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Three-Dimensional Stereophotogrammetry

in Hand Surgery

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CHAPTER 1

Introduction
GENERAL IDEA

Among all body injuries, hand injuries are considered to have the highest incidence, causing large community expenses. The yearly incidence of hand traumas in industrialized countries varies between 475 to 1700 per 100,000 inhabitants, though the exact numbers are not known. In the Netherlands, of all patients seen in the emergency department, around 15 to 20 percent have a hand injury. Given this high incidence of hand traumas, a basic anatomic knowledge of the hand is necessary for every physician. Ideally, an integrative approach of different teaching methods, including computer-assisted learning, would lead to excellent anatomic knowledge of a certain body part, for example the hand. Computer-assisted learning has been widely established in literature, since it facilitates obtaining anatomic knowledge in a flexible and efficient way. An interesting approach comprises computer programs that provide virtual three-dimensional (3D) representations of human anatomy. With medical imaging quickly becoming a more cost-effective source for (pre)clinical instruction, a growing number of 3D teaching models for complex anatomic regions are being developed. These models are used in both medical education and clinical practice. They support comprehension of complex spatial anatomy in diagnostic and surgical interventions. Furthermore, the increasing demand for complex and minimally invasive surgical interventions leads to more extensive use of computer-based models in treatment planning and simulation of surgical approaches and procedures.

Unfortunately, because of the rising number of undergraduate students and increasing costs, time consuming and labor intensive dissection courses are applied decreasingly in medical curricula. Anatomy of the hand is more and more taught by lectures and individual study, using mainly two-dimensional (2D) atlases and illustrations. However, because of the dynamic nature of hand movements, many perceptions of functional anatomy are not well illustrated in standard textbooks and figures. Computer based learning programs on the other hand would be highly appreciated and used by both students and residents within the constraints of limited work hours and with data sets widely accessible at any time.

This is what in 2009 brought us to the first idea of developing a three-dimensional hand anatomy teaching program. Therefore, we decided to use the 3D stereophotogrammetry alignment readily available in our hospital in the department of Maxillofacial Surgery. In this department, the 3D photographs were already extensively used in pre- and postoperative evaluations of various surgical procedures. The knowledge of the system based on the use in this medical field was
translated to the hand. So far, this was the first time 3D stereophotogrammetry was used for hand imaging.

3D hand imaging techniques
In current medical practice, different imaging techniques exist to capture the fascinating image of the hand. Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) scan imaging techniques are the most common used and well known. Since this thesis focuses on 3D imaging, we performed a systematic review on 3D imaging techniques of the hand to give an overview of the techniques currently existing. The results of this review are presented below.

METHOD
The electronic databases Medline, Embase and Cochrane central were searched to identify studies utilizing 3D imaging of the hand. The keywords ‘stereophotogrammetry’, ‘3D imaging’ and ‘three dimensional imaging’, combined with ‘hand’ were used. Terms were searched for in title and abstract and were, where applicable, also mapped to medical subject headings. No limits were set on language or publication status. Thereafter, titles and abstracts were screened by two persons. After abstract screening, full text articles were retrieved to identify studies eligible for inclusion. Papers met inclusion criteria if they described the use of 3D imaging of the hand for any purpose.

RESULTS
The search strategy in Medline, Embase and Cochrane central yielded 284 results of which 52 articles were duplicate search results. After duplicate removal 232 abstracts were screened and 13 studies were selected for full text analysis. In total 13 research articles described the use of 3D imaging of the hand and were included in the review (figure 1). In the next paragraphs, the results are presented classified by type of imaging technique.
Conventional radiography

Wilhelm Röntgen (1845-1923) discovered the path of electrical rays, so called ‘x-rays’, which later proved to be one of the greatest achievements in the field of medical science (figure 2). In conventional radiography (CR) images are produced by x-rays, which are basically the same thing as visible light rays. Both are wavelike forms of electromagnetic energy carried by particles called photons. The difference between x-rays and visible light rays is the energy level of the individual photons. Conventional radiology suffers from the limitations like all 2D projections: magnification, distortion and misrepresentation of structures. Carelsen et al. describes the first experiences with 3D Rotational X-ray (3D-RX) for intraoperative imaging in wrist surgery. They prospectively analyzed the performance of the surgeon as well as the occurrence of revision surgeries, comparing conventional methods versus 3D imaging. This resulted in a significant difference in findings in preference of intraoperative 3D-RX (p < 0.05), while
none of the 56 patients treated with the aid of 3D-RX needed revision surgery. This confirms the generally accepted knowledge that an anatomical reconstruction of the hand or wrist joint is a basis for optimal outcome. In the opinion of the authors, the extra surgery time and radiation dose is justified by the added precision, while saving potential revision surgery.

Figure 2. Hand mit Ringen (Hand with Rings): a print of one of the first X-rays by Wilhelm Röntgen of the left hand of his wife

**Computed tomography**

In the 1960’s a new imaging technique was developed, namely computed tomography (CT). With this new technique it was possible to image a slice through the body of a patient. The discovery of computed tomography was done by Allan McLeod Cormack and Godfrey Hounsfield. After the development of the first CT scanners around 1972 (figure 3), CT went through an evolution and the systems and application of computed tomography improved significantly over the years. In CT scanning, individual axial slices of the object are sequentially reconstructed using a mathematically technique. Subsequently, the slices are assembled to construct the volume and a 3D image. This transition from 2D images as in CR to 3D images is a major advantage of CT scan imaging. However, it still suffers from disadvantages as radiation dose, access and costs. In our systematic review we found no articles on 3D CT imaging of the hand. We do not have a clear explanation for this. In clinical practice, CT images are being used mostly in wrist surgery, so maybe our clinical search with the term ‘hand’ did not find wrist
surgery articles. Another explanation is that three-dimensional CT images are not yet extensively being used in wrist surgery.

![Figure 3. Godfrey Hounsfield with an early version of the CT scanner](image)

**Figure 3. Godfrey Hounsfield with an early version of the CT scanner**

*Magnetic Resonance Imaging*

Dr. Lauterbur (1909-2007), a chemist working at the State University of New York, published the first true Magnetic Resonance (MR) image in Nature in 1973. Applying magnetic field gradients rotated by 45°, he was able to attain four different one-dimensional projections of a nuclear magnetic resonance (NMR) signal. These data were then mathematically projected in reverse to form a two-dimensional tomographic image. The research of physician Raymond Damadian (1936), led him to the first medical experiments with NMR. He discovered that tumor cells and normal tissue cells could be distinguished in vivo by the NMR signal. Damadian invented an apparatus and method to use NMR safely and accurately to scan the human body, the method now well known as magnetic resonance imaging (MRI).

MRI can assess inflammation (figure 4), as well as bone damage and has been used extensively as a diagnostic measure and outcome measure in the follow-up of different hand diseases (e.g. rheumatoid arthritis, psoriasis)\textsuperscript{26, 27}. The application of MR imaging in hand and wrist surgery became widespread, with the possibility to shift from a 2D to a 3D approach of the hand. However, MRI has certain disadvantages. The interpretation of hundreds of images may be difficult and time-consuming, and the costs are high.

Li et al. evaluated the diagnostic performance of 3D MR maximum intensity projection in the assessment of synovitis of hands and wrists of rheumatoid arthritis (RA) patients\textsuperscript{26}. They describe MRI as the leading imaging modality in establishing
an early diagnosis of RA, and thereafter provided useful guidance for treatment modifications. They used contrast-enhanced imaging and found that 3D MR images could directly and clearly display the presence and location of synovitis with just one image. However, small abnormal changes were difficult to detect.

![Image of bilateral MR images of the hand and wrist of a patient with inflammatory arthritis. The arrows point out different areas of synovitis. M. Navalho. Radiology 2012.](image)

**Figure 4.** Bilateral MR images of the hand and wrist of a patient with inflammatory arthritis. The arrows point out different areas of synovitis. M. Navalho. Radiology 2012.

**Laser or light projection techniques**

Laser alignment is used for various purposes as a simple, easily applicable measurement system. In clinical settings, it is not being used extensively as an imaging technique. One of its applications is in anthropometry, where it can be used to measure progressive hand deformities. Another possible 3D imaging system is based upon the projection of light. The outline of the soft tissues of the hand for example can be visualized and used in biometric recognition for example. In the surgical field, this technique is not known.

Our review resulted in two articles using laser or light projection techniques. Highton et al. developed a laser-aligned measuring device to facilitate the measurement of linear hand dimensions. Their objective was to produce a simple, clinically applicable system to measure progressive hand deformities in patients with arthritis. They conclude that the laser-aligned system has acceptable accuracy for measurement of hand dimensions and is a portable and practical alternative to photography based systems.

Palmprint and hand shape as two kinds of important biometric characteristics, were used by Zhang et al to develop a 3D imaging system for verification and identification. They designed a method to get accurate 3D shape and color texture information of the palmprint and hand by projecting composite color fringe pattern images (figure 5).
3D stereophotogrammetry

The principle of 3D stereophotogrammetry is based upon the phenomenon of visual triangulation, whereby the brain combines two slightly different images from both our eyes, to create a three-dimensional scene. Sir Charles Wheatstone (1802-1875) created around 1838 the first viewing instrument for representing 3D figures, which he called the stereoscope (figure 6).

With the use of 3D stereophotogrammetry techniques nowadays it is possible to accurately reproduce the surface area of the hand. Furthermore, it is possible to map realistic color and texture data onto the geometric shape which finally results in a lifelike 3D rendered photograph (figure 7). The combination of fast acquisition speed and expanded surface coverage (up to 360 degrees) offers various advantages over other imaging modalities like laser scanning or CT scan imaging (as mentioned above). With decreasing costs, 3D stereophotogrammetric imaging systems are becoming increasingly involved in clinical and research settings.

Figure 5. Hardware of the 3D palmprint and hand imaging system. Zhang. Applied Optics 2013.

Figure 6. Example of a stereoscope
3D stereophotogrammetry has several advantages. It is a safe and non-invasive technique. Furthermore, it is able to capture superior quality ‘external surface’ photographs in less than 2 ms. After processing the data, an accurate digital model of the patient’s hand is created, which can be used immediately in a clinical setting. The disadvantage of the technique is mainly the difficulty in fixed positioning of the hand. During image acquisition the patient should keep the hand as still as possible, which can be difficult for some patients, for example younger children. Another limitation is the complexity to capture information of hollow structures, like the webspaces.

Four of the articles deriving from our systematic search use the technique of stereophotogrammetry, three of which are presented later in this thesis as separate chapters.

Ghosh and Poirier describe the use of a stereometric camera in an anthropometric study of hands\(^34\). Three-dimensional data at 21 specific points and for nine specific distances were obtained on each hand of ten persons. They discuss this photogrammetry technology as an innovation in studies on human body anthropometry, applicable universally for all types of hands with an accuracy better than 0.5mm. The technique used by these authors is comparable to that described in Chapter 3 on landmark reproducibility\(^35\).

**CONCLUSION**

After reviewing the literature, we concluded that different techniques currently exist for 3D hand imaging. They all have known advantages and disadvantages, as
described above. For 3D soft tissue imaging of the hand, 3D stereophotogrammetry is not yet widespread known in literature. 3D photographs would provide an objective basis for quantifying and qualifying clinical treatment outcomes.

**THESIS OUTLINE AND OBJECTIVES**

Currently, no easy to use, safe 3D technique exists for soft tissue hand imaging. Therefore, the main objective of this thesis was to develop a 3D hand imaging technique and prove its effective use in clinical practice. Chapter 2 and 3 will describe the development of the 3D hand imaging technique using 3D stereophotogrammetry. The development process consists of proving the accuracy and reproducibility of 3D images of the hand. One of the most important steps is the registration of landmarks on the hand, on which the further calculations are based.

The second part of this thesis will focus on the clinical application of 3D hand imaging in treatment planning and evaluation. We will cooperate with the endocrinological department and use the technique in the follow-up of acromegaly patients in remission of their disease. In Chapter 4, this first clinical application using 3D hand images will be described.

Furthermore, 3D stereophotogrammetry will be used in patients with lymphedema of the upper extremity, in particular of the hand. Using 3D volume measurements, the differences in volume of the lymphedema hand compared to the non-edema hand are calculated. This will confirm the accurate use of 3D stereophotographs in clinical practice (Chapter 5).

Chapter 6 will describe the application of 3D images in the differentiation between young and old hands. We hypothesize that the soft tissue volume measurements derived from 3D hand images, can be used to objectify the differences arising from the aging process. The results of this hypothesis are presented in this chapter.

In Chapter 7 we will start a pilot on the use of 3D images to improve the surgical technique of syndactyly patients. The pilot study aims to develop a first step in designing a virtual incision pattern to optimize desyndactylization surgery.

The related developments using 3D stereophotogrammetry of the hand, and future perspectives will be discussed in Chapter 8.

**Objectives**

The first part focuses on the validity of 3D stereophotogrammetry in imaging the hand. The development of an accurate and reproducible 3D hand stereophoto-
graph are discussed. The following questions have to be answered before this new imaging technique could be implemented in clinical practice.

1) Is 3D stereophotogrammetry an accurate imaging technique to create reproducible images of the hand?
2) What are reproducible and accurate landmarks of the hand and can they be used to develop a valid method for imaging of the hand using 3D stereophotogrammetry?

The second part focuses on the clinical application of 3D hand stereophotogrammetry. A group of acromegaly patients in long-term remission of their disease was investigated. Furthermore, the 3D imaging technique was applied to lymphedema patients with edema of the hand. In a pilot study, subjects were divided into different age groups and the impact of aging on their 3D hand images was measured. Also, a first step in the development of a virtual incision pattern for optimalization of syndactyly surgery, based on 3D images is described.

Research questions to be answered are as follows:
3) Is it possible to compare 3D soft tissue characteristics of the hand of acromegaly patients with those of healthy control subjects, using 3D hand stereophotographs?
4) Can 3D imaging be used as a reproducible tool in qualifying and quantifying different areas in the hand to evaluate lymphedema or the aging process of the hand?
5) Can 3D hand images be used as the basis to design a preoperative virtual incision pattern for a desyndactylization procedure?
REFERENCES


CHAPTER 2

Development of a three-dimensional hand model using three-dimensional stereophotogrammetry: assessment of image reproducibility


ABSTRACT

Purpose
Using three-dimensional (3D) stereophotogrammetry precise images and reconstructions of the human body can be produced. Over the last few years, this technique is mainly being developed in the field of maxillofacial reconstructive surgery, creating fusion images with computed tomography (CT) data for precise planning and prediction of treatment outcome. Though, in hand surgery 3D stereophotogrammetry is not yet being used in clinical settings.

Methods
A total of 34 three-dimensional hand photographs were analyzed to investigate the reproducibility. For every individual, 3D photographs were captured at two different time points (baseline T0 and one week later T1). Using two different registration methods, the reproducibility of the methods was analyzed. Furthermore, the differences between 3D photos of men and women were compared in a distance map as a first clinical pilot testing our registration method.

Results
The absolute mean registration error for the complete hand was 1.46 mm. This reduced to an error of 0.56 mm isolating the region to the palm of the hand. When comparing hands of both sexes, it was seen that the male hand was larger (broader base and longer fingers) than the female hand.

Conclusions
This study shows that 3D stereophotogrammetry can produce reproducible images of the hand without harmful side effects for the patient, so proving to be a reliable method for soft tissue analysis. Its potential use in everyday practice of hand surgery needs to be further explored.
INTRODUCTION

Nowadays, three-dimensional (3D) surface imaging is being implemented in various healthcare and non-healthcare areas, such as anthropology, reconstructive surgery, craniofacial surgery and orthodontics. One of the surface imaging techniques being used more and more is 3D stereophotogrammetry\(^1\,^2\). Within the broad field of reconstructive surgery, it has already found solid applications in maxillofacial surgery\(^3\,^4\,^5\) and is upcoming in breast and free flap reconstructive surgery\(^5\,^7\,^8\). However, 3D imaging of the hand is an unexplored field so far. The possibilities of this technique in the clinical and pre-clinical setting are numerous, for example using it for preoperative planning or postoperative evaluation of hand surgeries, and for various educational purposes.

The aim of this study was to develop a noninvasive, objective and valid method of photographing the hand using 3D stereophotogrammetry. Thereafter, making use of the standardized 3D images, we started evaluation of the reproducibility and validity of newly defined soft tissue landmarks of the hand for clinical purposes, by using our registration method on images of the hands of men and women.

SUBJECTS AND METHODS

Subjects
Seventeen adult Caucasian individuals (4 male, 13 female; mean age 39.1 years, range 26 – 64 years) without any preexistent hand deformities were randomly selected from our departments. All individuals gave written informed consent to participate in this study. Approval by a medical ethics review board was not obtained, since the digital photography method used was previously described by the review board as not invasive or harmful. This study was conducted in compliance with the World Medical Association Declaration of Helsinki on medical research ethics. 3D photographs of both the left and right hand were taken, resulting in a total of 34 images. The photographs were taken with the subject positioned as shown in figure 1. The individual in this figure has given written informed consent (as outlined in PLOS consent form) to publish these case details.

Imaging methods
For every individual, 3D photographs were captured at two different time points (baseline T0 and one week later T1). The 3D photographs were captured with a 3D stereophotogrammetrical camera setup and the software program Modular System v1.0 (3dMDface System, 3dMD, Atlanta, USA). The camera setup con-
sisted of five pods, each equipped with three digital cameras and a flash. Prior to its use, the camera was calibrated to define a 3D coordinate system for the 3D photograph, which was referred to as the original 3D coordinate system\textsuperscript{12,13}. The 3D photographs were taken with each individual seated with the arm in a 90 degree flexion in the elbow joint and the hand kept in a pre-designed template with the fingers in a fully spreaded, upright position (figure 1). In order to achieve exact images of both the palmar and dorsal aspect of the hand, the template was removed by an assistant, directly before the photograph was taken. The patient was instructed not to move the hand to another position and to keep it absolutely still after removal of the template.

![Example of the three-dimensional stereophotogrammetrical camera alignment](image1)

**Figure 1.** Example of the three-dimensional stereophotogrammetrical camera alignment

**Reproducibility of the 3D photographs**

The 3D photographs of the left and right hand of the same individual acquired at different time points were registered using the Iterative Closest Point (rigid registration) algorithm\textsuperscript{14}. After registration the difference between the two surfaces was calculated as an error or distance map indicating the amount of similarity
between the registered surfaces. This distance map computes the difference (Euclidean distance) between the 3D photographs on a large number of points and is an objective measure for the reproducibility of the acquired 3D photographs. The absolute mean value as well as the 50th and 90th percentile of the registration error were computed in millimeters.

Apart from the distance map of the complete 3D model of the hand, a distance map was calculated of only the palm of the hand. Hereby it was possible to investigate whether the palm is a more rigid region compared to the individual fingers which have more variables of free movement. For the distance map of the palm of the hand, the 50th and 90th percentiles were computed.

Landmarks and registration

After investigating the reproducibility of the image acquisition method, anatomical landmarks were placed on each of the 34 photographs according to the method developed by Hoevenaren et al.\textsuperscript{15}. These landmarks could then be used for comparing different hands and to compute an average hand model. In order to compare different hands and compute an average hand, the landmark sets of all 17 left hands and 17 right hands were registered using two different registration methods.

Method 1

The first registration method was a general Procrustes registration of the complete landmark set of either the left or right hand images. At first, one of the landmark sets is randomly selected as a reference set. Towards this set, all other landmark sets are registered by matching the similar landmarks in each set. After completing this registration an average hand surface model can be computed. Thereafter, this complete process of matching similar landmarks of each set is repeated, now using the newly created average hand as reference set for the registration procedure. After complete registration, a new average hand surface model is computed.

Method 2

The second method uses an adapted version of the Iterative Closest Point algorithm in which the hand is divided into different anatomical sub regions namely the palm of the hand, the thumb, the index finger, middle finger, ring finger and the little finger. All different sets were then registered with a randomly selected reference set, resulting in a computed, average hand. Also in this method, the complete procedure was repeated with the average hand performing as the reference set (see method 1).
For both registration methods the RMS error was calculated as a measure of precision of the computed model. The reproducibility of method 1 and method 2 were evaluated using the paired t-test. Statistical analyses were performed with the IBM SPSS software program, version 20.0 for Windows (IBM Corp., Armonk, NY, USA). The level of significance for all statistical analyses was set at 5%.

Comparison of Male and Female Hands

Using the described registration methods, it was now possible to register the hands of different subjects in a clinical setting. As a pilot study, the average hand of five male and five female subjects were calculated and compared.

RESULTS

Reproducibility

The absolute mean registration error for the complete hand was 1.46 mm. The 50th and 90th percentile of the registration error were respectively 0.97 mm and 2.95 mm for the complete set of hands. Isolating the region to the inside of the hand, the absolute mean error was reduced to 0.56 mm. The 50th and 90th percentile of the registration error were respectively 0.47 mm and 1.11 mm for the isolated region of the hand palm. The registration errors indicating the reproducibility of the image acquisition method are illustrated in figure 2.

![Figure 2](image)

**Figure 2.** The registration errors indicating the reproducibility of the image acquisition method are illustrated here. Reproducibility of 3D images with deviation on vertical axes in millimeters and on horizontal axes the measured hands. H1L is the first left hand, H1R is the first right hand, etc. The mean deviations of registration on the complete hand and on the palm of the hand are respectively 1.46 mm and 0.56 mm.
Assessment of image reproducibility

*Calculation of average hands*

For the registration of method 1 a RMS error of 0.94 mm was found. For method 2, in which the fingers were registered as separate models the RMS error decreased to 0.42 mm. The variation of registered landmark sets could also be illustrated. Figure 3 illustrates the average landmark set and ellipsoids which are calculated as two times the standard deviation.

![Figure 3](image.png)

*Comparison between male and female hands*

The male and female hands were compared using method 2. An illustration of the difference between the male and female average hands can be found in Figure 4. In general the male hand is larger (broader base and longer fingers) than the female hand.

**DISCUSSION**

With the advent of digital technology, digital photography has become an increasingly important tool in reconstructive surgery, in particular in maxillofacial surgery. With the introduction of systems such as the 3dMDface System (3dMD LLC, Atlanta, USA), Di3D (Dimensional Imaging, Glasgow, UK) and 3D-Sensors FaceSCAN3D (3D Shape GmbH, Erlangen, Germany), the applicability of 3D photography in daily practice has become reality. 3D stereophotogrammetry is safe, noninvasive and able to capture superior quality ‘external surface’ 3D photographs in less than 10 milliseconds. Especially these characteristics are ideal to collect 3D data even of hands of young children or elderly patients. After
processing the data, an exact digital model of the patients hand is created which can be used in a clinical setting immediately.

In the complex field of hand surgery, 3D photography is not yet being used in clinical settings as far as we know. However, the hand is a complex anatomic part of the body and its injuries are very incapacitating for the patient, making precise planning of every hand surgery procedure and predicting its outcome necessary in obtaining a satisfying postoperative result for both patient and doctor.

3D imaging

At present, the gold standard in imaging soft and bony tissues of the hand are computed tomography (CT) data or magnetic resonance imaging (MRI) scan images with their known side effects. However, these techniques do not produce a real-life image of the outer surface of the hand. The shortcomings of CT and MRI scan images have caused a search for a minimally invasive 3D imaging technique, which could produce a realistic and exact virtual surface model of the hand. Among others, advantages of 3D stereophotogrammetry over MRI and CT are its non-invasiveness, lack of harmful radiation, immediate available images and good patient tolerance. Furthermore, the usage of 3D stereophotogrammetry is highly cost effective, given the very short amount of time needed for photographing and low production costs, compared to the time consuming CT or MRI scan images. Besides the absence of potential dangerous side effects described above, there is the possibility of patient-specific modeling. 3D imaging has the potential to precisely simulate the pre-operative experience for surgery planning with reliable surface visualization leading to a more profound understanding of the anatomical structures to be reconstructed and therefore improved final surgery outcome.

Figure 4. Illustration of the differences between the male (in green) and female (in red) average hands
The aim of this study was to develop a noninvasive, objective and valid method of photographing the hand using 3D stereophotogrammetry. Furthermore, we evaluated the reproducibility and possibility of computing an average hand and using it in a clinical pilot.

3D stereophotogrammetry

A review of literature showed there is no information on the reproducibility and validity of 3D hand photography yet. Earlier studies were performed to investigate the precision of 3D stereophotogrammetry. The majority of these studies focused on reliably measuring distances between typical anthropometric points on the 3D reconstructed images against corresponding points on live subjects or phantom models (e.g. plaster casts) as a form of validation\textsuperscript{12,21--26}. Some other studies use more complex methods to obtain and analyze 3D shapes\textsuperscript{27--29}. Kau et al., Maal et al. and Ma et al. investigated the reproducibility of several 3D acquisition systems. Kau et al. found an RMS error of 0.4 mm using a Minolta Vivid 900 laser scanner\textsuperscript{30}. Maal et al. used 3D stereophotogrammetry, assessed the reproducibility and also found a value of 0.4 mm\textsuperscript{31}. Ma et al. found a reproducibility of their structured light system of 0.2 mm\textsuperscript{22}.

Image reproducibility

In this study two different registration methods were used, method 1 matching complete hands and method 2 matching subregions of the hand. We found a significant higher registration error for method 1. An explanation for this could be found in the fact that it was difficult for the study subjects to keep their fingers completely still at time of photography. Therefore, we designed method 2, correcting for the movement of the individual fingers.

Average hand model

Using method 2 as valid registration method, an average model of both left and right hand 3D images was created. This method of landmark registration and matching has already found solid applications in maxillofacial surgery. In this study, as stated above, one of the difficulties in creating reproducible images of the hand is the movement of the individual fingers. However, we corrected this error by designing a new method of landmark based registration, matching each individual finger per image and therefore creating a more precise image.

In maxillofacial surgery ‘the average face’ is an instrument often used to which other facial images are being compared\textsuperscript{32,33}. It is mainly being used in comparing preoperative images of patients and predicting treatment outcome, thereby reducing operating time. In literature, no publications exist on the average hand.
Given the proven reproducibility and clinical value of calculations based on the average face, we developed a method of creating an average hand model. One of the drawbacks of this study is the small population on which this model is based. Therefore, a database of 3D hand images is being collected at the moment, created from study subjects from different age categories.

Clinical relevance

The possibilities of the clinical and pre-clinical use of 3D photography of the hand are numerous. 3D images could be used in pre- and postoperative hand trauma surgeries, thereby quantifying the soft tissue loss and identifying the optimal reconstructive surgery type. Furthermore, during follow-up after nerve injuries of the upper extremity, soft tissue volume deficiencies can be calculated, evaluating treatment results and indicating the need for revision surgery. A normative database based on soft tissue data is not yet available, but needed. This database could be used among others in growth studies of both normal child development and pathologic growth, for example in patients with acromegaly, and in objectifying the sex-specific differences of the hand.

Using the landmark based registration method, we describe the first clinical pilot with this study. Though a very small population, we confirmed the reliable use of the method calculating differences in hands of both men and women. Further research with a larger study population is necessary to validate the advanced clinical use.

Besides its use in clinical practice, the developed 3D hand model can be used for various educational purposes. Computer-assisted learning has been widely established in medical anatomy learning, since it facilitates obtaining anatomic knowledge in a flexible and efficient way. With medical imaging quickly becoming a more cost-effective source for clinical and pre-clinical training, a growing number of 3D models for different anatomic regions are being developed. Since 3D photography produces precise images and reconstructions of the human body, these models support comprehension of spatial anatomy in diagnostic and surgical interventions. Also, 3D real-life models based on 3D stereophotogrammetry could be used for exact simulation in surgical resident training, increasing the knowledge of the difficult anatomical areas of the human body and therefore improving the quality of teaching.

In addition, there is an application in forensic medicine, where with the aid of a database, skin reconstructions can be created out of osseous parts of the hand for identification purposes.

Since the hand is not a static anatomical structure and precise finger movement is one of its main functions, our future research focuses among others on com-
bining 3D techniques with CT data. Recently, the possibility of creating fusion images with CT data is extensively being used for even more precise planning and predicting treatment outcome. In conclusion, this study shows that 3D stereophotogrammetry produces precise and reproducible 3D images of the hand. This proves 3D photography to be a reliable method for soft tissue analysis. Its potential use in everyday practice of hand surgery and the concept of fusing 3D photography images with radiologic images of the interior hand structures needs to be further explored.
CHAPTER 2

REFERENCES


Chapter 2

Assessment of image reproducibility


CHAPTER 3

Development of a three-dimensional hand model using 3D stereophotogrammetry: evaluation of landmark reproducibility


ABSTRACT

Background
Using three-dimensional (3D) photography, exact images of the human body can be produced. Over the last few years, this technique is mainly being developed in the field of maxillofacial reconstructive surgery, creating fusion images with CT data for accurate planning and predicting treatment outcome. Though, in hand surgery 3D photography is not yet being used in clinical settings.

Methods
The aim of this study was to develop a valid method for imaging the hand using 3D stereophotogrammetry. The reproducibility of 30 soft tissue landmarks was determined using 3D stereophotogrammetric images. Analysis was performed by two observers on twenty 3D photographs. Reproducibility and reliability of the landmark identification were determined using statistical analysis.

Results
Intra- and interobserver reproducibility of the landmarks were high. This study showed a high reliability coefficient for intraobserver (1.00) and interobserver reliability (0.99).
Identification of the landmarks on the palmar aspect of individual fingers was more precise than identification of landmarks of the thumb.

Conclusions
This study shows that 3D photography can safely produce accurate and reproducible images of the hand, which makes the technique a reliable method for soft tissue analysis. 3D images can be a helpful tool in pre- and postoperative evaluation of reconstructive trauma surgery, esthetic surgery of the hand and for educational purposes. The use in everyday practice of hand surgery and the concept of fusing 3D photography images with radiologic images of the interior hand structures needs to be further explored.
INTRODUCTION

Given the continuing technological progress in computer science and high demands from surgeons as well as patients on surgical capabilities, three-dimensional (3D) imaging techniques are being used more and more in clinical settings to image soft and bony tissues. For soft tissue analysis, multiple 3D imaging techniques have been introduced, such as Digital Imaging and Communications in Medicine (DICOM) files from computed tomography (CT) and cone-beam CT (CBCT) imaging\(^1\), surface laser scanning\(^2,3\) and 3D stereophotogrammetry\(^4\).

3D Stereophotogrammetry is currently developing as a new, promising technique that is capturing the surgical field\(^5\)–\(^11\). Within the broad field of reconstructive surgery, it has already found solid applications in maxillofacial surgery\(^9,12\)–\(^14\) and is upcoming in breast and free flap reconstructive surgery\(^10,13,15\)–\(^18\). Within these clinical fields, 3D models based on 3D photographs are currently changing technically highly challenging operations into predictable and feasible procedures\(^8\).

However, 3D photography in hand and wrist surgery is still a field to be discovered, with a growing need for exact preoperative planning, real-life anatomic training models and precise follow-up and evaluation methods in this complex anatomical field of surgery.

In order to perform soft tissue analysis on the collected data, predefined landmarks were required. In recent literature, no consistent description of soft tissue landmarks of the complete hand exists. A variety of landmarks on the palmar aspect of the hand are described in different anatomical studies\(^19\)–\(^21\), with Kaplan’s cardinal line being one of the more notable surface markers\(^22\)–\(^24\).

The aim of this study was to evaluate the reproducibility and validity of newly defined soft tissue landmarks of the hand using 3D stereophotogrammetry.

SUBJECTS AND METHODS

Subject

Twenty adult Caucasian individuals (3 male, 17 female; mean age 38.7 years, range 20 – 64 years) without any preexistent hand deformities were randomly selected from our departments and 3D photographs of both the left and right hand were taken. Written informed consent was given prior to inclusion.

Imaging methods

For all individuals 3D photographs were captured with a 3D stereophotogrammetrical camera setup and the software program Modular System v1.0 (3dMD-
faceTM System, 3dMD, Atlanta, USA). The camera setup consisted of five pods, each equipped with three digital cameras and a flash. Prior to its use, the camera was calibrated to define a 3D coordinate system for the 3D photograph, which was referred to as the original 3D coordinate system. The imaging method was validated in a previous pilot study by Hoevenaren et al. The 3D photographs were taken with each subject seated with flexion in the elbow joint and the hand kept in a pre-designed template with the fingers in a fully abducted and extended position. In order to achieve accurate images of both the palmar and dorsal aspect of the hand, the template was removed by an assistant, less than one second before the photograph was taken. The patient was instructed to keep the hand absolutely still and not to move the hand to another position after removal of the template.

3D photograph-based reference frame

Based on experience using a reference frame in maxillofacial surgery, this method was copied for setting up a reference frame for the 3D hand images and developed by two of the authors (T.M. and I.H.). The reference frame was set up for each 3D photograph by one observer (I.H.) prior to landmark identification. The cephalometry plug-in tool of Maxilim® was used for creating the coordinate system. First, the horizontal orientation was defined by placing the middle finger over a prefixed vertical line. Hereby, the horizontal orientation line on the screen was focused on the ulnar (lateral) side of the base of the little finger, indicating the horizontal position (figure 1 and 2). The ‘pupil reconstructed point’ was marked, defined as the midpoint of the base of the middle finger (palmar aspect of the metacarpal joint crease), resulting finally in the 3D photograph based reference frame (figure 3).

Figure 1. Step 1 of the setup of the 3D photograph based reference frame. Placing the middle finger over the vertical line and the ulnar side of the little finger on the horizontal line. Marking of the most distal midpoint of the middle finger and the ulnar (lateral) side of the base of the little finger

Figure 2. Step 2 of the setup of the 3D photograph based reference frame. Rotating the hand into the upright position, orientating on the middle finger
Landmark identification

In this study 30 landmarks were defined based on known topographical and bone-related anatomical landmarks of the hand (Table 1). Thereafter, two observers (both residents in plastic surgery) independently identified the selected landmarks on each of the 3D photographs. One of the observers repeated the landmark placing after three months to prevent memory bias. In this way an inter- and intraobserver analysis of the reproducibility could be calculated. After completing the landmark identification, measurements were automatically computed and exported to Excel (Microsoft Office 2003, Microsoft Corporation, Redmond, USA).

Table 1 Overview of landmarks

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Webspace 2</td>
<td>w2</td>
<td>The most inferior midpoint of the space between 2nd and 3rd finger</td>
</tr>
<tr>
<td>2 Webspace 3</td>
<td>w3</td>
<td>The most inferior midpoint of the space between 3rd and 4th finger</td>
</tr>
<tr>
<td>3 Webspace 4</td>
<td>w4</td>
<td>The most inferior midpoint of the space between 4th and 5th finger</td>
</tr>
<tr>
<td>4 DIP 2 midline</td>
<td>DIP2m</td>
<td>The midline of the 2nd DIP joint crease</td>
</tr>
<tr>
<td>5 DIP 3 midline</td>
<td>DIP3m</td>
<td>The midline of the 3rd DIP joint crease</td>
</tr>
<tr>
<td>6 DIP 4 midline</td>
<td>DIP4m</td>
<td>The midline of the 4th DIP joint crease</td>
</tr>
<tr>
<td>7 DIP 5 midline</td>
<td>DIP5m</td>
<td>The midline of the 5th DIP joint crease</td>
</tr>
<tr>
<td>8 MCP 2 midline</td>
<td>MCP2m</td>
<td>The midline of the 2nd MCP joint crease</td>
</tr>
<tr>
<td>9 MCP 3 midline</td>
<td>MCP3m</td>
<td>The midline of the 3rd MCP joint crease</td>
</tr>
<tr>
<td>10 MCP 4 midline</td>
<td>MCP4m</td>
<td>The midline of the 4th MCP joint crease</td>
</tr>
<tr>
<td>11 MCP 5 midline</td>
<td>MCP5m</td>
<td>The midline of the 5th MCP joint crease</td>
</tr>
</tbody>
</table>
Statistical analysis

The statistical data analysis was performed using the SAS® 9.2 software program. Inter- and intraobserver reproducibility of each landmark localization was calculated and tested for statistical significant differences between observers. A mean difference (bias) of less than 0.5 mm was considered highly accurate. A mean difference between 0.5 and 1.0 mm was less accurate but clinically irrelevant. A mean difference of more than 1.0 mm was defined as clinically relevant. For statistical testing the significance level was set at $p < 0.05$. The reliability coefficient quantifies the quality of the measurement procedure in relation to the target population. It can be interpreted as the proportion of the variance due to subject-to-subject variability in error free measurements (a reliability of 1 means that error free measurements are made, a reliability of 0.5 means that the error variance is equal to the subject-to-subject variance). A reliability coefficient higher

Table 1 Overview of landmarks (continued)

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 MCP 2 radial side</td>
<td>MCP2r</td>
<td>The most radial point of the 2nd MCP joint crease</td>
</tr>
<tr>
<td>13 MCP 5 ulnar side</td>
<td>MCP5u</td>
<td>The most ulnar point of the 5th MCP joint crease</td>
</tr>
<tr>
<td>14 PIP 2 midline</td>
<td>PIP2m</td>
<td>The midline of the 2nd PIP joint crease</td>
</tr>
<tr>
<td>15 PIP 3 midline</td>
<td>PIP3m</td>
<td>The midline of the 3rd PIP joint crease</td>
</tr>
<tr>
<td>16 PIP 4 midline</td>
<td>PIP4m</td>
<td>The midline of the 4th PIP joint crease</td>
</tr>
<tr>
<td>17 PIP 5 midline</td>
<td>PIP5m</td>
<td>The midline of the 5th PIP joint crease</td>
</tr>
<tr>
<td>18 D1 top</td>
<td>D1t</td>
<td>The most distal midpoint of the fingertip of the 1st finger</td>
</tr>
<tr>
<td>19 D2 top</td>
<td>D2t</td>
<td>The most distal midpoint of the fingertip of the 2nd finger</td>
</tr>
<tr>
<td>20 D3 top</td>
<td>D3t</td>
<td>The most distal midpoint of the fingertip of the 3rd finger</td>
</tr>
<tr>
<td>21 D4 top</td>
<td>D4t</td>
<td>The most distal midpoint of the fingertip of the 4th finger</td>
</tr>
<tr>
<td>22 D5 top</td>
<td>D5t</td>
<td>The most distal midpoint of the fingertip of the 5th finger</td>
</tr>
<tr>
<td>23 Distal wrist crease (central)</td>
<td>dwc</td>
<td>The central point of the distal wrist crease</td>
</tr>
<tr>
<td>24 IP D1 radial side</td>
<td>IP1r</td>
<td>The most radial point of the IP joint crease</td>
</tr>
<tr>
<td>25 IP D1 ulnar side</td>
<td>IP1u</td>
<td>The most ulnar point of the IP joint crease</td>
</tr>
<tr>
<td>26 PIP 2 midline*</td>
<td>PIP2m*</td>
<td>The midline of the 2nd PIP joint crease</td>
</tr>
<tr>
<td>27 PIP 3 midline*</td>
<td>PIP3m*</td>
<td>The midline of the 3rd PIP joint crease</td>
</tr>
<tr>
<td>28 PIP 4 midline*</td>
<td>PIP4m*</td>
<td>The midline of the 4th PIP joint crease</td>
</tr>
<tr>
<td>29 PIP 5 midline*</td>
<td>PIP5m*</td>
<td>The midline of the 5th PIP joint crease</td>
</tr>
<tr>
<td>30 IP D1 radial side*</td>
<td>IP1r*</td>
<td>The most radial point of the IP joint crease</td>
</tr>
</tbody>
</table>

Definitions of the thirty newly defined landmarks for the 3D photograph based soft tissue analysis of the hand. Landmarks on the dorsum of the hand are marked with an asterisk.
Evaluation of landmark reproducibility

than 0.8 was considered sufficient, meaning that the measurement procedure is suitable to use in the target population.

RESULTS

A total of 30 landmarks were identified on 20 3D photographs, 10 left hand photos and 10 right hand photos (Table 1). Table 2 shows the mean differences in relation to the observer identifying the landmarks. Observer 1 identified the landmarks twice, leading to the intra-observer error. Furthermore, no statistically significant differences in the landmark positioning were found for the inter- and intraobserver analysis (p > 0.95). Table 3 gives the standard deviations of the inter- and intraobserver errors for each of the 30 landmarks. Landmarks marked with an asterisk show a statistical significant difference. The analysis revealed a slightly greater difference for the right hand photographs compared to the left hand photographs. Intra- and interobserver reliability of the landmarks were high, expressed in the reliability coefficient. This coefficient was respectively 1.00 (range 0.99 – 1.00) for intraobserver and 0.99 (range 0.99 – 1.00) for interobserver reliability.

Table 2 Results of inter- and intraobserver mean differences

<table>
<thead>
<tr>
<th>Observer</th>
<th>Side</th>
<th>Mean distance</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.5-1.0 mm</td>
<td>&gt; 1.0 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>%</td>
<td>N</td>
<td>%</td>
</tr>
<tr>
<td>intra</td>
<td>Left</td>
<td>19</td>
<td>63</td>
<td>11</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>15</td>
<td>50</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>inter</td>
<td>Left</td>
<td>10</td>
<td>33</td>
<td>20</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>5</td>
<td>17</td>
<td>25</td>
<td>83</td>
</tr>
</tbody>
</table>

Mean differences in relation to the observer identifying the landmarks. Number and percentage of landmarks in relation to the mean difference
<table>
<thead>
<tr>
<th>No.</th>
<th>Landmark</th>
<th>Inter SD</th>
<th>Intra SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Webspace 2</td>
<td>0.836</td>
<td>0.607</td>
</tr>
<tr>
<td>2</td>
<td>Webspace 3</td>
<td>0.802</td>
<td>0.657</td>
</tr>
<tr>
<td>3</td>
<td>Webspace 4</td>
<td>1.005</td>
<td>0.801</td>
</tr>
<tr>
<td>4</td>
<td>DIP 2 midline</td>
<td>0.859</td>
<td>0.544</td>
</tr>
<tr>
<td>5</td>
<td>DIP 3 midline</td>
<td>0.607</td>
<td>0.622</td>
</tr>
<tr>
<td>6</td>
<td>DIP 4 midline</td>
<td>0.703</td>
<td>0.646</td>
</tr>
<tr>
<td>7</td>
<td>DIP 5 midline</td>
<td>0.605</td>
<td>0.673</td>
</tr>
<tr>
<td>8</td>
<td>MCP 2 midline</td>
<td>1.160</td>
<td>0.733</td>
</tr>
<tr>
<td>9</td>
<td>MCP 3 midline</td>
<td>0.864</td>
<td>0.741</td>
</tr>
<tr>
<td>10</td>
<td>MCP 4 midline</td>
<td>0.887</td>
<td>0.610</td>
</tr>
<tr>
<td>11</td>
<td>MCP 5 midline</td>
<td>1.090</td>
<td>0.715</td>
</tr>
<tr>
<td>12</td>
<td>MCP2 radial side</td>
<td>1.347</td>
<td>0.980</td>
</tr>
<tr>
<td>13</td>
<td>MCP5 ulnar side</td>
<td>1.093</td>
<td>1.159</td>
</tr>
<tr>
<td>14</td>
<td>PIP 2 midline*</td>
<td>1.252</td>
<td>0.672</td>
</tr>
<tr>
<td>15</td>
<td>PIP 3 midline</td>
<td>1.133</td>
<td>0.934</td>
</tr>
<tr>
<td>16</td>
<td>PIP 4 midline</td>
<td>1.007</td>
<td>0.617</td>
</tr>
<tr>
<td>17</td>
<td>PIP 5 midline</td>
<td>0.741</td>
<td>0.610</td>
</tr>
<tr>
<td>18</td>
<td>D1 Top</td>
<td>1.756</td>
<td>1.372</td>
</tr>
<tr>
<td>19</td>
<td>D2 Top*</td>
<td>1.480</td>
<td>0.709</td>
</tr>
<tr>
<td>20</td>
<td>D3 Top*</td>
<td>1.045</td>
<td>0.534</td>
</tr>
<tr>
<td>21</td>
<td>D4 Top</td>
<td>1.143</td>
<td>0.669</td>
</tr>
<tr>
<td>22</td>
<td>D5 Top*</td>
<td>1.026</td>
<td>2.006</td>
</tr>
<tr>
<td>23</td>
<td>Distal wrist crease (central)*</td>
<td>1.903</td>
<td>1.060</td>
</tr>
<tr>
<td>24</td>
<td>IP D1 radial side**</td>
<td>3.077</td>
<td>1.420</td>
</tr>
<tr>
<td>25</td>
<td>IP D1 ulnar side*</td>
<td>2.537</td>
<td>1.679</td>
</tr>
<tr>
<td>26</td>
<td>PIP 2 midline (dorsal)</td>
<td>1.225</td>
<td>1.093</td>
</tr>
<tr>
<td>27</td>
<td>PIP 3 midline (dorsal)</td>
<td>1.302</td>
<td>0.945</td>
</tr>
<tr>
<td>28</td>
<td>PIP 4 midline (dorsal)</td>
<td>1.011</td>
<td>0.921</td>
</tr>
<tr>
<td>29</td>
<td>PIP 5 midline (dorsal)</td>
<td>1.227</td>
<td>0.964</td>
</tr>
<tr>
<td>30</td>
<td>IP D1 radial side (dorsal)*</td>
<td>2.050</td>
<td>1.531</td>
</tr>
</tbody>
</table>

Given are the standard deviations of the inter- and intraobserver errors for each of the 30 landmarks. Landmarks marked with an asterisk show a significant difference (*SD > 0.5; **SD > 1.0) between the inter- and intraobserver analysis.
DISCUSSION

Introduction and aim of the study
The aim of this study was to evaluate the reproducibility and validity of 30 newly defined soft tissue landmarks of the hand using 3D stereophotogrammetric images. This imaging technique allows for accurate and realistic documentation and in combination with landmark based soft tissue analysis can produce a valuable and easy to use tool in the everyday practice of a hand surgeon for pre- and postoperative evaluation purposes.

Landmarks
In recent literature, no consistent description of soft tissue landmarks of the complete hand exists. A variety of landmarks on the palmar aspect of the hand are described in different anatomical studies. Kaplan’s cardinal line, originally described in 1953 by E.B. Kaplan, is one of the more notable surface markers. His description of this landmark was a line “drawn from the apex of the interdigital fold between the thumb and index finger toward the ulnar side of the hand, parallel with the middle crease of the hand”. Although various adapted descriptions followed the original one, it has been extensively used as a surface landmark for surgical incisions and to help locate deep structures. Studies defining other topographical surface landmarks used in for example carpal tunnel release (CTR) are multitude. The restricted visual field in CTR for instance confirms the importance of topographical markers to locate underlying vulnerable structures, preventing through precise incision lines iatrogenic injuries and ensuring optimal patient outcome.

Results of landmarks
A total of 30 landmarks were defined, based on the visible aspects of the hand in 3D images. This total number of landmarks is less than the amount generally used in maxillofacial surgery, however sufficient to perform a reliable soft tissue analysis of the hand. Furthermore, we did not focus on the dorsal aspect of the hand, since landmark placement could be more difficult in the absence of exact bony tissue orientation points compared to the palmar aspect, leading to less accurate calculations.

This study revealed a high reproducibility and reliability for most of the landmarks. However, these results are derived mainly from maxillofacial surgery studies. To the best of our knowledge, there are no studies based on the validity of soft tissue landmarks of the hand. Accuracy of hand measurements can be compared to facial measurements, given the comparable surface area and numerous soft tissue
structures in a relatively small anatomical area. Though, the face is a more static anatomical structure, while the hand is subject to movements during imaging, what makes exact imaging more difficult.

Identification of the landmarks on the palmar aspect of the individual fingers was more precise than identification of landmarks of the thumb. This can be explained by the position of the thumb in a 45 degree angle with regards to the vertical plane of the fingers. This makes identification of the landmarks of the thumb using a fixed reference frame focused on the vertical plane/middle finger, more difficult. Other landmarks with high variability in both the inter- and intraobserver analysis, were those located on the fingertips. A possible explanation for this accuracy difference, is the quality of the 3D images. Although the cameras are positioned around the hand and one with a view from above, often artefacts around the fingertips were seen on the individual images. Recently, the quality of the 3D photographs has improved, especially the color tone and the visualization of detailed structures, which may increase the reproducibility and reliability of these landmarks.

3D imaging of hands

Three-dimensional (3D) imaging techniques are being used extensively in a variety of medical fields with a wide range of applications. One of these techniques is 3D stereophotogrammetry, which is embedded in clinical practice with positive results. 3D stereophotogrammetry has proven to be a reproducible imaging technique, by earlier studies investigating the accuracy of stereophotogrammetry. These studies mostly focused on reliably measuring distances between typical anthropometric points on the 3D reconstructed images against corresponding points on live subjects of phantom models (eg, plaster casts) as a form of validation.

Among others, reconstructive surgery is one of the surgical fields in which 3D computer based planning of difficult procedures has proven to be very successful. In the complex field of hand surgery, 3D photography is not yet being used in a clinical setting. However, the hand is a complex anatomic part of the body and its injuries are very incapacitating for the patient, making precise planning of every hand surgery procedure and predicting its outcome, necessary in obtaining a satisfying postoperative result for both patient and doctor.

Advantages of 3D imaging

Comparing this new technique of visualizing the soft tissues of the hand with other imaging techniques, the advantages are clear. For example, a standard photograph is a one dimensional image, while an image derived from the 3D
camera setting can be viewed from multiple angles. Also, performing exact tissue analysis on standard photographs is not possible, making it less valuable for clinical follow-up. A recent review of literature showed there is no information on the reproducibility and validity of 3D hand photography yet. At present, the gold standard in imaging soft and bony tissues are CT or MRI scan images with their known radiation side effects. The shortcomings in surface reproduction of CT and MRI scan images have caused a search for a minimally invasive 3D imaging technique, which could produce a realistic and accurate virtual surface model of the hand. Among others, advantages of 3D stereophotogrammetry over MRI and CT are its non-invasiveness, lack of harmful radiation, immediate available images and good patient tolerance. Furthermore, the usage of 3D stereophotogrammetry is highly cost effective, given the very short amount of time needed for photographing and low production costs, compared to the time consuming MRI or CT scan.

Recently, the possibility of creating fusion images with CT data is extensively being used for even more accurate planning and predicting treatment outcome. With this study we describe the first step in developing a 3D imaging technique of both soft and bony tissues, by combining the 3D image with CT scan data.

Besides the absence of potential dangerous side effects described above, there is the possibility of patient-specific modeling. 3D imaging has the potential to accurately simulate the pre-operative experience for surgery planning with reliable surface visualization leading to a more profound understanding of the anatomical structures to be reconstructed and therefore improved final outcome. Also, 3D real-life models based on 3D stereophotogrammetry could be used for accurate simulation in surgical resident training, increasing the knowledge of the difficult anatomical areas of the human body and therefore improving the quality of teaching.

**Results of landmark positioning**

In the present study, the mean difference of the actual distance between two similar landmarks was calculated. This implied setting up a reference frame for each individual photo. The use of this reference frame enlarges the reproducibility of the landmark positioning, because all images are visualized in the same standardized way. Furthermore, because two observers placed the landmarks on the same set of images, it is important to exclude positioning bias from allowance of free movement of the image. By setting up a reference frame, each individual image is being observed from the same viewpoint, therefore facilitating landmark positioning and enlarging accuracy. However, analyzing the results
revealed almost half of the landmarks placed with a mean distance greater than 1.0 mm, despite no systematic inter- and intra-observer differences were found. It is unclear what could have caused this differences and clinical impact needs to be further explored. In other reliability studies on facial landmarks, intra- and interobserver differences are highly variable, ranging from studies with results of less than 0.5 mm\textsuperscript{12} to the majority of landmarks having a mean difference of more than 1.0 mm\textsuperscript{12,43}.

A point of discussion remains the extrapolation of these results from maxillofacial implementation to the anatomical region of the hand. The anatomical areas of the hand and face are comparable to a certain extent, both containing bony structures marked subcutaneously by soft tissue landmarks and many vulnerable structures in a small surface area. However, the face is easier to capture on camera since it has limited movement with good subject instructions, compared to the large individual finger movements.

*Clinical relevance*

The possibilities of the clinical and pre-clinical use of 3D photography of the hand and soft tissue analysis are numerous. 3D images could be used in preoperative settings for calculating soft tissue volume deficiencies following nerve injuries of the upper extremity, giving the physician a strong diagnostic tool during treatment. During complex surgeries on the hand, the total duration of the surgery can be reduced, calculating beforehand with 3D images the amount of tissue needed for reconstruction and the optimal donor site. Postoperatively, treatment results can be objectively qualified, leading to improvement of treatment schedules. A normative database based on soft tissue data is not yet available, but needed. This database could be used among others in growth studies of both normal child development and pathologic growth, and in objectifying the sex- or age-specific differences of the hand. In aesthetic plastic surgery, 3D hand images can be a valuable tool in volumetric hand rejuvenation\textsuperscript{44}.

Combining 3D techniques with CT data and real-life camera images produces a four-dimensional (4D) image in which precise movements of the hand can be registered for functional analysis and for pre-operative planning of bony and soft tissue reconstruction in mutilating injuries of the hand.

In addition to its use in clinical practice, 3D stereophotogrammetry can produce images for designing a standard real-life 3D hand model for various educational purposes. Computer-assisted learning has been widely established in medical anatomy learning, since it facilitates obtaining anatomic knowledge in a flexible and efficient way\textsuperscript{41,45–50}. With medical imaging quickly becoming a more cost-effective source for clinical and pre-clinical training, a growing number of 3D
models for different anatomic regions are being developed$^{27,28,50,51}$. Since 3D photography produces highly accurate images and reconstructions of the human body, these models support comprehension of spatial anatomy in diagnostic and surgical interventions$^{10,28,51,52}$.

In conclusion, this study shows that 3D stereophotogrammetry produces accurate and reproducible 3D images of the hand. This proves 3D photography, in this stage, to be a reliable method for soft tissue analysis. We are currently improving the 3D imaging technique, implementing it in our first clinical pilot analyzing hand anomalies after treatment, of which the first results are highly promising. This study is also the first step in developing a fusion model of 3D images and radiologic images of the bony structures of the hand, improving its usefulness in everyday practice of hand surgery.

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REFERENCES

Evaluation of landmark reproducibility

Chapter 3


CHAPTER 4

Three-dimensional soft tissue analysis of the hand: a novel method to investigate effects of acromegaly


ABSTRACT

Background
Acral overgrowth is a highly common clinical sign in patients with active acromegaly. To what extent this overgrowth persists after long-term remission of acromegaly is largely unknown. Using the new imaging technique of three-dimensional (3D) stereophotogrammetry, it is possible to accurately investigate soft tissue changes of the hand. The aim of the recent study was to compare the 3D soft tissue characteristics of the hands of patients in long-term remission of acromegaly to those of a healthy pair matched control group.

Methods
A case-control study was performed at a tertiary referral center. Twelve patients in remission of acromegaly (58% male, mean age 58.3 years, mean BMI 29.6 kg/m²) were compared to twelve age-, gender-, ethnicity-, and BMI-matched control subjects. Of each individual 3D photographs of both hands were acquired and analyzed using a 3D computer software program.

Results
The patients in long-term remission of acromegaly have overgrowth of soft tissue of the hand compared to matched control subjects, with a larger length and width of the hand (p = 0.0025, p = 0.0017 respectively). Furthermore the diameters measured at the proximal interphalangeal (PIP) joints of the individual fingers are larger in the acromegaly patients.

Conclusions
Significant soft tissue overgrowth of the hand persists in former acromegaly patients, even after long-term remission. Analysis of 3D hand photographs is an accurate and easy tool to evaluate the acral soft tissue patterns in acromegaly.
INTRODUCTION

Acromegaly is an uncommon clinical condition that is caused by prolonged exposure to immoderate quantities of growth hormone (GH). There is often a significant delay in diagnosis and treatment, since features of acromegaly develop insidiously. Besides numerous metabolic changes, the GH excess causes proliferation of many tissues, including connective tissue, cartilage, bone and skin, which causes musculoskeletal related disorders and acral overgrowth. Musculoskeletal related disorders account for the main functional disability in patients with acromegaly. Following successful treatment of acromegaly some features of the disease may show partial reversibility, but results are conflicting. Concerning the hands of patients in long-term remission of acromegaly, the late effects of the disease have not been fully characterized. Previous studies have focused mainly on calculations derived from radiographic images of the bony tissue of the hand. None of these methods is a standardized method in the follow-up protocol so far. Furthermore, very little is known about the effect of acromegaly on soft tissue changes of the hand, which are equally affected. This can be explained by the fact that until recently no reliable and proven effective method was available for analyzing soft tissue changes. In the past years, 3D imaging techniques have evolved rapidly and are increasingly used in clinical settings for soft and bony tissue imaging. Three-dimensional stereophotogrammetry has been developed for accurate soft tissue analysis. It is a fast technique that provides excellent geometry and texture information with good patient tolerance. Furthermore, in contrast to frequently used imaging techniques like standardized radiographs, there is no use of harmful ionizing radiation. Therefore, 3D stereophotogrammetry provides a new opportunity to quantify acral disproportions in patients with acromegaly. Recently we introduced a standardized method to analyse 3D stereophotographs of the hand.

The aim of the present study was to evaluate the differences in soft tissue characteristics of the hands between patients in long-term remission of acromegaly and matched control subjects. This study is the first study that uses 3D stereophotogrammetry of the hand in combination with the analysis according to Hoevenaren et al. to investigate the effects of a specific disease, namely acromegaly.

MATERIALS AND METHODS

Adult patients in remission of acromegaly at least 2 years after successful pituitary surgery, visiting the Department of Internal Medicine, Division of Endocrinol-
ogy, of the Radboud University Nijmegen Medical Center, were eligible for this case-control study. The diagnosis of acromegaly was based on clinical symptoms and biochemical tests, with remission being defined as disappearance of clinical signs of active GH hypersecretion and normalization of biochemical tests\textsuperscript{9, 15}. Excluded were patients with a history of hand surgery and patients who received GH substitution. Twelve patients met all inclusion criteria and participated in this study. Seven patients were male, with a mean age of 58.3 years (SD 10.3) and a BMI of 29.6 kg/m\textsuperscript{2} (SD 4.3). Each patient was matched to a healthy age-, gender-, BMI- and ethnicity matched control subject, recruited via an announcement in a newspaper. They had no history of hand surgery or trauma and did not use hormonal substitutes. In the control group, seven subjects were male, with a mean age of 59.0 years (SD 10.5) and a BMI of 28.3 kg/m\textsuperscript{2} (SD 3.7). The age and BMI were pair matched between patients and controls.

Three-dimensional stereophotographs were obtained of both hands from all patients and control subjects, using a stereophotogrammetrical camera set-up (3dMD\textsuperscript{TM} Cranial\textsuperscript{TM} System, 3dMD LLC, Atlanta, USA). To exclude a recurrence of acromegaly, serum insulin-like growth factor type-1 (IGF-1) was determined in all patients on the day of the study. Figure 1 shows an example of an obtained stereophotograph of a control subject compared to a normal photograph, and figure 2 shows the 3D stereophotograph of a patient and a matched control. The photographs were taken by a trained technician following the principles described in the study by Hoevenaren et al. Using these principles, data from the 3D stereophotogrammetry were transferred to a 3D virtual model using Maxilim\textsuperscript{®} software.

\textbf{Figure 1.} An example is shown of a 3D stereophotograph of the hand (left side) and a normal 2D photograph (right side). In the photograph obtained through 3D stereophotogrammetry, markings and calculations can easily be done through the available software, as shown in the photograph by the yellow dots and blue lines.
A novel method to investigate effects of acromegaly

(Medicim NV, Mechelen, Belgium). A reference frame was set up according to a reproducible method, in order to align all hand models in the same orientation. Thirty soft tissue landmarks were identified on each image. After completing the landmark identification, measurements were automatically computed on each individual image using the different landmarks.

Statistical analysis
The hand parameters were separately analyzed using the Holm’s method for correction for multiple testing. The multiple correction was necessary for accurate comparison of the acromegaly patients with the control group. Per parameter a mixed linear model was fitted with fixed factor group (patient or control). To deal with the correlation of the data within a matched pair, the residual covariance matrix was not specified (unstructured). Estimations of differences between patients and controls was done using the mixed linear model. The confidence intervals were corrected for multiple testing. Statistical significance was defined as $p < 0.05$.

RESULTS
Table 1 shows the calculated measurements derived from the defined landmarks. Hand width and length were significantly larger in the acromegaly patients compared to the healthy matched controls ($p = 0.0017$ and $p = 0.0025$, respectively). There was an average difference of 7.5 mm in the width and 9.1 mm in the length of the hands. The calculated diameter of the individual fingers at the level of the proximal interphalangeal (PIP) joint, resulted in higher diameters in the patient group compared

Figure 2. This figure shows an example of a 3D stereophotograph of the hand of an acromegaly patient (right side) and a matched control (left side). Clearly visible are the differences in finger and hand dimensions and the overall volume. The yellow dots are part of the landmark positioning.
to the control group. In the third finger this was a significant difference ($p < 0.03$), however in the other fingers there was a none significant trend. These measurements indicate soft tissue overgrowth in the patient group. With respect to the length of the individual fingers, all fingers were larger in the acromegaly group, however only the fifth finger showed a significant difference. Furthermore we calculated the volumes of the hands of both groups. This resulted in a mean hand volume of $488.8 \text{ cm}^3$ in the acromegaly group and $393.4 \text{ cm}^3$ in the control group.

Table 1. Results

<table>
<thead>
<tr>
<th></th>
<th>CONTROL</th>
<th>PATIENT</th>
<th>PATIENT VS CONTROL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distance</td>
<td>Distance</td>
<td>Difference</td>
</tr>
<tr>
<td>Length of the hand</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>Length of 2nd finger</td>
<td>Mean</td>
<td>186.0</td>
<td>186.4</td>
</tr>
<tr>
<td>Length of 3rd finger</td>
<td>Mean</td>
<td>73.9</td>
<td>74.5</td>
</tr>
<tr>
<td>Length of 4th finger</td>
<td>Mean</td>
<td>79.9</td>
<td>79.9</td>
</tr>
<tr>
<td>Length of 5th finger</td>
<td>Mean</td>
<td>74.6</td>
<td>75.3</td>
</tr>
<tr>
<td>Width of the hand</td>
<td>Mean</td>
<td>60.3</td>
<td>61.0</td>
</tr>
<tr>
<td>Diameter at the 1st IP joint</td>
<td>Mean</td>
<td>13.4</td>
<td>13.8</td>
</tr>
<tr>
<td>Diameter at the 2nd PIP joint</td>
<td>Mean</td>
<td>19.2</td>
<td>20.3</td>
</tr>
<tr>
<td>Diameter at the 3rd PIP joint</td>
<td>Mean</td>
<td>20.2</td>
<td>20.7</td>
</tr>
<tr>
<td>Diameter at the 4th PIP joint</td>
<td>Mean</td>
<td>18.8</td>
<td>19.6</td>
</tr>
<tr>
<td>Diameter at the 5th PIP joint</td>
<td>Mean</td>
<td>16.7</td>
<td>17.0</td>
</tr>
</tbody>
</table>

Results of the measurements of the control and patient group and calculated differences, including 95% confidence interval (CI) between the patient and control group, with corresponding p-values. Distances are in millimeters. Holm’s corrected p-values are presented. Differences and CIs were calculated with the mixed linear model. Significant P-values are appointed with an asterisk.
DISCUSSION

This study is the first that uses 3D stereophotogrammetry of the hand in combination with specific 3D analysis to investigate the effects of a specific disease, namely acromegaly. To do so, we compared the 3D photographs of the hands of 12 patients in long-term remission of acromegaly and 12 healthy pair matched control subjects. Accurate digital models were created of the hands of every individual patient, which can be used in a clinical setting immediately. The digital models were analyzed using the recently published 3D soft tissue analysis according to Hoevenaren et al. In order to quantify soft tissue changes, we used different calculations on the predefined landmarks. Compared to the matched control group, the hands of the patients in long-term remission of acromegaly were 7.5 mm larger in width and 9.1 mm in length. This confirms the clinical impression that the hands are larger in patients in long-term remission of acromegaly, but it is the first time this is objectified and quantified. The length measurements of the individual fingers showed that only the fifth finger was significantly longer in patients in long-term remission of acromegaly, but there was a non-significant trend that all individual fingers were longer. This is an interesting finding, since in all our patients acromegaly was diagnosed during adulthood, after the closure of the epiphyseal growth plates.

Furthermore, the diameter at the proximal interphalangeal joints of the third finger was significantly larger, with a non-significant trend towards a larger interphalangeal joint in the other fingers. This could be, in combination with known persisting arthropathy and the calculated volume difference, an explanation for the impaired joint function in patients in long-term remission of acromegaly, since a larger diameter in the 3D photographs is a sign of soft tissue overgrowth. A strength of this study is the matching of patients and control subjects for age, gender, ethnicity and BMI. None of the previously published studies on problems of the hand in patients with acromegaly compared the patients to a matched control group. Furthermore, the 3D soft tissue analysis has a low intra- and interobserver measurement error, not exceeding 1 mm. In this study, all measurements were performed by one experienced observer in order to reduce the magnitude of the measurement error even more. The relatively small sample size is a limitation of this study, which is caused by the strict inclusion and exclusion criteria and the fact that acromegaly is a rare disease. There are still certain disadvantages in the method and analysis described. As known from previous results, the landmark positioning in the first finger is less accurate than in other fingers and therefore we did not calculate the length of this individual finger. Additionally, there was no significant difference in the diameter measured at the interphalangeal joint of the
first finger, although there was a non significant trend. This might be explained by the small sample size and difficult landmark positioning. Recent improvements to the camera set-up are integrated in the photographing process, leading to more detailed photographs and more precise landmark positioning in future research. Another possible improvement for future research will be the integration of CT scan images of the hand to our current 3D photographs to characterize bony tissue\(^8\). This will lead to more detailed conclusions on what specific types of tissue are affected in patients with acral overgrowth.

**Clinical relevance and future perspectives**

Our findings underscore once more that patients have to be informed that even after long-term remission of acromegaly the acral overgrowth persists. Besides esthetic concerns this may most likely lead to joint related symptoms and impaired movement, thus impairment in everyday activity and reduced quality of life\(^3\). Early stage counseling and hand therapy can be embedded as part of the treatment process and follow-up.

Furthermore, since the technique of 3D stereophotogrammetry of the hand is fast, accurate, relatively easy to perform, and harmless for the patient\(^10\)-\(^12\), it is a very promising technique for the follow-up of patients in both clinical and research settings. For acromegaly at present only blood values of IGF-1 and GH are recommended to detect possible disease activity and to evaluate the results of therapy or possible complications in the follow-up period\(^19\). However, especially during medical therapy, these values may not adequately reflect disease activity in peripheral tissues\(^20\). Using the 3D imaging technique, it is possible to compare different treatment options and their effect on soft tissues. Furthermore 3D imaging offers an additional patient-friendly method that could be easily used to investigate possible recurrences in an early state if laboratory measurements are conflicting. Although we have now demonstrated that acral overgrowth of the soft tissue of the hands is not completely reversible after long-term remission, it is still unknown whether it is at least partially reversible after remission and how long the process of remodeling takes. Longitudinal prospective studies are required to evaluate of what extent the acral overgrowth is reversible after remission and how different treatment modalities for acromegaly affect acral overgrowth.

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CHAPTER 5

Three-dimensional stereophotogrammetry as an accurate tool in analysis of lymphedema of the hand


ABSTRACT

Background
Lymphedema of the upper extremity is a frequently seen manifestation after breast cancer surgery. Three-dimensional (3D) stereophotogrammetry is a reliable technique in clinical practice, for example in volume measurements. The purpose of this research was to investigate if 3D imaging could be used as a reproducible and useful tool in qualifying and quantifying lymphedema of the hand.

Methods
Eighteen patients with unilateral lymphedema of the hand (mean age 56.5 years, 5 left and 10 right sided edema) were included. Of each individual 3D photographs of both hands were captured and volumes were calculated using 3D computer software programs. 3D images of the lymphedema hand were compared to the images of the normal, non-affected hand in the same patient. The resulting volume difference was linked with the patients self reported discomfort. Furthermore, the normal variance in hand volume was calculated in fifteen healthy subjects.

Results
After analyzing the hand volumes of all patients with lymphedema, a significant larger volume of the affected side was found in correlation to the normal hand of the patients with self reported discomfort. This difference was larger than that between the healthy hands of the control subjects.

Conclusions
This pilot study shows that 3D photography is a reproducible and useful tool in volume measurements of the edematous hand. Changes in hand volume can be easily detected, creating an opportunity for the timely initiation of treatment and simplifying the follow-up process.
INTRODUCTION

Arm lymphedema is a chronic swelling of the upper extremity caused by impairment of lymph drainage and is a frequent manifestation following breast cancer surgery. The exact incidence reported in literature varies widely, from 6% to 57% \(^1\). Women who develop lymphedema are known to have more psychological, social, sexual and functional morbidity, with a significant impact on the quality of life \(^5,6\). Early detection and treatment of lymphedema are therefore important, since current studies also show that this may decrease progression of lymphedema to an irreversible stage \(^1,7,8\).

In order to objectify upper extremity swelling and document treatment outcome, a practical, reliable and accurate method of volume measurement is necessary. Examples of measurement tools currently used are water displacement, circumference measurements and bioelectrical impedance, with water displacement being considered the most reliable method in volume measurement at this moment \(^9\)-\(^13\).

Recently, the attention of lymphedema therapy has shifted from fully conservative to operative interventions. Therefore, it is necessary to evaluate the effect of a surgical procedure by measuring the exact areas and amount of volume differences, in the arm as well as in the hand. For example after lymphedema shunt surgery, some patients only experience improvement of the hand or at a certain area of the upper extremity. Using the known volume measurement techniques, it is not possible to measure a specific area that is improved after surgery. Given this and other shortcomings of each of the above mentioned methods, the use of three-dimensional (3D) stereophotogrammetry in measuring upper extremity lymphedema was analyzed. 3D stereophotogrammetry is developing as a promising technique in the surgical field \(^14\)-\(^16\). In a study \(^17\), we showed that this noninvasive, patient-friendly and easy-to-use, is an accurate method in measuring upper extremity volume in patients with lymphedema. However, in this study the upper extremity was measured as one body part, including the hand. The aim of this pilot study was to investigate the use of 3D stereophotogrammetry as a reproducible and useful tool in measuring lymphedema of the hand alone.

PATIENTS AND METHODS

Eighteen patients with unilateral upper extremity lymphedema visiting the outpatient clinic of the department of Plastic, Reconstructive and Hand surgery of the Radboud University Nijmegen Medical Center, were included in the study. Lymphedema was defined as self-reported heaviness and swelling. Nine patients
reported lymphedema of solely the arm, excluding the hand (all female, mean age 52.7 years, 4 with left-, 5 with right-sided edema). Nine patients reported lymphedema of the arm including the hand (all female, mean age 63.1 years, 3 with left-, 6 with right-sided edema). In all patients the lymphedema was a result of breast cancer treatment. All patients underwent a mastectomy and axillary lymph node dissection, fourteen were additionally treated with radiation therapy (seven of whom reported edema of the hand). Patients who underwent previous lymphedema surgery were excluded. To determine the normal volume variation between hands, a control group of fifteen healthy women (mean age 65 years, all right-handed) was included. All participants gave informed consent prior to inclusion. Approval by a medical ethics review board was not obtained, since the digital photography method used was previously described by the review board as not invasive or harmful. This study was conducted in compliance with the World Medical Association Declaration of Helsinki on medical research ethics.

For all individuals, 3D images of both hands were captured with a 3D stereophotogrammetrical camera setup (3dMD Cranial, Atlanta, USA). The camera setup consisted of five pods, each equipped with three digital cameras and a flash. The images were taken with the lower arm and hand in an upright position. Subsequent to image acquisition, a previously developed reference frame was setup for each 3D photograph. Minor adjustments were made to the described reference frame, as the horizontal positioning was based on the dorsum of the hand. A landmark was placed at the distal wrist crease as cutoff point and volume measurements of the hand were performed. To determine the reproducibility of the described measurement method, a control group of nine healthy individuals was measured twice. All measurements were performed in Autodesk 3ds Max 2015 (Autodesk Inc., USA). An example of the reference frame is seen in figure 1. An example of a 3D photograph of a healthy and edematous hand is shown in figure 2.
Acquisition and 3D measurements were performed by researchers with broad experience in 3D volumetry and the 3dMD system. The mean difference in hand volume was calculated for all groups. A Kruskal-Wallis test with post hoc analysis was performed to determine a significant difference between all groups. Data analysis were performed using IBM SPSS Statistics, Version 23.0 (IBM Crop., Armon, NY, USA).

**Figure 1.** In this figure, the setup of the reference frame is seen, with the hand positioned based on the dorsum of the hand. A landmark was placed at the distal wrist crease as cutoff point.

**Figure 2.** These two 3D stereophotogrammetric images show both hands of a patients with right-sided edema. Clearly visible are the differences in volume between the right-sided, affected hand and the left-sided, nonaffected hand.
RESULTS

A summary of the results of volume measurements is given in Table 1. The average volume of the edematous hand was 383 ml (range 260 – 615) and of the non-edematous hand 310 ml (range 229 – 425). Mean difference between the hands in patients with edema of the hand was 73 ml (22.5 %, SD 64 ml). Mean difference between the hands in patients with edema of the arm alone was 4 ml (1.6 %, SD 12 ml).

Table 1. Results of volume measurements

<table>
<thead>
<tr>
<th>Patient number</th>
<th>Age (yr)</th>
<th>Affected side</th>
<th>Volume (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Affected side</td>
<td>Non-affected side</td>
</tr>
<tr>
<td>1</td>
<td>67.2</td>
<td>R</td>
<td>432</td>
</tr>
<tr>
<td>2</td>
<td>68.6</td>
<td>L</td>
<td>290</td>
</tr>
<tr>
<td>3</td>
<td>41.3</td>
<td>R</td>
<td>260</td>
</tr>
<tr>
<td>4</td>
<td>53.3</td>
<td>R</td>
<td>343</td>
</tr>
<tr>
<td>5</td>
<td>57.3</td>
<td>L</td>
<td>330</td>
</tr>
<tr>
<td>6</td>
<td>34.0</td>
<td>R</td>
<td>324</td>
</tr>
<tr>
<td>7</td>
<td>35.6</td>
<td>L</td>
<td>290</td>
</tr>
<tr>
<td>8</td>
<td>46.7</td>
<td>L</td>
<td>296</td>
</tr>
<tr>
<td>9</td>
<td>70.0</td>
<td>R</td>
<td>352</td>
</tr>
<tr>
<td>10</td>
<td>52.7</td>
<td>R</td>
<td>317</td>
</tr>
<tr>
<td>11</td>
<td>68.5</td>
<td>R</td>
<td>326</td>
</tr>
<tr>
<td>12</td>
<td>57.5</td>
<td>R</td>
<td>615</td>
</tr>
<tr>
<td>13</td>
<td>67.4</td>
<td>R</td>
<td>280</td>
</tr>
<tr>
<td>14</td>
<td>50.9</td>
<td>R</td>
<td>334</td>
</tr>
<tr>
<td>15</td>
<td>64.4</td>
<td>L</td>
<td>284</td>
</tr>
<tr>
<td>16</td>
<td>68.0</td>
<td>R</td>
<td>380</td>
</tr>
<tr>
<td>17</td>
<td>72.7</td>
<td>L</td>
<td>455</td>
</tr>
<tr>
<td>18</td>
<td>66.0</td>
<td>L</td>
<td>457</td>
</tr>
</tbody>
</table>

This table shows the volumetric results of the 18 patients. R = Right, L = Left
Patient 1-9 reported no edema of the hand, whereas patients 10-18 reported edema of the hand by self-report

The healthy control group showed a mean difference between both hands of 8 ml (2.7 %), with the mean volume of the right hand being 288 ml and mean volume of the left hand 280 ml. In this group, all patients were right handed. Results per group are presented in Table 2.
Table 2. Results per group

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of subjects</th>
<th>Mean difference L/R (ml) (%)</th>
<th>SD (ml) (%)</th>
<th>Min-Max (ml) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No edema of the hand</td>
<td>9</td>
<td>4 (1.6)</td>
<td>12 (3.9)</td>
<td>-19 – 17 (-5.3 – 6.1)</td>
</tr>
<tr>
<td>Edema of the hand</td>
<td>9</td>
<td>73 (22.5)</td>
<td>64 (22.5)</td>
<td>34 – 220 (9.8 – 55.7)</td>
</tr>
<tr>
<td>Control</td>
<td>15</td>
<td>8 (2.7)</td>
<td>8 (2.9)</td>
<td>-8 – 21 (-2.6 – 8.3)</td>
</tr>
</tbody>
</table>

Legend: R = Right, L = Left

Reproducibility of the described measurement method showed an average difference between two consecutive measurements of 5.2 ml (SD = 5.2, range 0-21). Kruskal-Wallis analysis showed there was a statistically significant difference in hand volume between groups, (Chi-Square = 18.9 , p < 0.00). Post hoc analysis showed a significant difference in hand volume between patients with edema of the hand and the control group (p < 0.00). A significant difference was seen between patients with edema of the hand and patients without edema of the hand (p < 0.00). No significant difference was found between the patients without edema of the hand and the control group (p = 0.77).

DISCUSSION

Lymphedema is a very common complication after breast cancer surgery. Early detection, timely intervention and frequent treatment evaluation are necessary aspects to prevent progression into an irreversible state, with consecutive negative impact on quality of life and health care costs. This requires a non-invasive and patient-friendly method of upper extremity volume determination, which can be easily used in the follow-up process.

To date, the water displacement method is seen as the gold standard for volume measurements. Waylett-Rendall et al. describe that water displacement can accurately assess the volume of hands with lymphedema. However, this method is time-consuming and impractical for volume measurements of the hand. Moreover, it is not applicable to all patients, as patients with skin defects cannot place their hand in water. Also, specific areas with lymphedema improvement after therapy cannot be identified using this technique, since it is measuring the upper extremity as one body part. In search for new volumetric techniques, different studies compared the volume of the arm using the water displacement...
or circumferential method. Others studied new three-dimensional (3D) imaging techniques, showing that 3D volume measurements are valid and reliable\(^19,20\). Three-dimensional imaging techniques are being used extensively in a variety of medical fields with a wide range of applications. One of these techniques is 3D stereophotogrammetry, which has proven to be a reproducible and precise technique, and is therefore embedded in clinical practice with positive results\(^14,16,21,22\). Among others, advantages of 3D stereophotogrammetry are its lack of harmful radiation, immediate available images, cost-effectiveness and good patient tolerance\(^15\). This imaging technique allows for realistic documentation and in combination with landmark based analysis can produce a valuable and easy to use tool in the follow-up process of patients with lymphedema. Another advantage of this technique is that specific areas of volume difference can be identified. Recently, a study by Hameeteman et al. demonstrated the reliable use of 3D stereophotogrammetry in patients with lymphedema of the upper extremity\(^17\). However, these studies investigate the upper extremity as one body part, including or excluding the hand. So far, no studies exist measuring the volume of edematous hands in lymphedema patients using 3D imaging techniques. Since the severity of edema and hand function are negatively correlated\(^23\) and have a negative impact on women’s functional mobility, we were interested in the degree of lymphedema of solely the hand.

In the lymphedema patients in this study, the volume differences between the edematous hand and the healthy hand were significant. An average difference of 73 ml (22.5 % increase) was found when the edematous hand was compared to the non-edematous hand. Compared to the control group, this difference in volume is more than the normal variation in volume between hands, since this was calculated as 8 ml (2.7 %). The larger volume can therefore be explained by the lymphedema in the hand. A point of discussion is the relatively small patient number used in this study. Furthermore, a correction for dominance of the hand is preferable, as in the control group a difference of 2.7 % was found between the dominant and non-dominant hand. Reproducibility of the volume measurements was found to be 5.2 ml (range 0 - 21), which is 1.4 % of the total hand volume. Although this indicates the used volume measurements are reliable, further research is recommended to reduce the range and prevent outliers.

Both conservative and surgical treatment options for lymphedema require a patient-friendly, easy to use and accurate tool for early detection and usage in the follow-up process. Early detection of lymphedema allows for a well-timed initiation of preventive measures, leading to a reduction in clinical lymphedema incidence from 36 % to 4 %\(^24\). Sarri et al. studied the effectiveness of early physiotherapeutic stimulation for lymphatic flow progression. They reinforce the need
to stimulate timely lymphatic drainage, considering that inflammation postopera-
tively blocks the passage of lymphatic drainage\textsuperscript{25}. Therefore, 3D images allowing
for early detection of lymphedema would be very helpful, leading to a timely start
of necessary conservative treatment.

Among other purposes, 3D images could be used in the work-up for lymphedema
surgery and the postoperative follow-up process. Microsurgical lymphatic vessel
transplantation has proven to effectively and persistently improve lymph drainage
in patients with upper extremity lymphedema. It is being used more and more as
a surgical treatment option in patients with breast cancer related upper extremity
lymphedema\textsuperscript{26,27}. However, the results of a review by Penha et al. showed that evi-
dence of the effectiveness of lymphatic microsurgery through comparative stud-
ies with consistent patient selection is lacking\textsuperscript{28}. The ultimate aim of lymphatic
surgery is to repair the lymphatic system. A well functioning lymphatic system
leads to volume reduction of the extremity. For calculating the effectiveness of
lymphatic microsurgery, a volume measurement method that analysis the volume
of different parts of the involved extremity would therefore be required.

The technique of 3D stereophotogrammetry is a tool that can be used for qualifying hand volumes. Furthermore, this study proves that it can be used as a quantifying measurement method, by calculating the exact difference in volume between healthy hands and edematous hands. For consistent and reliable interpretation of volume measurements, 3D stereophotogrammetry could be an excellent method of choice. With this technique, specific affected areas in the upper extremity can be imaged and volume differences calculated. In the future, this technique could also be used for measuring other body parts affected by lymphedema, for example the lower extremity or the foot\textsuperscript{29,30}.

A disadvantage of the described method is that not every clinic has the availability
of a 3D camera system and the trained personnel to perform the image acquisi-
tion and 3D volume measurements. Currently, one of the senior technicians in
our clinic is training colleagues in other hospitals to overcome this problem in the
future. Furthermore, the precise positioning of the hands and individual fingers
is still a difficult element of 3D hand photography. Currently, our research group
is developing more accurate techniques to overcome this problem in future.

In conclusion, this pilot study shows that 3D stereophotogrammetry besides
its effective use in measuring upper extremity lymphedema, also can be used as
an accurate and reproducible tool in analyzing lymphedema of the hand. This
patient-friendly, easy to use technique provides precise and reproducible hand
images. Changes in hand volume of lymphedema patients can be easily detected,
creating an opportunity for the timely start of treatment options and evaluating
the outcome of these treatments reliably during the follow-up process. Therefore, we strongly recommend the use of this method in the diagnostic and follow-up process of patients with upper extremity lymphedema.
REFERENCES


CHAPTER 6

The effect of aging on the three-dimensional aspect of the hand: a pilot study


ABSTRACT

Background
With rejuvenation treatments of the skin gaining more and more popularity, the inquiry for rejuvenation of the hand grows. Until now, no imaging tool exists to analyze the aging process of the hand. Three-dimensional (3D) stereophotogrammetry is a reliable technique which is used among other purposes in soft tissue analysis of the upper extremity. The goal of this pilot study was to investigate the possibility of visualizing the hand aging process using 3D stereophotogrammetry.

Methods
A total of 64 healthy volunteers were divided into four groups based on age and sex, and a 3D photograph of both hands was captured. Differences in the aspect of the dorsum of the hands were quantified and visualized using two methods. The first method quantified the smoothness of the old and young dorsa. The second method visualized the differences between an average young and old hand by creating a color-coded distance map.

Results
The first method showed that the young hands were smoother than the old hands, however this was not statistically significant (p=0.30). The distance map resulting from the second method showed a relative volume loss in the intermetacarpal spaces of the average old hand. These differences were not present when comparing the male with female hands.

Conclusions
This pilot study shows that 3D stereophotogrammetry can be used to visualize the exact areas of volume loss on the dorsum of the aging hand. Therewith, specific treatment areas can be identified and the results of different aesthetic hand surgery procedures can be objectively analyzed and compared.
INTRODUCTION

Rejuvenation of the aging skin is gaining more and more popularity, in particular of the facial skin. Since patients are achieving a younger appearance through facial rejuvenation, an inconsistency develops between a young face and aged hands. Therefore, a rising number of patients is requesting for rejuvenation treatment of the hand\(^1\). The hand aging process is characterized by epidermal changes and volume loss, most prominently seen on the dorsal side of the hand. The epidermal changes include textural changes and skin laxity, while the volume loss, caused by dermal atrophy and loss of subcutaneous fat, leads to deeper intermetacarpal spaces, more prominent bones and tendons and bulging veins\(^1,2\).

Different treatment options exist to improve contour by redistributing volume, for example injectables as hyaluronic acid and the transfer of autologous fat\(^1,3,4\). In order to objectively visualize the changes of the aging hand to document and compare different treatment outcomes, a practical, reliable and valid method of volume measurement is needed. Until now, an objective method to measure local volume deficits does not exist. Different methods were already developed, but none of them is currently used as the gold standard\(^2,5\).

Three-dimensional (3D) stereophotogrammetry is a new, promising imaging technique in the surgical field\(^6,7\). In a recent study, Hoevenaren et al. proved the use of 3D imaging in of the hand using a landmark based soft tissue analysis\(^8\). Currently, the clinical volumetric use of 3D imaging by comparing the volumes of the hands and extremities of lymphedema patients and healthy control persons is investigated, with promising results\(^9\).

The goal of this pilot study was to examine the use of 3D stereophotogrammetry as a valid tool in objectifying the changes of smoothness of the surface and the localized volume changes of the dorsum of the aging hand.

SUBJECTS AND METHODS

Healthy subjects aged between 18-25 years and older than 60 years were recruited for this study. Subjects with a history of hand surgery, hand trauma or any other condition which affects hand volume (e.g. macrodactyly) were excluded from this study. Also excluded were subjects performing physically heavy manual labor. The subjects were divided into four groups, depending on sex and age: young men, young women, old men, and old women (Table 1). We also recorded the body mass index (BMI) of all subjects. A total of 16 subjects per group was included. Written informed consent was given prior to inclusion. Approval by a medical
ethics review board was not obtained, since the digital photography method used was previously described by the review board as not invasive or harmful. This study was conducted in compliance with the World Medical Association Declaration of Helsinki on medical research ethics.

**Table 1.** Characteristics of the four subject groups

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
<th>Age ± SD (years)</th>
<th>BMI ± SD (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young men</td>
<td>16</td>
<td>23.4 (1.9)</td>
<td>22.5 (2.0)</td>
</tr>
<tr>
<td>Young women</td>
<td>16</td>
<td>22.6 (1.9)</td>
<td>21.8 (2.2)</td>
</tr>
<tr>
<td>Old men</td>
<td>16</td>
<td>65.1 (7.2)</td>
<td>27.0 (4.2)</td>
</tr>
<tr>
<td>Old women</td>
<td>16</td>
<td>63.4 (4.7)</td>
<td>23.7 (2.3)</td>
</tr>
</tbody>
</table>

BMI, body mass index

For all subjects, 3D images of the hands were captured with a 3D stereophotogrammetrical camera setup and the software program Modular System v1.0 (3dMDCranial System, 3dMD, Atlanta, USA). Before every individual image was taken, the subject was asked not to perform heavy exercise or sport activities on that day, to prevent inter-individual artifacts. The camera setup consisted of five pods, each equipped with three digital cameras and a flash. The images were taken with the lower arm and hand in an upright position, following the method we validated in recent research. Acquisition of the images and the 3D measurements were performed by researchers with broad experience in 3D volumetry and the 3dMD system. **Figure 1** shows an example of a 3D photograph of a young and an old hand.

**Figure 1.** Left and right images are a 3D image of a young hand (age 21 years) and a 3D image of an old hand (age 69 years), respectively. The skin changes on the dorsum of the old hand are clearly visible compared to those on the young hand.
Selecting the region of interest

The dorsum of the hand is the most targeted area in rejuvenation therapy. Therefore, this area was selected as the region of interest to investigate the differences between old and young hands. In order to select the dorsum, the 3D photographs were first aligned in a reference frame (figure 2).

Figure 2. Alignment using a reference frame. In the frontal view, the median plane of the reference frame is aligned with the middle finger, while the horizontal plane is aligned with the distal wrist crease. Finally, from a sagittal viewpoint, the dorsum was aligned with a vertical plane.

In the frontal view the median plane of the reference frame was aligned with the middle finger, while the horizontal plane was aligned with the distal wrist crease. Finally, from a sagittal viewpoint, the dorsum was aligned with the vertical plane. After alignment, the fingers and thumb were removed from the 3D photograph at the level of the metacarpophalangeal joint (figure 3). Finally, all vertices (3D data points) that were visible in the front view according to the reference frame were deleted so only the dorsum of the hand remained.

Figure 3. The fingers and thumb were removed from the 3D photograph at the level of the metacarpophalangeal joints. Subsequently, the frontal part of the hand was removed.
Method 1. Quantifying smoothness of the dorsa

The first objective was to quantify the smoothness of the dorsal hand surface to compare the smoothness of young and old hands. To investigate this, a smoothed version of each dorsum was created and compared with the original unsmoothed dorsum (figure 4). To smooth the dorsum, a smoothing filter (Relax Modifier) was applied to the 3D photographs using 3D Studio Max® (AutoDesk™, California, USA). After the 3D photograph was smoothed, the distance between the original and smoothed dorsum was calculated for each point of the 3D photograph. For all hands, the differences were visualized in a color-coded distance map. In a distance map, a higher intensity of discoloration corresponds with a larger distance between the surfaces. This higher intensity can be interpreted as more wrinkles, imperfections or tissue atrophy being present in the analyzed dorsum. Finally, the absolute averages of the distance map values of the old and young hands were plotted to visualize differences between the age groups.

![Figure 4. Method 1: Quantifying smoothness of the dorsa. A: The original 3D image of a hand. B: The hand image is trimmed according to the method described in Figure 3. C, D: The texture is removed and a smoothed version of the hand is created. E: The overlay of the images B and D that shows the changes of the hand image due to the smoothing method. F: The smoothed hand with a distance map from the original hand. The intensity of the red and green color correlates with the increase in negative and positive distance to the original hand, respectively.]

SPSS (version 20.0.1, IBM corp., Armonk, NY, USA) was used to perform a two-sample T test to compare the smoothness-ratio between the old and young population. We used \( p \leq 0.05 \) to define a significant difference.

Method 2. Comparing average dorsa

The second objective was to objectify localized volume changes in the dorsum of the aging hand. The average of a homogeneous set of individual hands typically produces a good representation of characteristic features common to the set and diminishes individual variations. Therefore, an average young dorsum and an average old dorsum were computed to investigate the local volume changes in aging. To compute an average dorsum of a group, one of the dorsa of the group was...
randomly selected and functioned as a reference dorsum. Initially, all dorsa of the group were roughly aligned and scaled to the reference dorsum using a Procrustes analyses\(^\text{11}\). Next, a fine alignment was performed using a surface based matching, based on the iterative closest point algorithm\(^\text{12}\). After the fine alignment, an average dorsum could be computed\(^\text{13}\). To exclude outliers, this alignment process was repeated multiple times with the computed average dorsum as a new reference hand. The difference between the averaged young and old dorsa was calculated and visualized as a color-coded distance map. Average hands were also computed for the gender groups in order to compare young male dorsa with old male dorsa and young female dorsa with old female dorsa respectively.

**RESULTS**

Table 1 shows the details of the four subject groups, including the BMI value. There was no significant difference in age between the young men and women (23.4 and 22.6 respectively) and the old men and women (65.1 and 63.4 respectively). The BMI for the old men was higher than that of the old women (27.0 and 23.7 respectively).

Method 1. Quantifying smoothness of the dorsa

Figure 5 shows the distributions of the absolute distance map values of all the old and young hand dorsa. A higher value on the x-axis corresponds with a larger distance between the data points of the original and the smoothed hand. This means that a curve close to 0 represents a group of very smooth original hand dorsa. A narrow curve represents a group of hands that have a similar average distance to the corresponding smoothed hand dorsa. The graph shows that the young dorsa are smoother (higher and smaller peak) than the old dorsa (average distance to the smoothed dorsum is 0.35 mm vs. 0.37 mm respectively). However, this result was not statistically significant (\(p = 0.30\)).
Figure 5. Results from method 1: Quantifying smoothness of the dorsa. This graph shows the absolute distances between the data points (mm) of the original hand image and its corresponding smoothed version for all old and young hands. The young hands show a smaller distance to the smoothed hands compared to the old hands. However, this difference is not statistically significant ($p = 0.30$).

Method 2. Comparing average dorsa

In figure 6, the soft tissue differences between the average old and young dorsa are shown as a color-coded distance map. In this figure, the green areas represent an increase of tissue and the red areas a reduction of tissue. When comparing the average dorsum of all young subjects with all old subjects, tissue reduction can be appreciated in the intermetacarpal spaces. Tissue increase is seen around the metacarpal heads.

Comparing the average young male dorsum with the average old male dorsum, a soft tissue reduction is seen in the center of the dorsum, while a soft tissue increase is present just distal and proximal of the first web space and on the ulnar side of the dorsum.

The differences between the average young and old female dorsa show roughly the same pattern as the young and old male dorsa comparison. However, the increase in tissue on the ulnar side is not seen in the female comparison.
The effect of aging on the 3D aspect of the hand

Figure 6. Results from method 2: Comparing average dorsa. This figure demonstrates a color-coded distance map of the difference between the average old and young hands. The areas in red and green represent a reduction and an increase in tissue, respectively.

DISCUSSION

Skin changes are among the most noticeable signs of aging. This is expressed greatest in the most visible areas of the human body: the face and the hands. Although advanced techniques for facial imaging exist, no imaging technique that evaluates the aging process of the hand has been described. This also applies to rejuvenation treatment options, which are numerous for facial rejuvenation, but are limited for the aging hand. Given the rising number of patients requesting for hand rejuvenation, some successful techniques were developed over the last years. These techniques are based on the visual aspects of the aging hand, anatomic knowledge of the aging skin and the involved specific areas of volume loss. For example, available options for improving the aesthetic aspect of the skin are chemical peels and laser or light therapy. For restoring the volume loss, hyaluronic acid injectables and autologous fat transfer are frequently used\textsuperscript{1,4}. With the treatment options expanding, so are the number and demands of the aesthetic patient population. This underlines the need for a valid, easy to use tool that objectifies and quantifies the local differences in the aging hand to compare different treatment options.

Until now, the method of water displacement is the gold standard for volume measurements of the upper extremity. It is a frequently used technique in breast cancer patients for measuring lymphedema of the arm\textsuperscript{14,15}. Although the water displacement technique is precise in measuring the volume of edematous hands\textsuperscript{5}, the technique is time-consuming and difficult to perform. Furthermore, this technique is unable to measure the exact locations of volume changes in a hand. Carruthers et al. developed a grading scale to objectify different affected areas of volume loss. This method uses a 5-point photonumeric rating scale to determine the severity of the aging hand. However, since this method is based on two-dimensional photographs only, local volume changes cannot be quantified.
in a volume unit. Furthermore, the scaling was performed by experts in aesthetic medicine, which makes the technique impractical to use in everyday clinical practice. In search for new techniques with the given setbacks of the existing upper extremity volume and soft tissue measurement methods, several studies investigated the use of 3D imaging techniques with positive results. One of these techniques is 3D stereophotogrammetry, which proved to be a valid and exact technique for capturing 3D surface information to calculate volumes. This minimally invasive, easy to use technique has many advantages over the existing volume measuring techniques, which are for example its lack of radiation, cost-effectiveness, and good patient tolerance. It allows for immediately available, precise 3D images of the surface of the hand. In combination with landmark based soft tissue analysis, it is a highly efficient tool in analyzing the aging hand.

In this pilot study, the differences in the surface areas of the dorsa of the aging hand compared to younger dorsa were investigated. This was achieved by using two different methods based on 3D photographs. The results of method 1 (quantifying smoothness of the dorsa) indicate that the dorsal surface of young patients is smoother than the surface of old patients, though not statistically significant. This can be translated into clinical practice as a more rimpling effect of the skin and tissue atrophy in aging hands. Often this is clearly visible in elderly patients, and now using the technique of 3D stereophotogrammetry, this visible effect of aging can be quantified creating a possibility to define exact treatment areas. With method 2 the average dorsa of old and young hands were compared. Distance maps showed a reduction of soft tissue in the intermetacarpal spaces of the aged hands. This can be explained by the known effects of aging on soft tissues: dermal and muscle atrophy and subcutaneous fat loss, leading to deeper intermetacarpal spaces. After dividing the group in male and female hands, an increase of soft tissue was seen on the ulnar side of the aged male hands. We do not have a clear explanation for this finding. When comparing the BMI of the young and old subjects, a higher BMI was found in the old men group. The higher BMI could explain the increase in hand contour on the ulnar side, with the increase of soft tissue being fatty tissue related to the higher BMI. Between the female groups, no large differences were seen. With the limited total number of subjects, this can lead to minimal differences in overall analyses comparing the two sex groups. Because the study group was small, the analyses were not corrected for BMI values.
Clinical relevance

Hand rejuvenation is an expanding field in soft tissue and volume regeneration. Using 3D stereophotogrammetry, exact images of the hand and different calculations are readily available. Until now, little is known about the specific volume quantities of the affected areas in the aging hand. With this knowledge, exact target areas for rejuvenation treatment can be identified, further optimizing existing treatment options and creating possibilities to compare results of different treatments. 3D imaging of the hands make the aesthetic surgeon able to document and evaluate treatment outcome for the individual patient. This creates patient-tailored treatment, which is highly important for the sophisticated aesthetic patient.

The unavailability of a 3D stereophotogrammetry setup in clinical practice is a known disadvantage of the technique. However, the number of hospitals using 3D imaging techniques is increasing, expanding the availability of the imaging system. Furthermore, the current camera system and software are updated continuously for even more detailed imaging possibilities. Improvements are being made to the 3D imaging technique, so exact volume measurements can be performed to also calculate volume loss per hand in the individual patient. One of the rejuvenation techniques to restore volume is autologous fat grafting. To facilitate a successful appliance of autologous fat grafts, the process of fatty tissue handling must be performed in a careful way. Exact volume measurements of the existing defect using 3D photographs will make precise planning of the amount of substitution possible, avoiding unnecessary adjustments with the risk of adverse outcomes such as necrosis and infection.

This pilot study shows that 3D stereophotogrammetry can be used to objectify differences in the dorsal surface of the aging hand, with volume measurements being developed as the next step in 3D hand imaging. This would allow objective comparison of the outcomes of different rejuvenation treatment options. More research with larger subject groups is necessary to create patient-tailored rejuvenation treatment options in the future.
REFERENCES


CHAPTER 7

Virtual incision pattern planning for optimalisation of syndactyly surgery

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SUMMARY

Syndactyly is a congenital condition, characterized by fusion of the fingers. If not treated correctly during infancy, syndactyly may hinder the normal development of hand function. Many surgical techniques have been developed, with the main goal to create a functional hand with the smallest number of operative corrections. Therefore, exact preoperative planning of the reconstructive procedure is essential. An imaging method commonly used for preoperative planning is three-dimensional (3D) surface imaging. The goal of this study was to implement the use of this technique in hand surgery, by designing a virtual planning tool for a desyndactylization procedure based on 3D hand images. A 3D image of a silicon syndactyly model was made on which the incision pattern was virtually designed. A surgical template of this pattern was printed, placed onto the silicon model and delineated. The accuracy of the transfer from the virtual delineation towards the real delineation was calculated, resulting in a mean difference of 0.82 mm. This first step indicates that by using 3D images, a virtual incision pattern can be created and transferred back onto the patient successfully in an easy and accurate way by using a template. Thereafter, 3D hand images of three syndactyly patients were made, and individual virtual incision patterns were created. Each pattern was transferred onto the patient by using a 3D printed template. The resulting incision pattern needed minor modifications by the surgeon before the surgery was performed. Further research and validation are necessary to develop the virtual planning of desyndactylization procedures.
INTRODUCTION

3D stereophotogrammetry imaging is recently introduced into the hand surgery field\(^1\,^2\). The advantages of this technique are its lack of radiation, cost-effectiveness and good patient tolerance. It allows for accurate, immediately available 3D soft tissue hand images.

To demonstrate its usefulness in clinical practice, we used 3D hand images during the preoperative planning process of a desyndactylization procedure. Syndactyly is a congenital abnormality, in which the fingers are fused. Preoperative evaluation of the soft and bony tissue elements in the syndactylized hand is necessary in every patient and done using conventional radiology images and computed tomography (CT) scan images. Hynes et al. found that CT angiographically guided release of adjacent webspaces benefits the patient\(^3\). However, CT imaging has numerous disadvantages, like radiation, costs, and need for anesthesia when used for children\(^4\,^5\).

Until now, no harmless imaging technique exists which evaluates the soft tissues in a three-dimensional (3D) method. The goal of this study was to implement the use of 3D stereophotogrammetry in hand surgery, by designing a method to virtually plan the incision pattern for a desyndactylization procedure, and transfer this planning onto the patient.

SUBJECTS AND METHODS

A 3D image of an adult subject was made to simulate syndactyly and scaled down to an average toddler size hand. This was used as a reference to create a silicon syndactyly model and a new 3D image of this model was created. All images were obtained with the 3dMD cranial system (3dMD cranial system, Atlanta, USA) which consist of 5 pods with a total of 15 cameras. The obtained 3D image was loaded into 3ds Max 2016 (Autodesk Inc, USA). Thereafter, the incision pattern was virtually planned on the dorsal side by an experienced hand surgeon (TW) in 3ds Max (figure 1).
Figure 1. This figure shows the virtually planned incision pattern, drawn on the dorsal side of a 3D image of a syndactyly model in 3ds Max.

Figure 2. The 3D image was made transparent as shown in this figure. By using this transparent model, the surgeon was able to plan the palmar side using the dorsal side as a reference (figure 2). To transfer the virtual planning to the silicon model, a patient specific surgical template was designed and printed using the Laser-Sinter-System EOS P 396 3D printer. This template could then be placed exactly onto the silicon syndactyly model (figure 3), after which the planning could be marked with a marker pen. To evaluate the transfer of the virtual planning onto the model, another 3D image of this model with the markings was obtained. This image was loaded into Maxilim (Medicim,
Virtual incision pattern planning for optimalisation of syndactyly surgery

Leuven, Belgium) and matched with the virtual planning using an Iterative Closest Point algorithm (ICP). Thereafter, landmarks were placed at the corners of the virtually planned and real delineation to calculate the accuracy.

Next, 3D images of three patients (two male, one female, average age 3.2 years) were obtained, and a virtual incision pattern was planned by the surgeon (TW). This planning was transferred onto the patient preoperatively. Postoperatively, the experiences of the surgeon using this template were obtained.

![Image](image.png)

**Figure 3.** The custom made template was placed onto a silicon syndactyly model

**RESULTS**

The virtual planning process was simple to perform, since the model could be viewed from any possible angle and using the transparent filter setting, an exact mirror image of the dorsal side could be drawn on the palmar side. The template had a precise fit onto the silicon model and the production costs were very low (average €50 including the planning process). Using a marker pen it was easy to draw the delineation on the surface. The accuracy of the landmarks placed on the virtual delineation compared to the real delineation was calculated, resulting in a mean difference of 0.82 ± 0.32 mm.

Transferring the incision pattern onto the patient was easy and fast, as reported by the surgeon. The template was found to be very helpful in copying the delineation from front to back. The resulting incision pattern needed minor modifications...
by the surgeon before the surgery was performed, not modifying the original surgical plan. The surgeries were performed without any problems with satisfying postoperative results.

**DISCUSSION**

Syndactyly is one of the most common congenital disorder of the limbs, in which normal hand development may be hindered when not treated timely. The basic principles of the desyndactylization procedure have been widely established. To reach the goal of creating a functional hand, every surgical procedure aims to produce a deep and wide webspace with as little as necessary skin grafts. 3D stereophotogrammetry is an easy to use, safe imaging technique, which has proven to be a valid method for capturing surface information and calculating volume deficits. By using 3D images for exact planning of the incision pattern, creating a deep webspace could be easier and therewith distal migration of the web, often requiring corrective surgery, would be avoided. Furthermore, when the amount of necessary skin can be calculated preoperatively, excessive skin grafting will be avoided, leading to less scarring.

With this first use of 3D images in preoperative planning, minor modifications were necessary due to the somewhat wide opening of the delineation in the template, resulting in broader markings on the patient than normally used. This was corrected peroperatively, as well as in the computer program for future delineations. The experiences of the hand surgeon proved the usage of the template to be easy and to simplify the surgical procedure, which will be helpful for less experienced surgeons or residents performing desyndactylization procedures.

In this study, we show an easy method for preoperative hand surgery planning based on 3D images. This first step proves that by using 3D hand images, a virtual incision pattern can be created and transferred back onto the patient successfully. The preoperative planning will reduce total surgery time, as the surgeon can directly copy the incision pattern from the template. The quality and therewith final result of the incision pattern will be higher, as different incisions and their results can be tested virtually, to reach the optimal, individual incision pattern. With our future research we will continue to develop the virtual planning tool for desyndactylization procedures, therewith expanding the implementation of 3D imaging in hand surgery.
REFERENCES


CHAPTER 8

General discussion and future aspects
INTRODUCTION

Three-dimensional (3D) imaging in clinical practice has been developing fast over the past decade. In the hand surgery field, different imaging methods are clinically available. Clinicians have been using mostly two-dimensional (2D) radiographic methods (for example conventional radiology, computed tomography (CT) and magnetic resonance imaging (MRI)), since 3D systems are expensive and complex to use. However, technological advances have made it possible that acquisition of 3D hand images is nowadays safe and affordable.

It is generally accepted that an anatomical, three-dimensional reconstruction of the hand and wrist joint is the basis for the best possible outcome. However, only very few articles concentrate on 3D imaging of the hand to achieve this. For example, when implants are used in the reconstructive process, conventional intraoperative radiological evaluation methods often fail to detect suboptimal positioning of implants. 3D images give the surgeon the opportunity to view the subject from every possible angle. Furthermore, it adds intraoperative precision, while saving potential revision surgery.

3D stereophotogrammetry of the hand is a new soft tissue imaging technique. The application of stereophotography to measurements of the hand was first described in 1987 by Ghosh et al., in an anthropometric study. They state that the procedure of photography ought to be simple, fast, capable of producing metric photographs and as little annoying as possible to the persons involved. These characteristics are found in stereophotogrammetry, the technique being further considered by the authors as a procedure of interest in minimizing bias and sources of various other errors.

In 2003, Highton developed a laser-aligned method for anthropometry of hands. They compare their technique to stereophotogrammetry and refer to the latter as a method which has much to recommend, but with the disadvantage that the images are not immediately available in a clinical setting. Furthermore, they experienced difficulty in placing landmarks on the hand. Both described disadvantages are nowadays improved, as the created images are readily available and a valid, reproducible landmark system is developed.

The first part of this thesis focused on the accuracy and reproducibility of 3D stereophotogrammetry in hand surgery (Chapter 2 and 3). The following chapters dealt with the clinical application of the 3D imaging technique in the hand surgery field. The results of these studies will be discussed in the following ‘Address to aims’ section. In addition, the results of this thesis are the basis for continuing research projects in the field of 3D hand imaging, described in ‘Future aspects’.
ADDRESS TO AIMS

1) Is 3D stereophotogrammetry an accurate imaging technique to create reproducible images of the hand? (Chapter 2)

In the second chapter the usage of three-dimensional stereophotogrammetry in capturing images of the hand is described. With the precision of stereophotogrammetry investigated in earlier studies\(^4,5\), the possibilities of usage in the clinical hand surgery field were found numerous. However, no studies existed where 3D stereophotogrammetry of the hand was used. Therefore, the first step in developing future clinical applications, was to prove image reproducibility. We developed a fixed setting, in which the arm was in a 90 degree flexion in the elbow joint and the hand kept in a pre-designed template with the fingers in a fully spreaded, upright position. This template was removed directly before the photograph was taken, in order to capture both the palmar and dorsal aspect of the hand. This setup was first used in 17 adult volunteers and 3D photographs were taken at two different moments in time. Two different registration methods were applied, one of the full hand, one of only the palmar aspect thus without the individual fingers. Landmarks were placed before further calculations, as described in Chapter 3 of this thesis\(^6\).

The registration method of the palmar aspect resulted in a lower mean registration error, proving the difficulty of creating reproducible images of the hand with the movement of the individual fingers. To date, this movement is still a challenge in capturing precise images of the hand. This study was performed some years ago and meanwhile the systems are highly improved. The current camera system is equipped with higher resolution cameras, leading to improved image quality making following calculations and landmark based matching easier and more precise. For the following clinical applications, the technique of surface-based registration and landmark positioning were successfully used.

2) What are reproducible and accurate landmarks of the hand and can they be used to develop a valid method for imaging of the hand using 3D stereophotogrammetry? (Chapter 3)

The next study was performed based on knowledge from the first studies using 3D stereophotogrammetry in maxillofacial surgery\(^7,8\). In recent literature, no consistent description of soft tissue landmarks of the complete hand exists. 3D hand images of 20 subjects were taken, using the method previously described in Chapter 2\(^9\). A 3D photograph-based reference frame was set up prior to landmark identification. The use of this reference frame enlarges the reproducibility of the landmark positioning, because all images are visualized in the same standardized way\(^9\). Thereafter, 30 landmarks were defined and placed
on the images, based on known topographical and bone-related landmarks of the hand and intra- and interobserver analysis of the reproducibility were calculated. Intra- and interobserver reliabilities of the landmarks were high, expressed in the reliability coefficient. This coefficient was, respectively 1.00 (range 0.99 - 1.00) for the intraobserver and 0.99 (range 0.99 - 1.00) for the interobserver reliability. The total of 30 defined landmarks proved sufficient to perform a reliable soft tissue analysis based on 3D hand images. Most of the landmarks were placed on the palmar aspect of the hand, since the landmark placement on the dorsal aspect was thought to be more difficult in the absence of exact bony tissue orientation points, leading to less accurate calculations. The study revealed a high reproducibility and reliability for most of the landmarks. The placing of landmarks on the fingertips was more difficult because of the lower quality of the 3D image in this area. When the images used in this study were to be recreated using the current software, the results would be highly improved, given the continuous updates in image quality and camera precision.

3) *Is it possible to compare 3D soft tissue characteristics of the hand of acromegaly patients with those of healthy control subjects, using 3D hand stereophotographs? (Chapter 4)*

The first two studies of this thesis focused on measuring the accuracy of the 3D imaging system and introducing this new technique in analyzing the hand in a 3D perspective. The fourth chapter described the first clinical application of 3D hand imaging, in a patient population of acromegaly patients. After the treatment of acromegaly patients it is largely unknown to what extent soft tissue overgrowth of the hand persists. Musculoskeletal-related disorders, including acral overgrowth, account for the main functional disability in these patients. Concerning the hands of patients in long-term remission of acromegaly, the late effects of the disease have not yet been fully characterized, with previous studies only using radiographic images of the bony tissue of the hand. 3D stereophotogrammetry provides a new opportunity to quantify acral disproportions in patients with acromegaly. Therefore, twelve patients in remission of acromegaly at least two years after successful pituitary surgery, were eligible for a case-control study, which we presented in Chapter 4. Their 3D hand images were compared to those of matched control subjects. Calculations were performed using the methods described in Chapter 2 and 3.

Hand width and length were significantly larger in the acromegaly patients compared to the healthy matched controls ($p = 0.0017$ and $p = 0.0025$ respectively), indicating soft tissue overgrowth in the patient group. Furthermore, the volumes of the hands of both groups were calculated, resulting in a mean hand volume of 488.8 cm$^3$ in the acromegaly group and 393.4 cm$^3$ in the control group.
The strength of this study was the comparison of a patient group with matched control subjects. Furthermore, using 3D stereophotogrammetry as a fast, accurate, easy to perform and harmless technique, it is possible in the future to compare different treatment options and their effect on soft tissues.

The small study population was a limitation, as well as the difficulty in landmark positioning on the first finger. The latter is currently improved as described in the paragraphs above, by continuous updating of the camera system. Another possible improvement for future research will be the integration of CT scan images of the hand to our current 3D photographs to characterize the bony tissue. This will lead to more detailed conclusions on the specific types of affected tissue and the effect of different treatment regimes on these tissues.

4) Can 3D imaging be used as a reproducible tool in qualifying and quantifying different areas in the hand to evaluate lymphedema or the aging process of the hand? (Chapter 5 and 6)

After the first successful introduction of 3D hand imaging as a tool in clinical evaluation of treatment, another important patient group with possible hand function problems are breast cancer patients in whom axillary lymph nodes are dissected. This can result in the development of lymphedema of the upper extremity, a frequently seen manifestation after breast cancer surgery, with an incidence varying from 6% to 57%. Early detection and treatment are important and in order to objectify upper extremity swelling, an accurate method of volume measurement is necessary. Nowadays, more and more operative interventions are performed for lymphedema therapy and therefore it is necessary to evaluate the effect of the surgical procedure on the different areas of the arm and hand. At this moment, water displacement is the most reliable method in volume measurement of the upper extremity. However, with this technique it is not possible to measure a specific area of the hand.

Therefore, the use of 3D stereophotogrammetry was analyzed in Chapter 5, since its usefulness in upper extremity volume measurements in patients with lymphedema was earlier proved by Hameeteman et al. After volume measurements on 3D images of 18 patients and 15 healthy control subjects, an average difference of 73 ml was found comparing the edematous hand with the non-edematous hand. This was more than the normal variation in volume between hands (8 ml). However, a correction for dominance of the hand was not performed and the patient group was relatively small. Also, specific areas in the hand with volume differences were not calculated. In conclusion, 3D stereophotogrammetry was found to be a useful tool in qualifying and quantifying hand volumes, but further
research is needed to optimize the reproducibility and further specify the affected hand areas.

Besides the use of 3D imaging in the reconstructive field, we introduced it in the esthetic surgery field. Chapter 6 described the usage of 3D images in visualizing the hand aging process. With rejuvenation treatments of the skin gaining more and more popularity, the inquiry for rejuvenation of the hand grows. The hand aging process is characterized by epidermal changes and volume loss in different areas of the hand. To objectively visualize these areas and compare different treatment outcomes, 3D stereophotogrammetry was investigated as a possible valid tool. Subjects were divided into groups based on age and sex. On the acquired 3D hand images the dorsa of all subjects were analyzed, resulting in a smoother surface in the young patients and reduced intermetacarpal space in elderly patients. The study was limited by a small study population. Therefore, the analyses were not corrected for BMI values, which could explain some of the differences in the resulting 3D images. With the current camera system and software updates, even more detailed images and calculations can be performed, leading to more exact volume measurements of the dorsa of hands. We further described the unavailability of the 3D stereophotogrammetry setup in more hospitals as a known disadvantage. However, with the number of hospitals using 3D stereophotogrammetry expanding, so is the availability of the imaging system. To conclude, in patients with lymphedema of the hand or patients requiring rejuvenation treatment, 3D stereophotogrammetry can be accurately used to qualify and quantify different areas in the hand.

5) Can 3D hand images be used as the basis to design a preoperative virtual incision pattern for a desyndactylization procedure? (Chapter 7)

Until now, the developed 3D hand imaging system was used to analyze and evaluate the changes in the hands of patients, compared to those of healthy reference groups. With the gained knowledge and experience from the previous studies, it was possible to take the 3D stereophotogrammetry one step further, and investigate its usefulness in 3D virtual surgery planning.

Syndactyly is a congenital hand condition, characterized by fusion of the fingers. Many different surgical techniques have been developed for treatment of syndactyly, with the common main goal to create a functional hand with the smallest number of operative corrections and complications. Exact preoperative planning of the reconstructive procedure is essential. Therefore, different imaging techniques are being used, for example CT and conventional radiology. However, these techniques have numerous disadvantages, which are among others radiation side effects, costs and need for anesthesia when used for children.
We evaluated the usage of 3D images during the preoperative planning process. First, we calculated the accuracy of a virtual planned and real delineation on a silicon model, resulting in a mean difference of 0.82 mm. Thereafter, 3D hand images of three syndactyly patients were made, and individual virtual incision patterns were created. Each pattern was transferred onto the patient by using a 3D printed template (figure 1). The resulting incision pattern needed minor modifications by the surgeon before the surgery was performed. This first step proved that a virtual incision pattern can be created and transferred back onto the patient successfully in an easy, low cost and accurate way by using a template. Future research has to be done, focusing on the next steps necessary in developing a clinically applicable virtual planning tool of desyndactylization procedures. Furthermore, the availability of the 3D stereophotogrammetry setup is expanded nationally, thereby stimulating cooperation with other hospitals for improving patient care.

Figure 1. Transferring the incision pattern onto the patient intraoperatively, demonstrated as an easy and fast procedure using the template

FUTURE ASPECTS

The results of the current studies on 3D imaging are promising in many surgical fields, as well as in the field of hand surgery, which is confirmed by the findings of this thesis. 3D stereophotogrammetry is a very promising technique with many advantages, as described in this thesis. The usage of 3D hand images adds precision to a surgical procedure, while saving potential revision surgery. There is no need for potential harmful contrast fluid, often necessary in MRI or CT imaging techniques. The images are readily available for further calculations or
intercollegial discussions. The technique is fast, accurate, with no excessive costs and as little annoying as possible to the persons involved.

Improvements of the imaging technique and camera set-up with special attention to the fixed positioning of the fingers can and have to be made. In this way, registration errors and errors due to different finger positioning will be excluded. Therefore, in the coming years research in close cooperation with the 3D lab will continue, further expanding and sharing our knowledge with other national hospitals. This will further improve treatment planning, outcome and evaluation, leading to better care for the individual patient. Future aspects will focus on improving existing knowledge and usage, and will extent to new topics beyond the hand surgery field.

Fusion images for preoperative planning

The possibility of creating fusion images with CT or MRI data will be investigated. Combining 3D techniques with other datasets creates a complete 3D image of the soft tissues as well as the bony tissues. This complete 3D image can simplify the preoperative planning process of different hand patients. Two examples of these patient groups are the congenital hand patients and hand trauma patients. In Chapter 7 we described the first step in designing a preoperative plan for a specific congenital hand patient group, namely syndactyly patients. The usage of 3D hand images of the soft tissues in creating a template for preoperative planning was described as successful. Combining the 3D images with information on the abnormalities of the bony tissues in syndactyly patients will further improve the precision of preoperative planning, therewith reducing the operating time.

A 3D image of the hand trauma patient with information on the affected bony structures will help the surgeon in the operating theatre to reconstruct these structures in the best possible way. In the severely damaged hand it is often difficult to recognize the specific anatomic structures. 3D images of the soft and bony tissues could support the surgeon during the difficult hand trauma surgery procedure.

Postoperative evaluation

With the use of 3D stereophotographs, postoperative evaluation of surgical outcome and hand function can be evaluated. Records can be made on the color, volume, scar formation, functional status and changes of these items over time. This can help the surgeon improving the surgical technique with feedback on the patients hand status. Furthermore, the patient can be informed on the healing process by visualizing the changes in the hand.
Augmented reality and hand therapy

Current research in our department focused on augmented reality, by using an Intel® RealSense™ camera (figure 2) to measure the fourth dimension of hand motion. With this camera, positions and orientations of the hand were used for calculating the range of motion of hand joints. The resulting 4D images could be used for functional analysis of the hand and further improve hand therapy protocols.

Figure 2. The Intel® RealSense™ camera

Many hand surgery patients require long term hand therapy sessions to maintain and improve hand function after surgery. Compliance to these intensive hand therapy protocols is an often faced problem by clinicians and hand therapists. The 4D camera could offer a possible solution in improving this compliance. The camera offers a cheap, portable system, which can be used in a home-based setting. For individual patients, monitoring hand function can then be performed online with the hand therapist providing feedback or giving new instructions.

Updating educational programs

The global concept of this thesis was developed from the lack of hand anatomy knowledge and anatomy courses in the medical education program. Future developments could contain the design of a standard real-life 3D hand model based on 3D stereophotographs, which can be used for various educational purposes. For example, consecutive steps in common surgical hand procedures could be simulated in 3D animated and photographed reconstructions. Not only medical students and surgical residents can be educated this way, but these images could be very illustrative for patients as well. Especially in the field of esthetic plastic
surgery, patients are more and more demanding nowadays. By using 3D images of their hands and simulating the postoperative result, a patient-tailored rejuvenation treatment plan can be proposed and discussed during the shared-decision making process. The simulation process could be developed as an analyzing tool and integrated into the patients personal electronic file. Therewith, the patient is able to view the expected postoperative result from their home, optimally preparing them for surgery and giving them better understanding of their future treatment result.

Usage beyond the hand: wound care and lymphatic microsurgery

Other new possible applications of 3D stereophotogrammetry are currently investigated in our department. One of these is the use of 3D photography in complex wound assessment and the evaluation of hypertrophic scars\(^\text{27}\). Furthermore, we are exploring the possibilities of evaluating the postoperative results after lymphatic microsurgery. This surgical treatment method for lymphedema has demonstrated to effectively improve lymph drainage in patients with upper extremity lymphedema and is being used more and more\(^\text{28}\). For calculating its effectiveness, a volume measurement method would be required. Using 3D images, specific affected areas in the upper extremity can be imaged and volume differences calculated. In the future, this technique could also be used for measuring other body parts affected by lymphedema, for example the lower extremity or the foot\(^\text{29}\).

In this thesis we developed a method of 3D imaging of the hand, using 3D stereophotogrammetry. We proved the added value of 3D imaging in the hand surgery field and created the basis for further improvements and new developments. Close cooperation between technicians and surgeons will remain very important in implementing this technique in the clinical hand surgery setting. Using the new results of future research, the surgeon will be provided with more detailed information. With the availability of augmented reality, the hand surgery resident will be able to prepare difficult hand procedures in detail. Patient-specific treatment plans can be created based on augmented reality images. This will create the opportunity to prepare the patient for surgery and evaluate treatment outcome for further improvements of surgical techniques. Finally, this will provide the patient with the best possible functional and esthetic outcome.
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General discussion and future aspects


Summary
Based on the growing number of three-dimensional (3D) teaching models for different anatomic regions and the more extensive use of computer-based models in treatment planning of surgical procedures, the idea of introducing 3D stereophotogrammetry in the field of hand surgery was created. Currently, different imaging techniques like Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) are being used for hand imaging. However, these existing techniques have numerous disadvantages, like radiation dose and costs. Compared to these techniques, 3D stereophotogrammetry is a safe and non-invasive technique for surface imaging of the hand, with the possibility of providing an objective basis for quantifying and qualifying clinical treatment outcome. Therefore, the main objective of this thesis was to investigate the usage of this 3D imaging technique for hand imaging and prove its effective use in clinical practice.

The accuracy of 3D stereophotogrammetry to create reproducible images of the hand was described in Chapter 2. A total of 34 three-dimensional hand photographs were analyzed to investigate the reproducibility, resulting in a small mean registration error. Furthermore, an average hand model was created using landmark based registration. From this study could be concluded that 3D stereophotogrammetry produces precise and reproducible 3D images of the hand.

Further efforts to prove the validity of 3D hand images were performed, developing a landmark registration system. The reproducibility of 30 soft tissue landmarks on the hand was determined using 3D stereophotogrammetric images. The results of the analysis of the landmarks, performed on 20 images by two observers, were described in Chapter 3. These study results revealed a high reliability coefficient for intraobserver and interobserver reliability, with more precise identification of the landmarks on the palmar aspect of the hand. It could be concluded that 3D stereophotography can safely produce accurate and reproducible images of the hand, creating a reliable method for soft tissue analysis.

After proving the reliability of 3D hand images produced by stereophotogrammetry, we focused on the clinical application of the technique. In the first clinical study (Chapter 4) a group of acromegaly patients in long-term remission of their disease were investigated. A case-control study was performed, in which 3D hand photographs of twelve acromegaly patients and their matched controls were acquired and analyzed. The patients in long-term remission showed to have soft tissue overgrowth of the hand compared to the control subjects, with larger length and width of the hand. These findings underscore that patients have to be informed that even after long-term remission of acromegaly the acral overgrowth persists. Furthermore, 3D stereophotogrammetry is a very promising technique for the follow-up of these patients, since it is fast, accurate, harmless and easy to perform.
Summary

Lymphedema of the upper extremity is a frequently observed manifestation following breast cancer surgery. To qualify and quantify lymphedema of the upper extremity, and in particular the hand, Chapter 5 described the use of 3D hand imaging for this purpose. A total of 18 patients with unilateral lymphedema of the hand were included, where after 3D hand images of both hands were obtained. The images of the lymphedema hand were compared with the normal unaffected hand of the same patient and linked to self-reported discomfort of the patient. In conclusion, the analyzed hand volume on the affected side was significantly larger compared to the unaffected side. This pilot study proved that changes in hand volume of lymphedema patients can be easily detected by using 3D hand images, creating an opportunity for timely initiation of treatment and evaluating treatment outcome.

With rejuvenation treatment of the hand gaining popularity, the need for a reliable tool to objectively visualize the changes of the aging hand and to compare different treatment outcomes, is growing. So far, no 3D imaging tool existed to visualize the aging process of the hand. In Chapter 6, this clinical application was investigated. 64 healthy volunteers were divided into four groups based on age and sex. 3D photographs of both hands were captured and analyzed by two different methods. The first method measured the smoothness of the dorsa of the old and young hands, and resulted in a non-significant difference in which the younger dorsa were smoother. In the second method, a color-coded distance map was created, showing a relative volume loss in the intermetacarpal space of the average old hands. On the basis of these findings, specific areas of esthetic treatment of the hand can be identified by 3D imaging, creating patient-tailored treatment options. Furthermore, it allows objective comparison of the outcomes of different rejuvenation treatments.

After these first clinical applications, we used 3D stereophotogrammetry during the preoperative planning process of a hand surgical procedure, namely desyndactylization (Chapter 7). 3D hand images were used as the basis for creating a virtual planning tool to design an optimal incision pattern for desyndactylization procedures. After producing a template and testing it on a silicon syndactyly model, 3D hand images were made of three syndactyly patients. Individual incision patterns were created and transferred onto the patient intraoperatively by using 3D printed templates. The planning process was simple to perform with satisfying accuracy and no adverse effects on the surgery process. With future research, the next steps in the process of developing the virtual planning tool will be created.

The content of this thesis showed the added value of 3D imaging in hand surgery. The usage of 3D hand images adds precision to a surgical procedure and...
will reduce valuable operating time. Close cooperation between technicians and surgeons will remain very important in implementing this technique in the clinical hand surgery setting. Future research and improvements to the 3D technique will further add to the value of 3D hand imaging.
Samenvatting
Gezien het toenemende aantal driedimensionale (3D) onderwijsmodellen voor verschillende anatomische gebieden en meer en meer gebruik van computergebaseerde modellen in de planning van chirurgische behandelingen, ontstond het idee om 3D stereofotogrammetrie te introduceren in het gebied van de handchirurgie. Tegenwoordig worden verschillende beeldvormende technieken gebruikt voor beeldvorming van de hand, zoals bijvoorbeeld Computed Tomography (CT) en Magnetic Resonance Imaging (MRI). Echter, deze technieken hebben diverse nadelen, waaronder stralingsdosis en kosten. In vergelijking met deze technieken is 3D stereofotogrammetrie een veилige en niet-invasieve techniek voor oppervlakte beeldvorming van de hand, met de mogelijkheid tot kwantificeren en kwalificeren van de uitkomsten van klinische behandelingen. Daardoor was het belangrijkste doel van dit proefschrift om het gebruik van deze 3D beeldvormende techniek te onderzoeken voor beeldvorming van de hand en het effectieve gebruik in de klinische praktijk aan te tonen.

De nauwkeurigheid van 3D stereofotogrammetrie om reproduceerbare afbeeldingen van de hand te verkrijgen, werd beschreven in Hoofdstuk 2. In totaal werden 34 driedimensionale handfoto’s geanalyseerd en werd de reproduceerbaarheid onderzocht, resulterend in een kleine gemiddelde registratiefout. Verder werd een gemiddeld handmodel ontworpen, gebruik makend van een landmark registratie systeem. Vanuit deze studie kon geconcludeerd worden dat 3D stereofotogrammetrie exacte en reproduceerbare 3D afbeeldingen van de hand creëert.

Vervolgens werd de validiteit van 3D handafbeeldingen onderzocht, waarbij een landmark registratie systeem werd ontwikkeld. De reproduceerbaarheid van 30 weke delen landmarks op de hand werd bepaald, gebruik makend van 3D stereofotogrammetrische afbeeldingen. Het resultaat van de analyse van deze landmarks, uitgevoerd op 20 afbeeldingen door twee beoordelaars, werd beschreven in Hoofdstuk 3. De resultaten van deze studie gaven een hoge betrouwbaarheidscoëfficiënt weer voor zowel de intraobserver als interobserver betrouwbaarheid, met meer exacte identificatie van de landmarks op de palmaire zijde van de hand. Geconcludeerd werd dat 3D stereofotogrammetrie veilig kan worden gebruikt voor nauwkeurige en reproduceerbare afbeeldingen van de hand.

Nadat de betrouwbaarheid van 3D handafbeeldingen geproduceerd met stereofotogrammetrie was bewezen, werd gefocust op de klinische toepassingen van de techniek. In de eerste klinische studie (Hoofdstuk 4) werd een groep acromegale patiënten onderzocht in lange termijn remissie van hun ziekte. In een case-control studie werden 3D handfoto’s van twaalf acromegale patiënten en gematchte controles verkregen en geanalyseerd. De patiënten in lange termijn remissie hadden weke delen overgroei van hun hand vergeleken met de controle groep, met grotere lengte en breedte van de hand. Deze bevindingen onderstrepen het belang
dat patiënten geïnformeerd moeten worden dat zelfs in lange termijn remissie van acromegalie, de acrale overgroei kan persisten. Verder is 3D stereofotogrammetrie een veelbelovende techniek voor de follow-up van deze patiënten, gezien de snelheid, nauwkeurigheid, veiligheid en eenvoud in uitvoering van de techniek. Lymfoedeem van de bovenste extremiteit is een veelvuldig gezien symptoom na borstkanker chirurgie. Om de mate van lymfoedeem van de bovenste extremiteit te kwalificeren en kwantificeren, in het bijzonder in de hand, beschreef Hoofdstuk 5 het gebruik van 3D beeldvorming van de hand voor dit doeleinde. In totaal werden 18 patiënten met unilateraal lymfoedeem van de hand geïncludeerd, waarna 3D handfoto’s van beide handen werden verkregen. De foto’s van de lymfoedeemhand werden vergeleken met de normale, niet-aangedane hand van dezelfde patiënt en gelinkt aan zelf-rapportages van ongemak van de patiënt. Concluderend was het geanalyseerde handvolume van de aangedane zijde significante groter dan het volume aan de niet-aangedane zijde. Deze pilotstudie toonde aan dat veranderingen in het handvolume van lymfoedeemPATIËNTEN EEN EVOLUMINIG CONKLUDEREND WAS HET GEANALYSEERDE HANDVOLUME VAN DE AANGEDANE ZIJDE SIGNIFICANT GROTTER DAN HET VOLUME AAN DE NIET-AANGEDANE ZIJDE. DEZE PILOTSTUDIE TOONDE AAN DAT VERANDERINGEN IN HET HANDVOLUME VAN LYMOFOEDEEMPATIËNTEN EEN EVOLUMINGEN WAARBIJ HET JONGERE DORSUM GLADDER WAS. BIJ DE TWEDE METHODE WERD EEN KLEUR-GECODEERDE DISTANCE MAP ONTWORPEN, WELKE EEN RELATIEF VOLUME VERLIES IN DE INTERMETACARPALE RUIMTE VAN DE GEMIDDELDE OUDER HAND LAAT ZIEN. OP BASIS VAN DEZE BEVINDINGEN KUNNEN SPECIFIEKE DOELGEBIEDEN VOOR ESTHETISCHE BEHANDELING VAN HAND WORDEN GEIDENTIFICEERD DOOR MIDDEL VAN 3D BEELDVORMING, WAT PATIËNT-SPECIFIEKE BEHANDELopties CREÉERT. VERDER BIEDT HET DE MOGELIJKHEID VOOR OBJECTIEVE VERGELIJKING VAN DE RESULTATEN VAN VERCHIETELINGEN. NA DEZE EERSTE KLINISCHE TOEPASSINGEN GEBRUIKten WE 3D STEREOFOOTOMANOMETRIE TIJDENS HET PREOPERATIEVE PLANNINGSPROCES VAN EEN HANDCHIRURGISCHE PROCEDURE, NAMelijk DESYNDACTYLISATIE (HOOFDSTUK 7). 3D HANDBFOTO’S WERDEN GEBRUIKT ALS BASIS VOOR HET ONTWERPEN VAN EEN VIRTUELE PLANNINGSMETHODE OM EEN OPTIMAAL INCISIEPATROON VOOR DESYNDACTYLISATIECHIRURGIE TE ONTWERPEN. NA PRODUCTIE VAN
een mal en testen van deze op een siliconen syndactyliemodel, werden 3D handfotografie gemaakt van drie syndactyliepatiënten. Individuele incisiepatronen werden ontworpen en overgebracht op de patiënt tijdens de operatie, gebruik makend van 3D geprinte mallen. Het planningsproces was eenvoudig uit te voeren met goede nauwkeurigheid en geen nadelige effecten op het chirurgische proces. Met toekomstig onderzoek zullen de volgende stappen in het proces van het ontwikkelen van een virtuele planningsmethode worden gecreëerd.

De inhoud van dit proefschrift toont de toegevoegde waarde van 3D beeldvorming in de handchirurgie. Het gebruik van 3D handfotografie voegt nauwkeurigheid toe aan de chirurgische procedure en zal de kostbare operatietijd besparen. Nauwe samenwerking tussen technici en chirurgen blijft zeer belangrijk bij de implementatie van deze techniek in de klinische handchirurgische praktijk. Toekomstig onderzoek en verbeteringen aan de 3D techniek zullen de waarde van 3D beeldvorming van de hand verder vergroten.
Dankwoord
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Curriculum Vitae
Curriculum Vitae

Inge van Doorn – Hoevenaren was born in ’s-Hertogenbosch on the 22nd of March in 1985. In 2003 she finished high school at the Gymnasium Camphiusianum in Gorinchem cum laude and started medical school at the Radboud University in Nijmegen. After finishing her doctoral degree cum laude, she started her clinical rotations and developed a special interest in plastic surgery. Particularly during her final clinical rotation at the department of Plastic, Reconstructive and Hand Surgery in the Radboud UMC in Nijmegen, she became inspired by prof. dr. Spauwen, head of the department at that time. It was also during this rotation that the first contacts with the 3D lab were made and the first research project was initiated, which formed the basis for this thesis.

After receiving her medical degree at the end of 2009, she started working as a junior anatomist at the department of Anatomy in the Radboud UMC (prof. dr. Ruiter). Here, the 3D research project was continued and directed toward 3D hand imaging. One year later, she returned to the department of Plastic, Reconstructive and Hand Surgery in the same hospital as a plastic surgery resident not in training (ANIOS). In the following years, she combined her clinical work with 3D hand imaging research.


Inge is married to Matthijs van Doorn in 2017 and they are living in Rhenen.
List of publications


List of publications


UITNODIGING

Voor het bijwonen van

dele openbare verdediging

van mijn proefschrift

Three-Dimensional Stereophotogrammetry in Hand Surgery

op donderdag 5 april 2018

om 10.30 uur precies

in de Aula van de

Radboud Universiteit,

Comeniuslaan 2

te Nijmegen.

Na afloop van de promotie is

er een receptie ter plaatse.

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