Int J Legal Med (2007) 121:511–515
DOI 10.1007/s00414-007-0204-4

TECHNICAL NOTE

Hand skin reconstruction from skeletal landmarks

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Received: 24 November 2006 / Accepted: 26 July 2007 / Published online: 25 September 2007
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Abstract Many studies related to three-dimensional facial reconstruction have been previously reported. On the other hand, no extensive work has been found in the literature about hand reconstruction as an identification method. In this paper, the feasibility of virtual reconstruction of hand skin based on (1) its skeleton and (2) another hand skin and skeleton used as template was assessed. One cadaver hand and one volunteer's hand have been used. For the two hands, computer models of the bones and skin were obtained from computerized tomography. A customized software allowed locating spatial coordinates of bony anatomical landmarks on the models. From these landmarks, the spatial relationships between the models were determined and used to interpolate the missing hand skin. The volume of the interpolated skin was compared to the real skin obtained from medical imaging for validation. Results seem to indicate that such a method is of interest to give forensic investigators morphological clues related to an individual hand skin based on its skeleton. Further work is in progress to finalize the method.

Keywords Forensic science · Hand · Skin · 3D modeling · Identification

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Introduction

In Western countries, people usually covers most of their body parts with clothing, with the exception of the head and both hands. These anatomical regions are therefore usually visible to, for example, family members or colleagues and are therefore potentially recognizable and identifiable. Since the first attempts of facial reconstruction at the end of the nineteenth century [1–4], many methods were developed to rebuild the face appearance of an individual from the bones of his or her skull. The goal of these reconstructions aimed to identify missing persons or rebuild the face of historical figures [5–13].

Progresses observed in image processing also had an impact on the analysis of a possible space relation between the features of the face, the soft tissue, and the cranial morphology. Computerized facial reconstruction aims at eliminating drawbacks from the manual methods by developing an accurate system. In 1989, Vanezis [14] published a first computer-assisted method for facial reconstruction. After digitalization of an unknown skull, the thickness of the soft tissue is virtually put on the skull using various specific landmarks to obtain the final facial reconstruction.

In the method reported by Evenhouse et al. [15], the unknown skull and the template face are processed using 37 markers connected to each other to form a polygonal frame. The last step of the method transforms the template face toward the unknown skull. Quatrehomme et al. [16] presented a new method based on warping where the reference markers and the thickness of facial tissue are not taken into account any more. This method processes so-called "crest lines," i.e., the cranial lines with the maximum local curves. Nelson and Michael [17] used the soft tissue volume rather than its thickness.

Jones [18] suggested, in a purely theoretical way, to use all available points of the skull surface. The unknown skull and a template head would be scanned. By automatic detection of the shape of the face, corresponding bone areas between the unknown and the template skulls would be determined. Kähler et al. [19] integrated in their reconstruction program 24 virtual muscles in the template to simulate facial mimics.

Claes et al. [20] reduced the template bias (because of current computerized techniques using a single static facial surface template) by using a flexible statistical model including a dense set of facial surface points, combined with an associated sparse set of skull-based landmarks. Vandermeulen et al. [21] investigated the possibility of using full three-dimensional (3D) cross-sectional computerized tomography (CT) images for establishing a reference database of densely sampled distances between the external surfaces of the skull and head for automated craniofacial reconstruction. Other identification methods notably with age estimation used CT scan techniques. Schulz et al. [22] determined the ossification status of the medial epiphysis of the clavicle using the classification by Schmeling.

Mühler et al. [23] concluded that for age estimation purposes, the slice thickness should be 1 mm to ensure maximum accuracy and diagnostic reliability.

Schmidt et al. [24] considered that a modified examination protocol is required for magnetic resonance examination of clavicular cartilage for the purpose of forensic age diagnostics of living subjects.

To the authors' knowledge, no extensive work has been reported in the literature about similar identification methods applied to skin reconstruction of the hand.

The aim of this paper was to estimate the feasibility of virtual skin reconstruction of an unknown hand from its skeleton and a template hand available from a database. Such computerized method would be useful for comparison and recognition of forensic materials.

Materials and methods

This study aimed to determine the feasibility of virtual reconstruction of hand skin based on the hand skeleton and some hand template taken as reference. To achieve this goal, an intact cadaver hand ($Hand_{cad}$) was obtained from a donor (European, female, age 72 years) of the body donation program of the Faculty of Medicine (Université Libre de Bruxelles). Sawing of the hand was performed at the level of the forearm, just above the wrist joint. A volunteer (European, male, age 55 years) gave his informed consent to allow analysis of his right hand ($Hand_{vol}$). All local ethical regulations were respected.

Medical imaging

Both $Hand_{cad}$ and $Hand_{vol}$ were imaged using spiral CT scan (image matrix=512×512, field of view=500 mm, pixel resolution=0.98 mm, slice thickness=1 mm). Low-dose sequence (intensity=40 mA, voltage=120 kVp) was used to limit X-ray radiation of the volunteer. The structures of interest (i.e., skin and bones) were extracted from the CT datasets using a commercially available segmentation software (Amira©, Germany) [25]. Four 3D models were obtained: two bone models ($Bone_{cad}$ and $Bone_{vol}$) and two skin models ($Skin_{cad}$ and $Skin_{vol}$; Fig. 1).

The next challenge is to interpolate and reconstruct this hand skin. The optimal result should be a 3D skin model ($Skin_{cad,\ interpol}$) similar to $Skin_{cad}$. The latter was therefore used as gold standard in this study to compare $Skin_{cad,\ interpol}$ with the Gold $Skin_{cad}$.

$Skin_{cad,\ interpol}$ was obtained by using both $Bone_{vol}$ and $Skin_{vol}$ as templates and $Bone_{cad}$ as the starting point according to the following procedure. This procedure

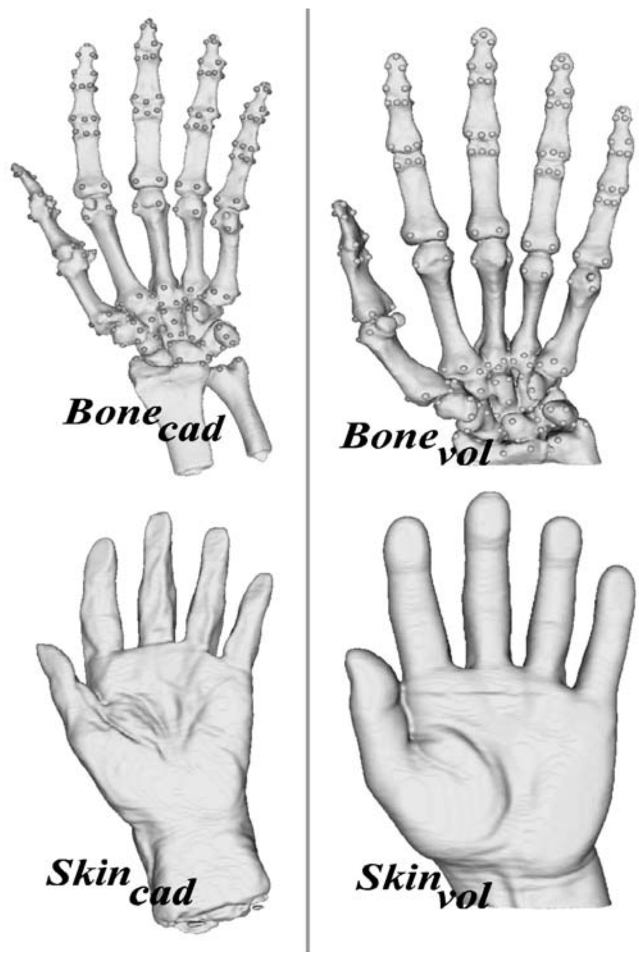

Fig. 1 Both cadaver and volunteer hands used in this study for the virtual skin reconstruction are depicted. $Skin_{cad}$ is used as the gold standard to estimate the precision of the method. Skeletal landmarks located on the bone models are also observable

included both “virtual palpation” and “data registration” as explained in the next section.

Virtual palpation

The first step of this reconstruction was to locate several anatomical landmarks ($AL_{i,\ cad}$) on $Bone_{cad}$ using virtual palpation [26]. The software system kept all coordinates of the selected $AL_{i,\ cad}$ for further use. Once virtual palpation was entirely performed on $Bone_{cad}$, a similar list ($AL_{i,\ vol}$) was located on $Bone_{vol}$ (see Fig. 1 with $AL_{i,\ cad}$ locations indicated by spheres on both $Bone_{vol}$ and $Bone_{cad}$ models). From this palpation, two AL lists were obtained: $AL_{i,\ cad}$ and $AL_{i,\ vol}$ (Fig. 1 shows ALs set on both $Bone_{cad}$ and $Bone_{vol}$; index i of each AL_i characterizes similar landmarks in both lists). A particular landmark AL_i must have the same index i in both $AL_{i,\ cad}$ and $AL_{i,\ vol}$. Once all AL_i landmarks have been selected, the data were ready for the next step, data registration and interpolation of $Skin_{cad,\ interpol}$. Virtual palpation used in this paper was implemented in a customized software interface called DataManager [27].

Data registration and interpolation of skin surface ($Skin_{cad,\ interpol}$)

Spatial data registration [28] was also performed into the DataManager software. In this study, the spatial transformation A, between both $Bone_{vol}$ and $Bone_{cad}$, was determined using their respective AL lists ($AL_{i,\ vol}$ and $AL_{i,\ cad}$) in singular value decomposition algorithms [29, 30]. The spatial transformation $A_{vol\rightarrow cad}$ allowed registration of $Bone_{vol}$ toward $Bone_{cad}$ according to: $Bone_{cad,\,interpol} = A_{vol\rightarrow cad} Bone_{vol}$.

More important for this study, interpolation of the “missing” skin of $Bone_{cad}$ was then found using the same spatial transformation: $Skin_{cad,\,interpol} = A_{vol\rightarrow cad} Skin_{vol}$.

$Skin_{cad,\ interpol}$ was then compared with the Gold $Skin_{cad}$ and the template $Skin_{vol}$ by comparing their respective volumes.

Results

Skin reconstruction

The feasibility study of cadaver skin reconstruction ($Skin_{cad}$) from its skeleton ($Bone_{cad}$) and a template hand seems promising. Indeed, comparison between $Skin_{cad}$, $Skin_{cad,interpol}$ and $Skin_{vol}$ is satisfactory (Fig. 2). $Skin_{vol}$ clearly shows the characteristics of a male hand (thicker fingers, broad palm) compared to $Skin_{cad}$ (longer fingers, thinner palm). $Skin_{cad,interpol}$ looks more like $Skin_{cad}$ than $Skin_{vol}$ which indicated that the template hand skin was transformed to the cadaver hand skin in a satisfactory way.

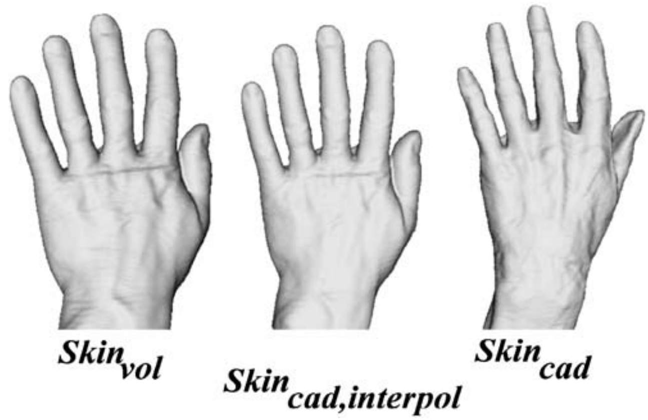

Fig. 2 Comparison between the original template (*$Skin_{vol}$*), the gold standard (*$Skin_{cad}$*), and the interpolated skin (*$Skin_{cad,\ interpol}$*). The latter has some of the female morphological characteristics of $Skin_{cad}$: reduced volume and thinner wrist, hand, and fingers

Furthermore, comparison of the respective volumes is indicative of the precision of the method: a 3.5% volume difference was found between the original cadaver $Skin_{cad}$ (volume=303.9 cm^3) and the interpolated $Skin_{cad,\ interpol}$ (volume=355.1 cm^3). On the other hand, the large difference (18%) found between $Skin_{cad,\ interpol}$ and the template $Skin_{vol}$ (volume=448.3 cm^3) indicates that an important skin transformation has been performed. This shows that the volume of the interpolated hand skin ($Skin_{cad,\ interpol}$) is closer to the gold standard ($Skin_{cad}$) than the original template ($Skin_{vol}$) used to start the interpolation process.

Discussion

The results of this feasibility study of skin interpolation ($Skin_{cad,\ interpol}$) from an isolated skeleton ($Bone_{cad}$) and a database ($Bone_{vol}$ and $Skin_{vol}$) are promising. The interpolated skin ($Skin_{cad,\ interpol}$) shows a 3.5% volume difference compared to the original reference skin ($Skin_{cad}$). Such accuracy should be satisfactory in most forensic contexts.

This study used a cadaver's hand, which skin was reconstructed from volunteer's hand skin. For taphonomic reasons, the cadaver hand did not show the same superficial aspect as a living hand. Comparing hands from two different living volunteers would probably lead to better results, but this was not the aim of the presented study. Using a cadaver hand allowed us to approach real forensic field conditions where human remains are found.

The optimal number of anatomical landmarks to locate should also be determined to speed up the virtual palpation process (currently, the method used 245 landmarks and virtual palpation requires at least 60 min). Standardizing the positions of the hand during medical imaging would also probably improve the results. The above results on skin reconstruction show potential within the forensic field.

Hand soft tissue is less recognizable than for the face. A particular face includes eyes, lips and ears that gives the face its recognizable and personal aspect. Slight modification of these features can change the aspect of a person. This is less relevant for the hands. The morphology of the hand is not transformed as a face could be by wearing glasses, having a beard, or having various hairstyles.

Positioning of landmarks on characteristic osseous parts (crests, tubercles, processes) is relatively simple and only requires limited knowledge of hand bone anatomy. Use of such system is therefore relatively straightforward.

The presented method should be able to allow hand skin reconstruction when the morphology of the unknown hand is normal and do not show any severe deformations. Forensic teams would, after recovering unknown hand remains, be able to reconstructed the missing skin envelop ($\mathrm{Skin}_{\mathrm{cad,\ interpol}}$).

Tackling hand reconstruction of the hand with severe pathological joint bendings (e.g., shoemaker thumb, severe arthritis) will probably lead to poor results. Note that similar problems are met in facial reconstruction. More sophisticated methods should be developed to solve such particular cases.

Further work will include the creation of a database, including bone and skin data, of various types of hands. The hand reconstruction system would then select the best template available from the database to start the reconstruction of the skin of an unknown hand.

Additional steps for the virtual reconstruction of the hand skin will also include full validation of the method on a larger sample of specimens and the development of an interface that will allow personalizing the hand skin further by adding particular anatomical or pathological details.

On the rebuilt hand, using dedicated software, we could include a particular type of nail, lay out a particular hairiness on the fingers, draw a scar or a tattoo, affix a jewel or imitate a deformation of the fingers (amputation, polyarthritis, osteoarthritis, etc.) or nails (oncophagy).

All these antemortem indications would be provided from the results of forensic investigation or the relatives of the supposed victim. The reconstructed hand with its characteristics, applied as the technique of the “identikit picture,” would become a significant element of identification that can be submitted to the relatives of the victim or the missing person for validation.

A parallel anthropometrical research enabled us to estimate the stature and weight of adult male subjects according to hands measurements, including hand volume [31].

Current work is tackling the relationships between the results of the virtual reconstruction of hand skin with individual anthropometrical measurements.

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