when a plastic shoeprint is found in a crime scene and casting of the impression cannot be made due the financial or human resources limitation.

Snow shoeprint can be very difficult to photograph and therefore,it is difficult to build reliable 3D models from them. A study using photogrammetry to build 3D snow shoeprints shown that the models were not repeatable and accurate due to the many holes created within the 3D shoeprint models (Larsen and col., 2020). Because photogrammetry software recognized common features through all the photos taken to the shoeprint, the texture and resolution of the photos are very important to build a high-quality 3D model (Westoboy and col., 2012). This study will focus on the use of different enhancing techniques to improve the photographic recovery method of snow shoeprints. This will help to understand which method provides a more reliable 3D shoeprint model, ensuring an accurate shoeprint analysis and forensic comparison.

Background

Shoeprints

When a shoeprint is found on a crime scene, the purpose of the examination and analysis of this evidence is to determine the class characteristics of the outsole and evaluate if it contains fine details to reveal specific marks, patterns or characteristics that individualize it from other shoeprints (Petraco and col., 2016). Also, this can assist in determining the number of suspects, suspect's path into the crime scene, as well as corroborate the witnesses or suspects testimony. In addition, it can help to analyze the gait of the suspect comparing to traits of the body movements as they walk on surveillance videos (Bodziak, 2017, chapter 1).

The shoeprints can classify in three categories depending on their appearance: Visible, Latent and Plastic impressions. A visible shoeprint is visible to the naked eye and does not need enhancement techniques or lighting to be observed (e.g.: a bloody shoeprint). In contrast, a latent shoeprint is invisible to the eye and additional methods are needed to make it visible; and a plastic shoeprint is made on a soft surface such as mud or snow, creating a three-dimensional impression. (Pereira, L., 2015)

Photographing is an important part of the documentation of evidence at the crime scene. In the same way, photographing a shoeprint impression can be the most effective technique for documentation and permanent record (SWGTREAD, 2005. Guide for the Collection of Footwear and Tire Impressions in the Field.). A digital camera with a tripod are essential to capture a high-quality shoeprint image. Some enhancing techniques such as oblique lighting help to increase the contrast and therefore the details on the shoeprint's photos (FBI, 2019. Handbook of forensic science).

The collection of two-dimensional shoeprints (visible and latent) are made using an electrostatic lifting device, footwear-sized gelatin lifters, or adhesive lifters; which are recommended for shoeprints developed with dark colored powders on non-porous surfaces (ANSI/ASB, 2020, Best Practice Recommendation for Lifting of Footwear and Tire Impressions.). If the impression was made on a movable surface (for example a bloody shoeprint on a sheet) the entire surface is packed and delivered to the laboratory, but if this is not the case, different collection methods are needed (Pereira, L., 2015).

The collection of 3D-dimensional shoe impressions require more intricate and time-consuming methods depending on the surface of the shoeprints are made. Casting is the most used method for the recovery of the 3D impression, giving a life-size 3D dimensional detailed molding impression which can be compared directly alongside the suspect's outsole (Bodziak, 2017, chapter 3). The FBI's Handbook for Forensic Science recommend the use of dental stone, with a compressive strength of 8,000 psi or greater for 3D shoeprint impressions. The preparation of this material includes the addition of water and vigorous massaging for approximate 3 to 5 minutes until it has the consistency of heavy cream. Later, the shoeprint impression is filled with the material until it has overflowed with a minimum of ½ to 1 inch of thickness, and then let it air- dry for 48 hours before packaging and delivery to the laboratory (FBI, 2019. Handbook of forensic science).

Snow shoeprints are particularly difficult to collect due to the different types of snow and the lower temperatures where the forensic technicians makee all the process. Many methods have been proposed for the collection, but all of them have some disadvantages. Casting with gypsum demonstrated many problems. Its weight could destroy some shoeprints details and exothermic reactions could occur whilst the gypsum hardens. Sulphur did not show any improvement when it was utilized. Higher temperatures of the sulfur could destroy details of impression or the whole snow shoeprint and it is not recommended its use when the shoeprint was made on loose powdery or frozen snow surfaces due the material tends to flow through the impression and collect under the surface (Buck and col., 2007). In both cases, the shoeprint impression is destroyed and the process is time-consuming.

Currently it is recommended enhance the snow shoeprint with different coating materials such as snow print wax to increase contrast for photography and to create a barrier between the impression and casting material. In this case, either dental stone products or sulfur can be used for casting (AAFS, 2020, Standards Board, Best Practice Recommendation for Casting Footwear and Tire Impression Evidence at the Crime Scene.). Even with this technique, both methods will destroy the shoeprint impressions and require skilled personnel with experience.

Photogrammetry

Advances in technology have permitted that new instruments and software were available to simplify multiple procedures in different areas. In forensics, some of these new technologies have replaced the traditional methods of evidence collection in different studies, demonstrated accuracy and reliability.

Photogrammetry is a low cost, non-invasive, easy to use method which simply require a digital camera and a computer with a photogrammetry software. Any digital camera can be used, even a phone camera, however it is recommended larger cameras, like DSLR, because they have a larger image sensor which is better for photogrammetry. (Kreimer, 2020, A Guide to Photogrammetry Photography).This method can be applied in different fields such as engineering, geoscience, archeology, anthropology, paleontology, and many more including forensics.

This method employs a high degree of overlapping images captured from multiple views. However, when a detailed image wants to be 3D reconstructed, multi-scaled images sets are recommended, so a whole site and close-range photos of the desired details are taken for a high-quality result (Michelleti, 2015). The camera geometry, position and orientation are automatically determining without the necessity of a pre-defined three-dimensional visible points. After the software utilizes a scale invariant feature transform (SIFT), which what the software identified common features through all the set of photos with what it is determining the spatial relationship between the different locations of the original in a 3D coordinate system. (Westoboy, 2012). For an optimal reconstruction of the 3D image a bundler adjustment system is used to estimate the camera position and extract the sparse constantly changing point clouds which are not suitable for the 3D reconstruction (Furukawa, 2007). At the end, the 3D point positions are estimated using a triangulation to gradually reconstruct a mesh over the surface of the model and then the texture with is wrapped around the mesh (Westoboy, 2012). The total time required to obtain the 3D model reconstructed will be dependent in the number of photos, the resolution of them and the computer hardware.

Previous Research

Casting have been the only recovery method used for plastic shoeprints from a long time; however, this method has shown multiple limitations that can influence in the high-quality of the shoeprint modeling. Many studies have been made to prove the efficacy of new recovery method that can be simpler and more reliable than the current method.

Thompson and col. conducted a study using a new digital method to recovery shoeprints. Using a 3D structured light scanning, they built multiple shoeprints from different substrates and compare the 3D shoeprint models with shoeprint casts. They found that 3D print models showed parts of the tread from the footwear that the traditional cast could not show. Results demonstrated that the use of this new method is a faster, non-destructive recovered method which offer the ability to print the models and to share it for comparison purposes (Thompson and col.,2018).

Buck and col. used the same method, 3D optical surface scanning, to scan snow shoeprints with a previous sprayed of Snow Print Wax on the impressions. The results shown that this is a suitable, non-destructive, and high accurate recovered method of shoeprint impression made on snow surface. Each 3D snow shoeprint models displayed more details of the outsole than the shoeprint casts (Buck and col., 2007).

The validity of the use Artec Spider Structured-Light Scanning (SLS) device as recovered method for shoeprint impressions made on soil and comparison of class characteristics was demonstrated by Montgomerie and col. The 3D shoeprint models build with this device shown precision and repeatability; however, the comparison of individual characteristics was not validated yet, therefore is recommended that this method can be performed before casting (Montgomerie, C., and col., 2020).

The high cost of the 3D scanner devices and the fact that is impractical to transport to a different location, led to experts to search for alternative methods.

Andalo and col. evaluated an alternative method using only a camera, and computer. This new method utilized a series of photographs from multiple views processed Computer Vision, Multiview stereo techniques to build accurate 3D models shoeprints. The study proved that the 3D shoeprint models built with this technology were comparable with 3D shoeprint models built with scanning, with the difference that this new method required only one camera with no surface limitations (Andalo and col., 2011).

Larsen, and col., examined the reliability and reproducibility of photogrammetry, a new easy to use recovery method of shoeprint impressions. In this study a freeware software designed specifically for forensic shoeprint, Digtrace was used to build 3D shoeprint models on different surfaces mud, sand, and snow. On sand and mud surfaces, the study demonstrated that there was a low variability between 3D shoeprint models with a repeatability of 97% and variation between models less than ~0.5 mm. On the other hand, 3D snow shoeprints models shown largest variability between models with displayed of multiple holes within the models (Larsen and col., 2020).

All previous research highlighted that the use of 3D technology as a solution for casting method limitations. Further studies are needed to validate photogrammetry in different surface, especially on snow, where the accuracy and repeatability have been demonstrated be low than in other surfaces.

This research sought to examine different photographic protocols to find if there is a superiority of one protocol over the other and standardize the way and number of photos shoeprint impression needs to build a reliable 3D model using photogrammetry. Also, the use of new techniques applied before taking of photographs of the snow shoeprints to build a reliable and accurate 3D snow shoeprint models was tested.

Materials and Methods

First Experiment

For the first experiment the following materials were used:

-Women shoe (Puma training shoe model cell phase - Black)

- Nikon Digital Camera- D3500

-Camera tripod.

-Laptop

-Scale

- DigTrace Pro v.1.8.1. software.

Two shoeprints were made of the same shoe on sand and mud. The locations used for the experiment were the Kuntner Park and the Fairfax Park in Fairfax, VA. Each shoeprint was used to build 20 three-dimensional shoeprint models, for each 3D model approximately 20 photographs were taken using two different protocols. (Figure 1 and 2)

Figure 1. *Shoeprint on mud surface*

Figure2. *Shoeprint on sand surface*

The first protocol used was the protocol recommended by the Digtrace manual. The first 5 overview photos included the whole shoeprint within the frame, one photo was made top-down at 90 degrees, and the other 4 were made from each side at ~45 degrees. Then, 15 closer photos perpendicular to the ground were made, dividing the shoeprint in 3 columns and 5 lines, these photos were taken sequentially creating overlapping segments along the length of the shoeprint starting at one corner. Between each set of photographs, the camera is put down and the photographer take a break for about 30 seconds. A scale is always placed next to the impression (Budka and col., 2016). (Figure 3)

The second protocol used was the one protocol used by Larsen et al. First, one photo was taken from directly above the impression at 90 degrees. Then two photos were taken from each side at 4 differing oblique angles. After that, the shoe impression was divided into 2 columns and 3 lines and each segment was photographed first from above (landscape), and then in portrait, ensuring overlap between photos and that enough surrounding areas are included. A scale was also placed next to the impression in all pictures (Larsen and col., 2020). (Figure 4)

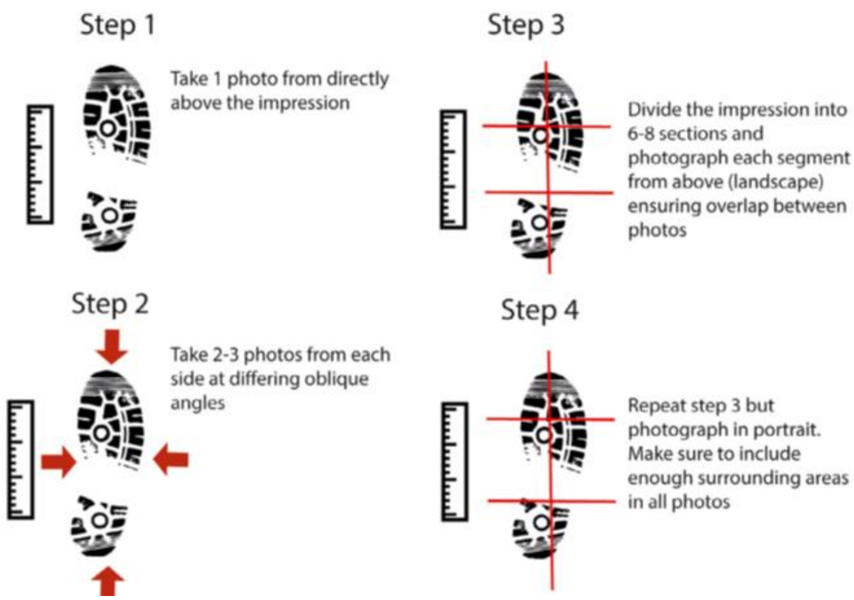
Figure 3. *Digtrace's photos protocol.*

A. One top-down photo at 90 degree and one from each side at ~45°

B. The shoeprint is divided in 3 columns and 5 lines, and sequentially each segment is photographed perpendicular to the ground. Each image needs to overlap with the image before and after by ~2/3.

Source: *Budka, M. and col. DigTrace Pro/Academic. User manual. October 2016. Available at: www.digtrace.co.uk*

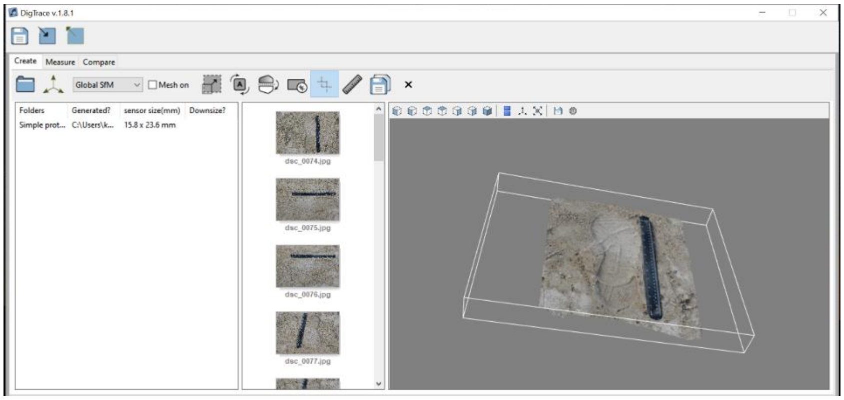
Figure 4. *Larsen et al. photos protocol.*



Source: *Larsen and cols., Empirical Evaluation of the Reliability of Photogrammetry Software in the Recovery of Three-Dimensional Footwear Impressions. Journal of Forensic Sci, 2020.*

After taking all the photos, these were saved in different folders and 3D models were created and scaled with DigTrace. The 3D models were numerated from 1 to 20 and were saved in 4 folders: sand A, sand B, mud A and mud B where A refers to the DigTrace photographic protocol and B refers to the photographic protocol used by Larsen et al. (Figure 5)

Figure 5. *3D shoeprint model built on Digtrace software.*



Second Experiment.

For the second experiment the materials used were:

- One women shoe (Puma training shoe model cell phase -Black)
- Nikon Camera - D3500
- Camera tripod.
- Laptop
- Scale
- DigTrace Pro v.1.8.1. software.
- Blue and red food dye McCormick
- Two 100 ml spray bottles
- Cold water
- A red filter for camera (50 mm.)
- Light lamp
- Black plastic bags

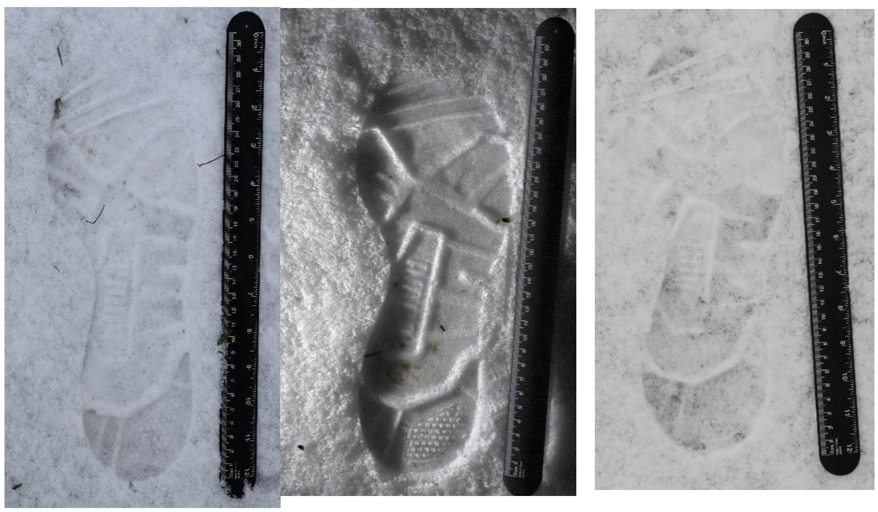
Five different shoeprints with the same women shoe were made outdoors with natural light on the snow at the Fairfax Park. (Figure 6)

Figure 6. *Shoeprint on snow surface*

- For the first shoeprint made on the snow, no alterations were made.
- For the second shoeprint made on the snow a red color dye was sprayed over the shoeprint. The red color dye was made with a red color food dye mixed with cold water in a 100 ml/3.5 oz clear spray bottle.
- For the third shoeprint made on the snow a blue color dye is sprayed over the shoeprint. The blue color dye was made with a blue color food dye mixed with cold water in a 100 ml/3.5 oz clear spray bottle.
- For the fourth shoeprint made on the snow was photographed with a red filter camera using black and white photos.

- For the fifth shoeprint made on the snow was photographed with a light positioned at an oblique low angle in multiple directions and black bags around the tripod to create shadows on the surface of the snow shoeprint. (Figure 7)

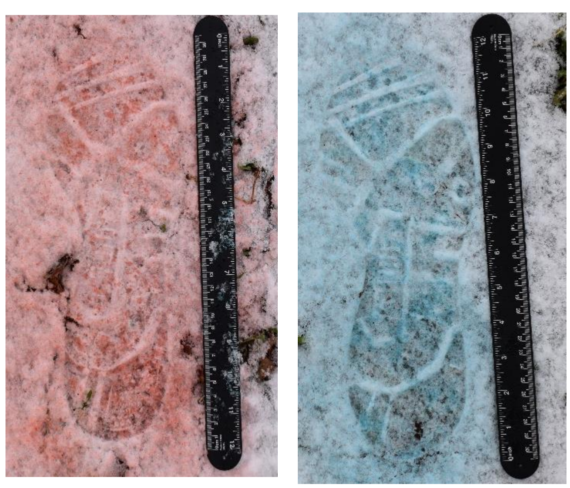
Figure 7. *Shoeprints on the snow with the 5 different techniques.*



A. Shoeprint without alteration

B. Shoeprint with oblique light.

C. Shoeprint with red camera filter/white-black photo.



D. Shoeprint with red dye.

E. Shoeprint with blue dye.

Each shoeprint was used to build 10 three-dimensional shoeprint models. For each 3D model 20 photographs of the shoeprint were taken using a protocol used by Larsen et al.

First, one photo was taken from directly above the impression (90 degrees). Then two photos were taken from each side at differing oblique angles. After that, the shoe impression was divided into 6 sections and each segment was photographed from above (landscape), and in portrait mode ensuring overlap between the photos and that enough surrounding areas are included. A scale was placed next to the impressions (Larsen and col. 2020). (Figure 4).

The photos were saved in different folders and 3D models were created and scaled in Dig Trace. The 3D models were numerated from 1 to 10 and were saved in 5 folders: A (without alteration), B (red dye), C (blue dye), D (white-black photo) and E (oblique light).

Analysis and Comparison

For data analysis and comparison of the 3D models a Microsoft Excel and CloudCompare v2.11.1 software was used., respectively.

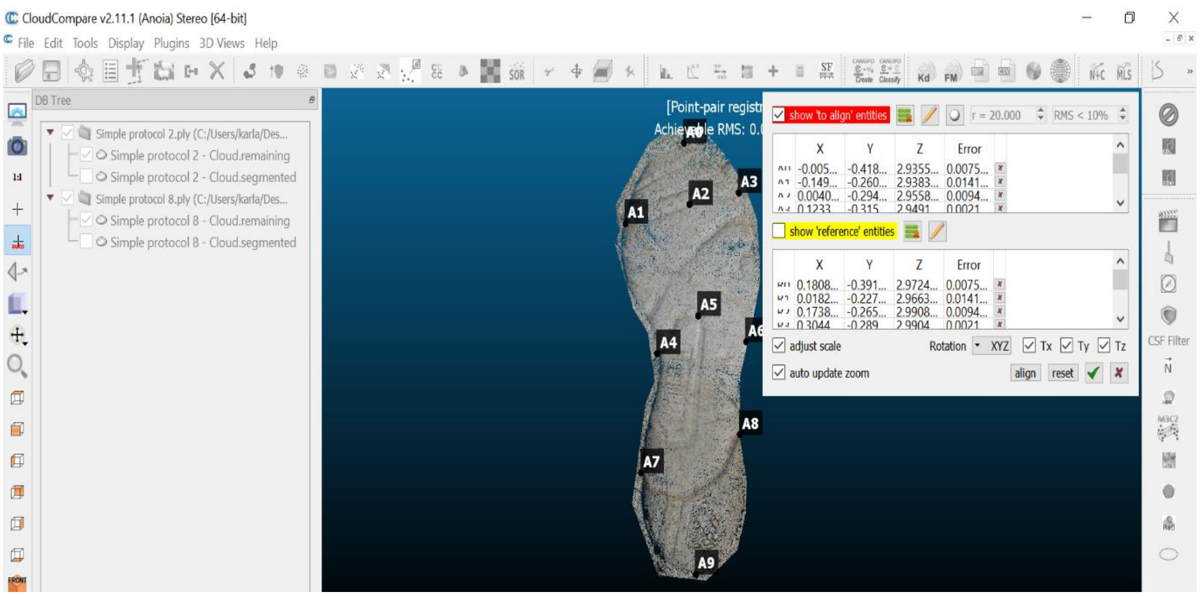
For the first experiment ten 3D models from folder sand A were randomly paired in an Excel spreadsheet to be model 1 and model 2. The same procedure was made to select the models from the other 3 folders (sand B, mud A, mud B).

For the second experiment, five 3D models from folder A (without alteration) were randomly paired to be model 1 and model 2. The same procedure was made to select the models from the other four folders B (red dye), C (blue dye), D (white-black photo) and E (oblique light).

After pair each model, point clouds of the 3D models (ply. files) created on Digtrace were imported into CloudCompare software to be registered and aligned.

First the cloud points were aligned using point pairs picked, a minimum of 10 points were picked distributed through all the shoeprint area (4 on the toes, 3 in the middle and 3 on the heel). After that, using an ICP (iterative closest point) algorithm a fine alignment was made. (Figure 8)

Figure 8. *Alignment using points pairs picking a minimum of 10 points distributed through the whole area of the shoeprint.*



After the alignment, a cloud-to-cloud point distance was computing using the nearest neighbor method. The mean distance, standard deviation, and color scale. An average of the measurements was calculated to compare different models. Also, a colorimetric scale is shown to demonstrate the areas where the shoeprints have more differences.

Results

First Experiment

Comparing the 3D models built over a sand surface reveal an average distance between points measured between cloud/cloud of 0.0968 mm with a standard deviation of +/- 0.1406 mm, with approximately 99% of the points have an interpoint distance less than or equal to 0.7149 mm. (Table 1). Using Larsen's protocol, the average distance between two points is 0.3081 mm with a standard deviation of +/- 0.3123 mm, and an approximately 99% of the interpoint distance less than or equal to 1.3817 mm. (Table 2).

Table 1. *Comparison of cloud-to-cloud of 3D models on sand surface using Digtrace's protocol.*

Model 1	Model 2	Mean distance (mm)	Std deviation	RMS	Distance between points (mm) of 99% of model
17	13	0.0440	0.0404	0.1216	0.2577
15	19	0.0387	0.0572	0.1383	0.3309
10	2	0.0543	0.0621	0.1587	0.2086
3	18	0.0993	0.1484	0.2209	0.7636
5	1	0.1913	0.4235	0.1034	2.1587
4	8	0.0881	0.0822	0.1657	0.4241
9	16	0.0260	0.0446	0.1209	0.2550
6	20	0.1044	0.1716	0.2252	0.9425
7	14	0.1403	0.2137	0.3064	0.9839
12	11	0.1819	0.1632	0.1354	0.8249
Average		**0.0968**	**0.1406**	**0.1696**	**0.7149**

Table 2. *Comparison of cloud-cloud of 3D models on sand surface using Larsen's protocol.*

Model 1	Model 2	Mean distance (mm)	Std deviation	RMS	Distance between points (mm) of 99% of model
3	19	0.3693	0.3640	0.4926	1.5076
12	16	0.2009	0.3004	0.4126	1.6785
7	9	0.1542	0.2177	0.3263	1.2487
5	20	0.3458	0.3877	0.5108	1.5842
18	2	0.3810	0.3865	0.4375	1.2446
14	8	0.3801	0.3743	0.5577	1.5623
15	10	0.3374	0.3184	0.5343	1.3421
6	17	0.2802	0.2414	0.4064	1.2108
11	1	0.3845	0.3294	0.6030	1.5109
13	4	0.2481	0.2041	0.4872	0.9273
Average		**0.3081**	**0.3123**	**0.4768**	**1.3817**

On the mud surface, the difference between the two photograph protocols is little. Using the Digtrace protocol, the average distance is 0.2522 mm with a standard error of +/- 0.3969 mm and an average distance between of 99% of the points is less than or equal between all the 3D models of 1.4257 mm. (Table 3). Larsen's protocol shows a mean distance between two cloud points in all the 3D footprints of 0.1025 mm with a standard error of +/- 0.1714 mm. The greatest difference between Digtrace's protocol and Larsen's protocol is the average inter-point distance of 99% of 3D shoeprints which is less than or equal to 0.95530 mm. (Table 4).

Table 3. *Comparison of cloud-to-cloud of 3D models on mud surface using Digtrace's protocol.*

Model 1	Model 2	Mean distance (mm)	Std deviation	RMS	Distance between points (mm) of 99% of model
18	2	0.1521	0.2905	0.3720	1.5411
16	20	0.0880	0.1791	0.2619	0.9481
14	8	0.8310	1.1463	0.3016	0.3344
12	5	0.1501	0.2884	0.3887	1.2909
9	15	0.3960	0.5505	0.7806	2.6868
3	7	0.0803	0.1119	0.2163	0.5710
1	17	0.0928	0.1115	0.4780	0.6915
13	19	0.2316	0.3724	0.4965	1.8206
4	10	0.2882	0.4870	0.6917	2.2335
11	6	0.2128	0.4317	0.7899	2.1393
Average		**0.2522**	**0.3969**	**0.4777**	**1.4257**

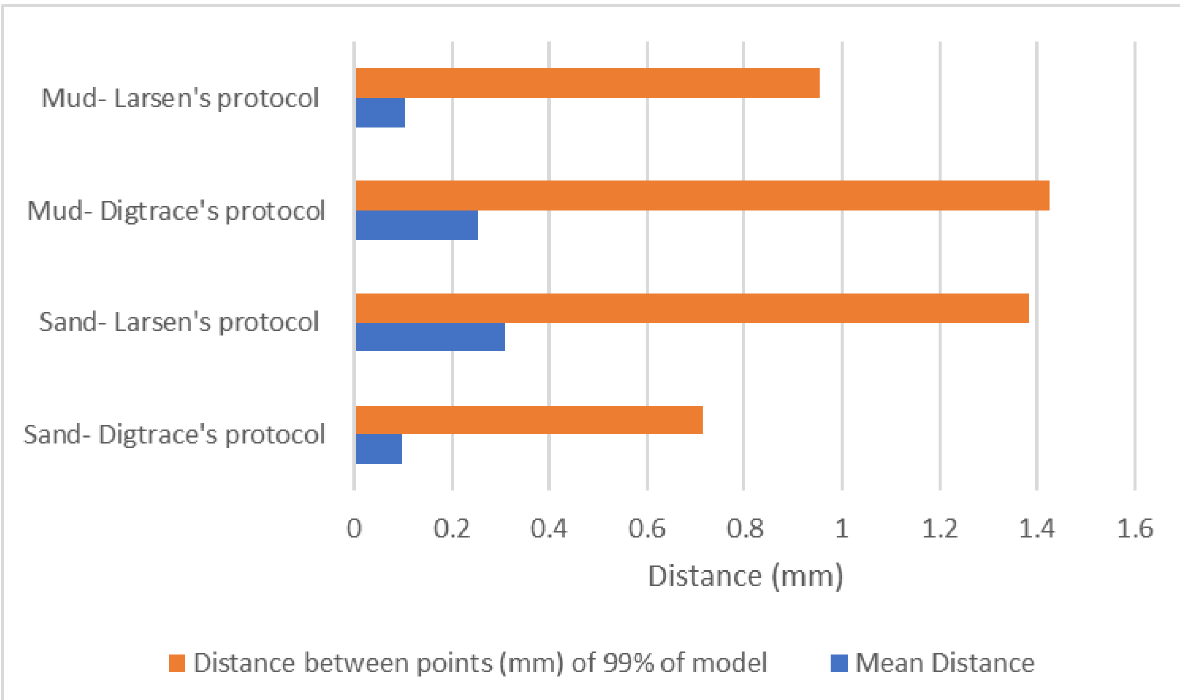
Table 4. *Comparison of cloud-to-cloud of 3D models on mud surface using Larsen's protocol.*

Model 1	Model 2	Mean distance (mm)	Std deviation	RMS	Distance between points (mm) of 99% of model
7	12	0.1375	0.2157	0.2970	1.2649
8	9	0.0559	0.1083	0.1412	0.5020
2	3	0.0756	0.1243	0.1269	0.9206
14	6	0.1015	0.1535	0.2398	0.7313
16	10	0.1483	0.3157	0.1907	1.5695
11	20	0.1480	0.1829	0.3033	0.6120
4	17	0.0851	0.1244	0.2275	1.5476
15	18	0.0954	0.1413	0.2526	0.4949
5	13	0.0785	0.1539	0.2159	0.7944
1	19	0.0995	0.1944	0.2577	1.0930
Average		**0.1025**	**0.1714**	**0.2252**	**0.9530**

Shoeprints made on sand surface and photographed with the Digtrace's protocol shown less mean distance error between two-point clouds (0.0968 mm) than with Larsen's protocol (0.3081 mm). Although, Digtrace's protocol shows less variability between 3D footprints models made on sand surface, this difference is only 0.2113 mm, which is not significant. The same pattern results are observed in the average inter-point distances of 99% of models, Digtrace's protocol (less than or equal to 0.7149 mm) and Larsen's protocol (less than or equal to 1.3817 mm) with a difference between protocols of 0.6668 mm.

On the other hand, shoeprints made on mud surface shows less dissimilarity between models using Larsen's protocol (average mean distance: 0.1025 mm) compare with Digtrace's protocol (average mean distance: 0.2522 mm). Despite this, the difference between the average mean error of these two protocols on mud surface is 0.1497 mm, which is not significant. (Chart 1)

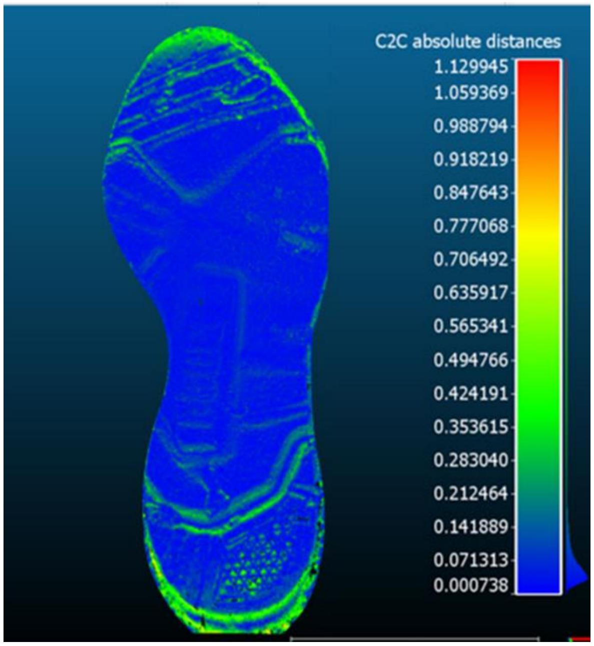
Figure 9. *Graphic of Larsen's protocol and Digtrace's protocol on mud and sand surfaces.*



Color scales were created on CloudCompare to show the difference in error distances between cloud-cloud points displayed through the whole shoeprint.

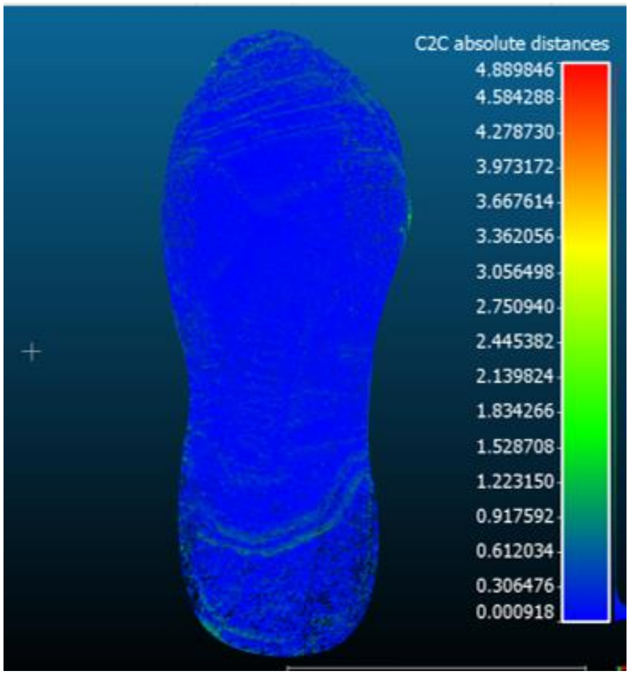
The color scale that display the difference between shoeprints made on sand surface using Digtrace 's photographic protocol (model 4 – model 8) shown that the majority of the shoeprint display blue color which indicate error distances between 0 to 0.141 mm. There are some bright green areas on the rim of the toes and parts of the heel which indicate error distances between 0.2 mm to 0.63 mm. (Figure 9)

Figure 10. *Color scale of shoeprint models (Model 4- Model 8) made on sand surface using Digtrace's photographic protocol.*



Comparing shoeprint models made on mud surface, the one with Larsen's photographic protocol (model 11-model 20) displayed most of the shoeprint in blue colors indicating error distances between 0 to 0.3 mm and small bright green parts on the heel indicating error distances 0.9 mm to 2.7 mm. (Figure 10)

Figure 11. *Color scale of shoeprint models (Model 11- Model 20) made on mud surface using Larsen's photographic protocol.*



Second Experiment

On the snow surface, using the Larsen's protocol, the average mean error distance between cloud-cloud points of shoeprint models is 0.214 mm, which does not vary much from the shoeprint models made on sand and mud surface. Despite this, the average inter-point distance of 99% of the snow footprint models is less than or equal to 2.1271 mm, which is quite high compared with the results shown on mud and sand surface (Table 5).

Table 5. *Comparison of cloud-to-cloud of 3D models on snow surface using Larsen's protocol.*

Model 1	Model 2	Mean distance (mm)	Std deviation	RMS	Distance between points (mm) of 99% of model
5	3	0.2356	0.2721	0.3596	2.0898
6	2	0.1623	0.2180	0.3060	1.1460
10	7	0.1885	0.3324	0.4052	2.1540
8	1	0.3557	0.6759	0.4300	3.7949
4	9	0.1279	0.1992	0.2830	1.4509
Average		**0.2140**	**0.3395**	**0.3567**	**2.1271**

Using the oblique light phototgraphing the snow shoeprint models reveals a larger mean distance (0.9479 mm) than the snow shoeprint models without any alteration with a difference of 0.7339 mm. But the biggest difference is shown on 99% of the inter-points distance which reveal values of less or equal to 5.6385 mm, which is approximately 3.5114 mm larger than the 99% interpoints error distance between models on snow surface with no alterations. (Table 6)

Table 6. *Comparison of cloud-to cloud of 3D models on snow surface using an oblique light.*

Model 1	Model 2	Mean distance (mm)	Std deviation	RMS	Distance between points (mm) of 99% of model
1	3	1.0390	1.0512	0.7632	5.1111
2	8	1.8701	2.4172	1.9552	9.4198
5	9	0.8207	1.2256	0.6942	6.6028
6	4	0.4082	0.4126	0.6095	2.4099
7	10	0.6019	0.7683	0.6789	4.6489
Average		**0.9479**	**1.1749**	**0.9402**	**5.6385**

The camera red filter with black and white photos shown only a little improvement of the mean distance (camera red filter/white-black photos: 0.20316 mm, snow with no alterations: 0.2140 mm) with a difference of 0.0109 mm with the snow shoeprint with no alteration. However, the distance between points of 99% of models revealed an increment of 0.1063 mm compared with doing no alteration on the snow shoeprint models. (Table 7)

Table 7. *Comparison of cloud-to cloud of 3D models on snow surface using a camera red filter / white-black photos.*

Model 1	**Model 2**	**Mean distance (mm)**	**Std deviation**	**RMS**	**Distance between points (mm) of 99% of model**
10	3	0.2231	0.5915	0.6606	3.4567
4	8	0.1752	0.2323	0.3105	1.4418
1	9	0.2536	0.3277	0.4410	1.7761
7	2	0.1916	0.2501	0.7015	1.3195
5	6	0.1723	0.6590	0.6917	3.1732
Average		**0.2031**	**0.4121**	**0.5610**	**2.2334**

The use of blue and red dyes on the snow shoeprints revealed a noticeable improvement of the reliability values.

The average mean distance error using red dye spray on the shoeprint is 0.0734 mm with a deviation +/- 0.1028 mm, and an interpoint distance of 99% of model is less than or equal to 0.6682 mm. (Table 8)

Table 8. *Comparison of cloud-to cloud of 3D models on snow surface using a red dye spray on the shoeprint.*

Model 1	Model 2	Mean distance (mm)	Std deviation	RMS	Distance between points (mm) of 99% of model
2	4	0.0583	0.0734	0.1115	0.4771
1	6	0.0560	0.0896	0.1285	0.5626
8	10	0.1017	0.1194	0.2139	0.6520
5	7	0.0987	0.1527	0.1519	1.2323
3	9	0.0525	0.0791	0.1171	0.4173
Average		**0.0734**	**0.1028**	**0.1445**	**0.6682**

The use of a blue dye showed a larger decrease on the average error distance and the 99% inter-point distance of the models than when a red dye is used, where the average mean distance when a blue dye is applied is 0.0648 mm and a 99% interpoint average error distance of models is less than or equal of 0.4992 mm. (Table 9)

Table 9. *Comparison of cloud-to cloud of 3D models on snow surface using a blue dye spray on the shoeprint.*

Model 1	**Model 2**	**Mean distance (mm)**	**Std deviation**	**RMS**	**Distance between points (mm) of 99% of model**
3	4	0.0709	0.1142	0.1258	0.7232
10	7	0.0843	0.0958	0.1376	0.5238
2	5	0.0522	0.0482	0.1203	0.5598
1	9	0.0419	0.0326	0.0906	0.1809
6	8	0.0751	0.0773	0.1424	0.5087
Average		**0.0648**	**0.0736**	**0.1233**	**0.4992**

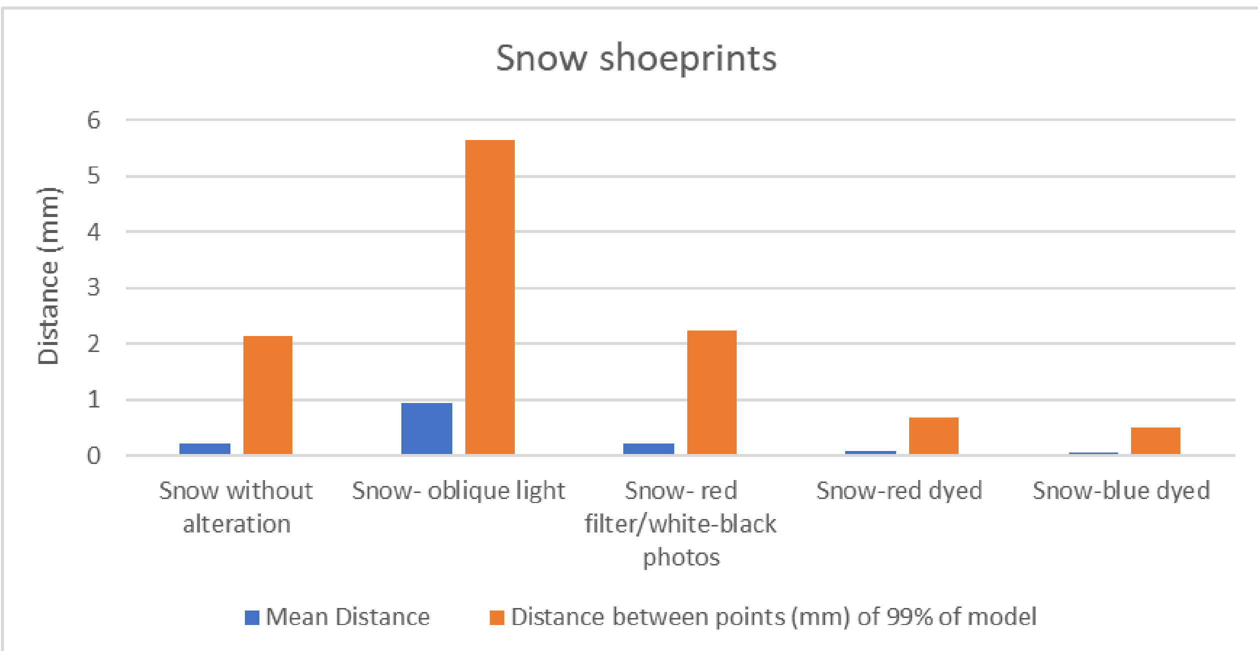
The used of different techniques over the snow shoeprint shown different results. The snow shoeprint photographed and built without any alteration shown a low average mean distance (0.2140 mm) but with a high 99% of the interpoints distance of all models (less than or equal to 2.1271 mm). Many of the snow shoeprints models built without any alteration displayed multiples holes which incremented the cloud-cloud distance.

Using oblique light from multiple positions shown an increase in the average mean distance error and 99% interpoint distance of the model.

The results using the red filter with white and black photos shown a little decrease in the average mean error distance of 0.0109 mm, but an increase of the interpoint distance in 99% of the points compared to the snow shoeprint models without alteration.

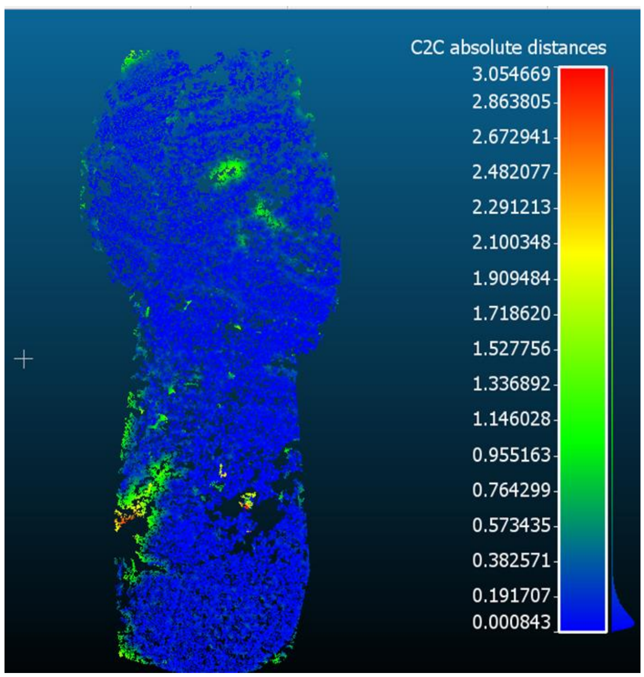
On the other hand, using red and blue dye onto the snow shoeprint before photographed revealed a considerable decreased of the mean error distance between two-point clouds, and in the same manner of the distance between cloud-cloud of 99% of the model. (Chart 2)

Figure 12. *Graphic with the different methods on the shoeprints made on the snow surface.*



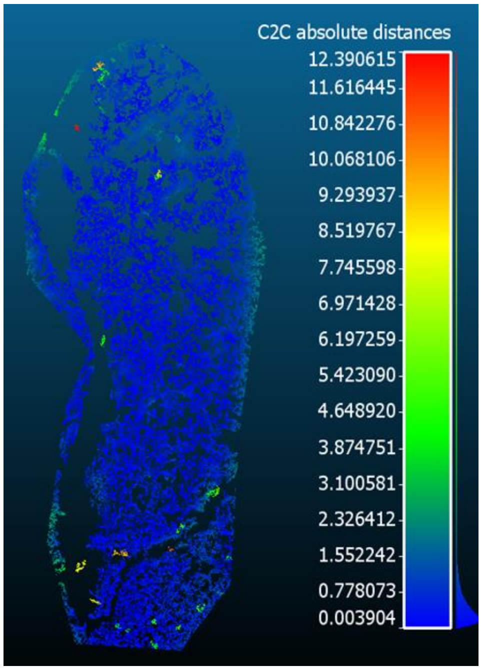
The color scale shown that the 3D snow shoeprint models without any alteration displayed incomplete shoeprints with multiple holes within the shoeprint. The comparison of model 6-model 2 shown blue color in most of the shoeprint, indicating that the distance between cloud-to-cloud point in this area between 0 to 0.3 mm. But some bright green areas are shown on the middle of the toes, and left side of the heel indicating distances between 0.5 mm to 1.7 mm. Orange and red points shown on the heel indicated error distance between 2.2 mm to 3 mm. (Figure 11).

Figure 13. *Color scale of shoeprint models (Model 6- Model 2) made on snow surface using Larsen's photographic protocol.*



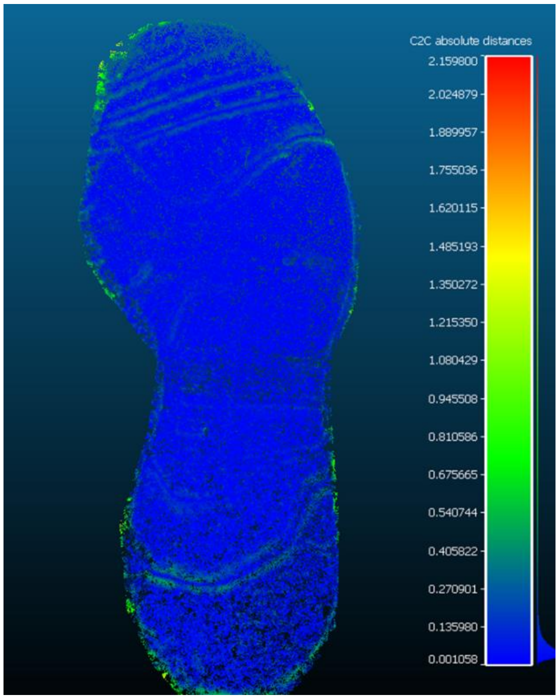
The comparison of 3D models using the oblique light shows also incomplete shoeprint models with multiple holes. This is due to shadow parts, created by the oblique light, displayed on the photos of the shoeprint was not detected by the software and so it was not displayed when the 3D model was built. Comparing model 1 and model 3 shown that most of the part of the shoeprints displays blue color indicating distance between cloud/cloud points from 0 to 1.5 mm, some bright green colors on the toes and heel indicating cloud points from approximately 2mm to 7 mm and a red point located on the toes indicating approximately 12 mm of error distance. (Figure 12)

Figure 14. *Color scale of shoeprint models (Model 1- Model 3) made on snow surface using oblique light.*



On the other hand, snow shoeprints photographed with blue dyes shown a better display of a complete shoeprint. The comparison between of model 7 – model 10 displayed a complete shoeprint with blue color in most of the shoeprint representing distances between cloud to cloud of 0 mm to 0.1 mm, and some bright green color parts specially in the heel and left part of the toes, representing distance of 0.5 mm to 1 mm. (Figure 13).

Figure 15. *Color scale of shoeprint models (Model 1- Model 3) made on snow surface using blue dye.*



Discussion

The comparison of Larsen's photographic protocol and Digtrace's protocol shown little difference between them, with only a slight decrease in the distance of clouds points in shoeprint's 3D models.

On the mud surface, Larsen's protocol reveals more accuracy reproducing 3D shoeprint models than the Digtrace's protocol, however, Digtrace's protocol models revealed less mean error distance and error in 99% of inter-point distance in all sand models than Larsen's protocol.

Because the difference in mean distances and 99% of the interpoint distances is small in either surfaces, we can conclude that there is no significant superiority of one protocol over the other one. A previous study that used the same surfaces and the Larsen's protocol, the results shown less mean distance with less 99% of the inter-point distance in all models of footprints made on sand compared with mud surface. In the mentioned study sand surfaces revealed a more reliable reproduction of 3D footprint models than mud surfaces. However, this study shown a more accurate reproducibility of 3D models on mud surface than sand surface, using the same photo protocol. This may be due to the variation in the surfaces' characteristics. In both cases sand and mud surfaces were used for the study, but there were made on different location sand the composition of the sand and mud may have been different, causing this discrepancy.

Even though, there are differences between the error mean distances and 99% of the interpoint distance on the mud and sand surfaces, the differences are not significant, being in both cases were less than 1 mm.

The second experiment shown the built of 3D models of the same shoeprint made on a snow surface, using multiple methods to improve the accuracy on the three-dimensional building of the footprint models. Despite the results revealed that the snow 3D shoeprint could be built with a low average of mean distances (0.2140 mm), the 99% of the interpoints distance of all models were higher (2.1271 mm) than in the mud and sand surfaces. This could be because in most of the 3D snow shoeprints multiple small holes were observed within the shoeprints, and in some of the cases the shoeprint model were not completely built, which caused higher 99% interpoint distances, as in the case of model 1 and 8 which shown a distance between 99% of the points of less than or equal than 3.7949 mm. This problem was also observed in Larsen's study, where the average 99% of the inter-point error was less than or equal to 3.123 mm. The author described the same problem than we had in this study, noting issues related to uniformity of the surface and the low contrast in the taken photos (Larsen, H., and col., 2020)

In this study we tried to improve the contrast of the photos so the 3D building of the model could be more accurate by using different techniques: oblique lights, a red camera filter/white-black photos, and food color dyes.

The oblique light created a shadow on the surface of the shoeprint, consequently, increasing the contrast and details of it. This technique shown an increase of shoeprint details in the pictures but produced a higher mean distance (0.9479 mm) and a higher error distance of the 99% of the points of all models (5.6385 mm) on the 3D models when compared with the models without any alteration. This demonstrated that even though the oblique light helped to increase the details of the snow shoeprints photos, it is not helpful for enhancing the construction of 3D models.

A previous study shown that red camera filters can produce higher contrast between different colored objects that reflect the same amount of light, as snow surfaces (Perovich, B. W., 2013). The colored filters let in some colored lights and block opposing colors, producing contrast (Aldred, J. 2018). This knowledge was applied on the snow shoeprints to create better quality photos and therefore better 3D models. The results using the red filter with white and black photos shown no increment of the reliability of the 3D models shoeprints. There was only a little decrease in the average mean error distance of 0.0109 mm, in contrast with the interpoint distance in 99% of the points which increased in 0.1063 mm compared to the snow 3D models without alteration. Using this technique did not show a benefit over not using any enhancing technique on the snow shoeprint photos.

Taking photos of snow shoeprints could be very challenging due the homogeneity and reflective white snow surface with lack of contrast. This problem is also observed when other objects are digitalized such as plaster casts, objects made of ivory, transparent objects, or enamel found on the teeth. In these cases, different techniques are used to reduce the reflection. Coating the object with paint, spray or chalk permits to opaque the surfaces, giving more contrast of the object when the photo is taken, and at the same time improving the quality of the 3D model reproduction (Mathys, A. 2019; Busby J., 2016)

Using one of this method, in this study a thin layer of food dye coating was sprayed on surface of the snow shoeprint. In the FBI's Handbook of Forensic Service Snow Print Wax J is recommended for casting snow and increase the contrast of the snow shoeprint photos (*Handbook of Forensic Services 1999*), however, in this study we tested the use food dyes because they have a lower cost, are easier to prepare, and are watery enough to be sprayed uniformly over all the surface creating a thin layer of paint. The results observed in this study shown that applying red dye onto the snow shoeprint decreased the mean error distance between two point clouds in 0.1405 mm (red-dyed : 0.0734 mm snow with no alteration: 0.2140 mm). The biggest difference between the unaltered and the red dyed models is seen on the interpoint distance of 99% of points of all models which is approximately 1.4588 mm. The blue dyed shoeprints showed a larger decrease on the average error distance and the 99% inter-point distance of the models, with a difference of 0.0086 mm of mean distance and 0.169 mm in 99% of the interpoint error distance with the red dyed models.

Spraying food dye over the snow shoeprints shown a considerable increase of the reliability of the building of 3D shoeprints models, allowing that the details of the shoeprint were reproduced more accurately in comparison to other methods.

Conclusion

It can be concluded that the comparison of Digtrace and Larsen photography protocols shown little difference between them with not significant variations on the different surfaces. This means that any of the protocols can be used to build reliable shoeprint 3D models and it will depend on the user which protocol would be more convenient for them.

Future studies will be required to analyze the inter-user reproducibility of this method. Due to external situations that occurred during the preparation of this study, it was not possible to test the reproducibility of the 3D models when the shoeprint photos are taken from different users but confirming this might give more validity to the photography protocols.

Photographing snow shoeprints can be very challenging because the lack of color contrast on the snow surface and the reflections that can affect the quality of the photos. These results showed that spraying food dyes on the snow shoeprint may increase considerably the accuracy of 3D models, reducing the error distance between cloud points.

On the other hand, using oblique light revealed an increase of the mean distance of the 3D models and the 99% of interpoints of all models, producing less accurate 3D shoeprints models.

The red camera filter/white-black photos shows a little decrease of the mean error distance and increase of the distance between points of 99% of the model, giving not much improvement in the built of the 3D shoeprint models.

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