



LJMU Research Online

Lee, W-J, Wilkinson, C, Hwang, H-S and Lee, S-M

Correlation Between Average Tissue Depth Data and Quantitative Accuracy of Forensic Craniofacial Reconstructions Measured by Geometric Surface Comparison Method

<http://researchonline.ljmu.ac.uk/id/eprint/1124/>

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Lee, W-J, Wilkinson, C, Hwang, H-S and Lee, S-M (2015) Correlation Between Average Tissue Depth Data and Quantitative Accuracy of Forensic Craniofacial Reconstructions Measured by Geometric Surface Comparison Method. Journal of Forensic Sciences. 60 (3). pp. 572-580. ISSN 0022-1198

LJMU has developed **LJMU Research Online** for users to access the research output of the University more effectively. Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Users may download and/or print one copy of any article(s) in LJMU Research Online to facilitate their private study or for non-commercial research. You may not engage in further distribution of the material or use it for any profit-making activities or any commercial gain.

The version presented here may differ from the published version or from the version of the record. Please see the repository URL above for details on accessing the published version and note that access may require a subscription.

For more information please contact researchonline@ljmu.ac.uk

<http://researchonline.ljmu.ac.uk/>

Correlation between average tissue depth data and quantitative accuracy of forensic facial reconstructions measured by geometric surface comparison method

Lee W-J, Wilkinson CM, Hwang H-S and Lee S-M

Journal of Forensic Sciences, 2015

Since forensic facial reconstruction (FFR; also known as forensic facial approximation) was introduced as an identification tool in forensic science, the accuracy has been of primary importance to practitioners and law enforcement agencies (1). Therefore, research into the FFR has been directed toward producing more reliable FFR and establishing better means of assessing their accuracy. Conventionally, the accuracy of FFR can be tested by comparison between a photographic image of the FFR and an ante-mortem photograph of the identified individual (2). However, it is difficult and problematic to use photographs of the decedent from a forensic scenario in those accuracy studies due to practical and ethical issues (3,4). For the reasons, researchers developed various methods to evaluate the accuracy by employing live subjects and objective methodologies derived from psychological research into facial recognition (5,6).

A number of methods are used to assess the accuracy of FFR, yet those might be divided into two main groups: qualitative and quantitative approaches. In the early period of accuracy studies into FFR, death masks or photographs of the deceased were compared with the reconstructed faces to determine the resemblance (7,8). These attempts are considered primitive qualitative studies on the accuracy of FFR. As photography became common place in society, comparison of a FFR with a photograph of the individual during life could also be employed for the accuracy studies (1), and attempted to grade the degree of resemblances between the faces. Gerasimov (9) demonstrated a close similarity between the FFR and a photograph of the target face using a qualitative comparison method. Helmer and colleagues (2) used a series of resemblance rating in the one-to-one matching study to compare directly the FFR to corresponding target face for similarities, and assessors are asked to

determine the degree of resemblance. This method can also be regarded as a qualitative approach to test the accuracy of FFR.

Some studies began to use quantitative method as a more objective assessment of the accuracy. In a study by Krogman (8), anthropometric comparison was applied to estimate the discrepancies on primary landmarks between the FFR and head of the cadaver. Besides this basic anthropometric technique, face pool comparison can be considered as an efficient qualitative approach (10). In the face pool performance, assessors are asked to identify a target individual from a range of faces in a pool, which is similar to identification parade technique. The Superimposition method overlays the FFR and a photograph of a target face (or a corresponding skull) using computer software, and compares the morphology and proportions of the faces (11).

The one-to-one comparison and face pool matching are very useful methods to assess the accuracy of FFR, but further objective methods were required to evaluate the accuracy quantitatively. Recently developed 3-dimensional (3D) geometric comparison (reverse modelling) software enabled the comparison of a FFR with the 3D model face of the corresponding subject or another FFR (6,12). Two 3D facial models can be aligned so that the differences in surface contours between two models can be computed numerically. In a study by Wilkinson and colleagues (6), computed tomography (CT) scanned skull models from two live individuals were used for FFR. The FFRs were generated from a 3D computer modelling system, and then the accuracy of the FFRs was assessed quantitatively using reverse modelling software and face pool comparison method. Based on the results, the researchers argued that the computerised modeling system for FFR produces a recognizable individual, with good levels of reliability and accuracy.

Lee and colleagues (12) performed a successive study employing similar methodology of the earlier research (6). The researchers used three Korean live subjects to investigate the accuracy of FFRs generated from computerised 3D modelling system and the validity of pre-existing prediction guidelines for facial components. The skull models for the study were scanned from cone-beam CT

(CBCT). The completed FFRs were compared with the corresponding 3D scanned faces of the subjects to assess quantitative accuracy using reverse modelling software. The results from the study demonstrated that the overall quantitative accuracy of the three Korean FFRs were comparable or even better than those from the study of Wilkinson and colleagues (6). The authors then concluded that computerised 3D modelling method can produce reliable FFR in acceptable level of resemblance, and that the pre-existing guidelines for the determination of the facial features of the FFR studied from White European ancestry groups are applicable to reconstruct the faces of adult Koreans. However, it was revealed that the average facial soft tissue depth data for adult Koreans used in the study (13) caused relatively large discrepancies around cheek regions of the FFRs, and the prediction guidelines for the nose and eyes of White European ancestry groups resulted in not ignorable errors. Therefore further study was suggested applying updated tissue depth data collected from contemporary Korean population group, and examining in succession the pre-existing prediction methods for facial features with the purpose of more reliably FFR of the North-eastern Asians.

As being proposed from the previous research (12), this study was designed primarily to investigate the possibility whether or not the updated average facial tissue depth data (14) may improve the accuracy of FFRs in terms of surface deviation errors between the FFR and the head of subject. Thus this study aims to assess the quantitative accuracy changes of FFRs generated from a computerised 3D modelling system when applying updated tissue depth data, to establish the availability of geometric surface comparison between FFRs and corresponding faces of live subjects scanned from CBCT, and to investigate the validity of facial guidelines for the FFR of Korean adults.

Materials and Methods

To give a consistency, this study followed the exactly same methodology used in the previous study (12) except for applying the updated average facial tissue depth dataset researched by

Hwang and colleagues (14).

For a single blind accuracy test, this research was carried out by two independent research groups, each in Republic of Korea and United Kingdom. The Department of Orthodontics at the School of Dentistry of the Chonnam National University (CNU) in Korea undertook the recruitment of participants and the collection of facial CBCT scan data from live subjects. The production of FFRs and comparisons between the FFRs and the CBCT scanned facial surfaces were performed by a researcher (WJL) in the Centre for Anatomy and Human Identification (CAHID) at the University of Dundee in the UK.

Acquisition of Facial Scan Data

Three volunteers (subject D, E, F – naming as ‘D, E, F’ instead of ‘A, B, C’ are to be distinguished from those in the previous study (12) named as subject A, B, C) were recruited from students at the CNU in Gwangju, Korea. All volunteers had neither any experiences of orthodontic treatment or facial plastic surgery nor facial deformities. Informed consents were obtained from all subjects. This study was approved by the Institutional Review Board for the Medical Science at the CNU Hospital, Gwangju, Korea. 3D images for the skulls and head surfaces were obtained using a CBCT scanner (Alphard Vega™, Asahi Roentgen Co., Kyoto, Japan) with a voxel size of 0.39 mm and Field of View (FOV) of 200 x 179 mm. The subjects were scanned to acquire 3D skull and facial images in the seated upright position with a neutral and relaxed facial expression (Fig. 1 and 3Dc-Fc). Immediately after the completion of CBCT scanning, the faces of each subject were photographed from frontal views using a digital single-lens reflex camera (EOS 400D, Canon®, Japan) with 50 mm zoom (AF 17-50 mm Lens, Tamron®, Japan) (Fig. 3Da-Fa). All slice images produced from the CBCT scanning were thresholded using Hounsfield Units (HUs) limits so as to be differentiated soft or hard tissue while using a 3D visualization computer programme (Amira™ version 5.2.2, USA). These images were stored as a format of Digital Imaging and Communications in Medicine (DICOM) files, and then were transmitted electronically to the CAHID at the University of Dundee with the facial

photographs of the subjects. The DICOM data of the heads were converted to stereolithography (STL) image files using the 3D visualization computer programme by an independent CAHID staff member. The researcher (WJL), with two and half years training in FFR, produced the FFRs. The 3D facial scan images and the photographs of the subjects were not exposed to the practitioner until the FFRs had been completed.

Preparation of the Skull Models

A 3D modelling system (FreeForm Modelling Plus™ software from SensAble Technologies, USA) was utilised for the procedure of FFR. The three skull models (skull D, E, F) were imported into FreeForm Modelling Plus as STL file format (Fig. 1 and 2). As the physical information except the ancestry on the three live subjects was unknown to the practitioner, anthropological assessments for the skulls were initially carried out in terms of sex and age determination. Skull D (Fig. 1D) was estimated as an North-eastern Asian, male and aged 26-30 years; Skull E (Fig. 1E) was estimated as an North-eastern Asian, female and aged 26-30 years; skull F (Fig. 1F) were estimated as an North-eastern Asian, male and 26-30 years. The actual ages of the subjects were informed from the CNU after completion of the FFRs as 27 years for subject D, 29 years for subject E and 28 years for subject F.

Facial Reconstruction

The faces of the subjects were reconstructed according to the combination method (1,15) (Fig. 2). Average facial soft tissue depths data for living Korean adults was utilised (14). The tissue depth pegs were placed onto the surface of the skull at the corresponding anatomical sites using modelling clay and scale tools to adjust the exact lengths of each peg in the Freeform software (Fig. 2B). Each individual facial muscle was rebuilt as accurately as possible following anatomical guidelines. A data bank of pre-modelled facial muscles containing fifteen major facial muscles and the parotid glands was utilised in the anatomical stage. Each muscle was imported and positioned onto the skull according to the analysis of those origins and insertions. The shape and size of the muscles were

altered utilising 3D deformation tools to customize the muscle to the target skull (Fig. 2C). The same guidelines as used in the previous study (12) were employed to predict facial components. For the final stage of facial reconstruction, a skin layer was added over the muscle and skull structure referring to the facial anatomy and musculature by utilising transparency tools in the FreeForm software.

Comparison of the FFRs and Face of the subject

The accuracy of the FFR was assessed using 3D geometrics surface comparison (reverse modeling) software between each FFR and the corresponding subject face. Firstly, the FFR and CBCT scanned face of the subject were aligned manually in Freeform referring to the embedded skull in the FFR and the CT scanned head (Fig. 3Dd-Fd) so that the two skull models were oriented identically in dimension and position. Therefore, the most reliable 3D geometric surface discrepancy between the FFR and the target facial images could be obtained. Since there was a relatively a large defect area on the occipital region of the subject head scan, due to the limitation of FOV, the back of the head including ears and below of jaw line of both the FFR and the scanned head were removed. Thus only the facial regions were compared (Fig. 3Dc-Fc). Secondly, the aligned models was imported as STL file format to the Geomagic Qualify software (Geomagic™ Qualify Version 10, USA) in order to assess geometric surface discrepancy between the FFR and the subject.

Results

The Geomagic Qualify software created shell-to-shell deviation maps for three comparisons between the FFR and subject's face (Fig. 3De-Fe). In the deviation maps, the colours on the spectrum bars and the faces of the FFRs indicate the distribution of the discrepancies: 'green' representing the deviation of within ± 1.0 mm: 'yellow to red' representing from above + 1.0 to + 10 mm: 'darkening blue' representing from below - 1.0 mm to - 10 mm. The '+' (the areas of the yellow to red) implies

that the skin surface of the FFR is more prominent than the subject's face, and the '-' (the areas of the bluish colour) implies that the skin surface of the FFR is less prominent than the subject's face.

The averages and standard deviations of the discrepancy (deviation) between the skin surfaces of FFR and subject are presented in Table 1. The percentage distributions for the deviations are presented in Tables 2 and 3. The deviations between the two shells (the errors) tabulated in the Tables 2 and 3 were computed as the minimum limit of discrepancy error defined within either ± 2 or ± 2.5 mm. The values from the previous study (12) were also presented in the Tables 1, 2 and 3 to demonstrate the differences between the two studies.

The averages on discrepancy between the facial surface of the FFRs and corresponding subjects were -0.1 mm for subject D, -0.2 mm for subject E and 0.4 mm for subject F. The standard deviations between the facial surfaces of the FFRs and corresponding subjects were 1.6 mm for subject D, 2.1 mm for subject E and 1.5 mm for subject F, which all standard deviations demonstrated lesser values than those from the previous study (12) that scored as 2.8, 2.4 and 2.2 mm for subject A, B and C respectively.

The deviation map for subject D (Fig. 3De) revealed that 81% of the overall surface of the FFR deviated within an error ± 2.0 mm in the alignment with the scanned face (Tab. 2), and the percentage was increased to 88% when the error deviation was broadened to within ± 2.5 mm (Tab. 3). Almost 100% of the facial surface was within an error ± 5.0 mm (Tab. 2 and 3). The most accurate areas (errors between ± 1.0 mm; green-coloured areas, occupied by 56% of the overall surface of the FFR) were found across the overall facial surface: majority of the forehead, the eyes and around the orbits, the nose except the nasal tip and nostrils, most of the cheeks, the lips and the chin area. Both lateral foreheads, parts of the lateral nose and the nasal tip, around the nostrils, partial lips and chin were between + 1.0 and + 2.5 mm (yellow-coloured areas; more prominent than the subject face). The small areas around the orbits, lateral orbits, both sides of the mouth corner and lateral portions of the cheeks were between - 1.0 and - 2.5 mm (light blue-coloured areas; less prominent than the subject

face). The largest areas of error ($\geq + 4$ mm and $\leq - 4$ mm) occurred at the minor parts of the both lateral foreheads and tip of the nose (orange-coloured areas; more prominent than the subject face), and at the left mouth corner and partial cheek area (dark blue-coloured areas; less prominent than the subject face).

The deviation map for subject E (Fig. 3Ee) presented that 69% of the FFR surface aligned with the scanned face within an error ± 2.0 mm (Tab.2), and the percentage was increased in 79% when the error deviation was broadened to within ± 2.5 mm (Tab. 3). 97% of the whole surface of the FFR was within an error ± 5.0 mm. The most accurate areas (errors between ± 1 mm; green-coloured areas, occupied by 41% of the overall surface of the FFR) were at the lower forehead, the eyes and the orbits, parts of the cheeks, parts of the dorsal nose, both lateral portions of the philtrum, the lower lip and the lateral chin. The majority of the frontal and lateral foreheads, lateral parts of the nasal bridge, the upper lip and the mouth corners and the medial chin were between $+ 1.0$ and $+ 2.5$ mm (yellow-coloured areas; more prominent than the subject face). The partial orbits, both temples and the lower chin were between $- 1.0$ and $- 2.5$ mm (light blue-coloured areas; less prominent than the subject face). The largest areas of error ($\geq + 4$ mm and $\leq - 4$ mm) were found at the minor portions of the lateral foreheads and the nasal tip (orange-coloured areas; more prominent than the subject face), and at the both small parts of the lower cheeks (dark blue-coloured areas; less prominent than the subject face).

The deviation map for subject F (Fig. 3Fe) revealed that 79% of the overall surface of the FFR was aligned to the target face within an error ± 2.0 mm (Tab. 1), and the proportion of the surface was increased in 87% when the error deviation was extended to within ± 2.5 mm (Tab. 2). 99% of the overall surface of the FFR deviated within an error ± 5.0 mm in the alignment with the scanned face of the subject. The most accurate areas (errors between ± 1 mm; green-coloured areas, occupied by 50% of the overall surface of the FFR) were found at the majority of the foreheads, parts of the orbits, the majority of the nose, the nasal tip, the upper cheeks, around the mouth, the lateral chin and the lower cheeks. The lateral forehead, the eyes and the parts of orbits, the lateral nose, the middle cheeks, the lips and the chin were between $+ 1.0$ and $+ 2.5$ mm (yellow-coloured areas; more prominent than

the subject face). The small parts of the lateral foreheads and the eyes, the mouth corners and the lateral chin were between - 1.0 and - 2.5 mm (light blue-coloured areas; less prominent than the subject face). The largest areas of error ($\geq + 4$ mm and $\leq - 4$ mm) occurred at the small parts of the mouth corners (dark blue-coloured areas; less prominent than the subject face). The small areas of the nasal tip and the temples of the FFR were more prominent than the subject face with the error deviation above + 4.0 mm (orange-coloured areas; more prominent than the subject face).

Discussion

Researchers in the early period of FFR employed death masks or photographs from cadavers to assess the accuracy of FFR (7,16). In those accuracy tests, the researchers decided the level of resemblance as their subjective opinion rather than relying on objective analysis (1,17). Later, these primitive qualitative methods developed into the one-to-one comparison where assessors are asked to determine the degree of resemblance between the FFR and the photograph of the target individual (2,10). Although these qualitative methodologies are still available and being used in current accuracy studies, it was necessary to assess the reliability of FFR with more scientific way, quantitatively. Face pool matching (10,18,19) where the assessors were asked to match an image of the FFR to a face pool of images including the target face are the representatives of quantitative methods. The one-to-one comparison and face pool matching are very useful qualitative/quantitative methods for the assessment of FFR accuracy. However, further objective methods were demanded, especially in reflection of being increased applications of computer assisted methods for producing FFRs. Recently developed 3D geometric surface comparison (reverse modelling) software enabled the comparison of a FFR with the 3D model of the corresponding subject face or another FFR acquired from CT or laser scanner. Two 3D facial models can be aligned so that the differences in surface contours between two models can be computed numerically. Some researchers have pioneered the accuracy of FFR generated from computer assisted techniques utilising the geometric comparison software (6).

In a study by Wilkinson and colleagues (6), CT scanned skull models from two live individuals (white North American male and female) were used for FFR. The FFR were produced from the skull models using a 3D computer modelling system (the same one utilised in this study). The accuracy of the FFR was assessed quantitatively using reverse modelling software (Rapidform™, INUS Technology Inc, Seoul, Korea). The results for the white male demonstrated that 60% of the FFR deviated with the facial scan no more than ± 2.5 mm. The results for the white female demonstrated that 52% of the FFR deviated with the facial scan no more than ± 2.5 mm. The accuracy of the two FFRs were also tested by employing another quantitative method, the face pool matching, and demonstrated 69% hit rate (49% above chance) for the male FFR and 71% (51% above chance) for the female FFR. The hit rates of this study are markedly higher than all the previous studies; Snow and colleagues (18) produced an average hit rate of 33% above chance, Wilkinson and Whittaker (10) recorded 34% above chance, Van Rensburg (20) produced 19% above chance, and Stephan and Henneberg (19) recorded 3% above chance. Therefore, the facts that majority of the FFRs surface demonstrated the least deviation error (no more than ± 2.5 mm) may result in the higher hit rates from the face pool matching performances, and proved that the assessment using the geometric surface comparison could be an effective tool to evaluate the accuracy of FFR.

Claes and colleagues (21) carried out a similar accuracy tests with Wilkinson and colleagues (6) for the 118 FFRs generated from an automated computerised system using a flexible statistical model. The researchers reported the results that the overall average absolute reconstruction error and standard deviation between the reconstructed skin surface and the real test skin surface are 1.14 mm and 1.04 mm. The face pool test of 18 randomly selected FFRs demonstrated identification success rate of 81%. The results from Clase and colleagues' study (21) also can be considered that the quantitative surface comparison method should be an appropriate tool to evaluate the accuracy of FFR.

Lee and colleagues (12) performed a successive study following the study of Wilkinson and colleagues (6). The research employed three Korean live subjects and their 3D scanned skull models for the FFRs, but the same methodology for the procedure of FFR and assessment of the accuracy as

the earlier study (6). The results demonstrated either equivalent deviation errors or better improved deviations between the FFRs and the target subjects (54%, 65% and 77% of the three FFR deviated with the facial scans no more than ± 2.5 mm) comparing to the results from the earlier study (52% and 60% of the two FFR deviated with the facial scan no more than ± 2.5 mm) (6). However, there were limitations of the research that the average tissue depth data for the Korean subjects (13) was obtained from the Korean population in Russia whose dietary and life-style were supposed to influence the 'average' shape of the face compared to the main population group in Korean peninsula. Indeed, more significantly prominent deviation errors were found on the cheek regions in all the comparisons (Fig. 4). Furthermore, the prediction guidelines for facial components used in the study (12) were derived mainly from White European population groups. Therefore, subsequent studies were required to evaluate the accuracy of FFR employing updated tissue depth data and prediction guidelines for facial components considering current Korean population group.

Continued from the previous study (12), this study used recently updated average tissue depth data for the Korean adult group (14) to conduct a subsequent study for the purpose of comparison of the results between the two studies. The results from this study demonstrated significant improvements than the previous study (12) in term of the deviation errors between the surface of the FFR and the target subject (Tab. 1-3). The averages and standard deviations of deviation errors between the FFRs and the faces of target subjects decreased commonly in the results of this study (Tab. 1), while the facial surface showing minimum deviation errors (within $-2.0 \leq X \leq 2.0$ and $-2.5 \leq X \leq 2.5$) increased in all three comparison of subject D, E and F comparing with A, B and C of the previous study (12)(Tab. 2 and 3). Although the sample size in both studies were too small to be analyzed statistically, the surfaces occupied by no more than ± 2.0 mm deviation error from this study demonstrated significant difference ($p = 0.04$) in paired t-test comparing to the previous study (12).

The improved quantitative accuracy of the FFRs in this study might be caused by three reasons: updated tissue depth dataset, aid of computerised modelling method and training/experience of the practitioner. The contribution of updated tissue depth data for adult Koreans (14) can be

detected in the geometric deviation maps between the current study (Fig. 3De-Fe) and the previous study (Fig. 4Ae-Ce). This result suggests that the FFR should be produced employing the average facial soft tissue depth data from contemporary population group rather than out of dated dataset for more accurate FFR. Especially, the current and previous studies utilised CBCT to acquire the soft and hard tissue scan data for the subjects, which allows the face to be in upright position eliminating the possible distortions of the facial soft tissue caused by the gravity with lower radiation doses (14,22). Thus it can be considered that the CBCT might provide more reliable (lesser distorted) facial soft tissue images and measurement data than the other scan equipments.

The experience of practitioner is one of the important factors for the accurate FFR. A recent study (23) about training/experience of practitioner associated with ancestry of the skull models and the practitioners suggested that the training/experience of practitioner may contribute the accuracy of FFR. Fifteen facial reconstructions from three ancestry groups were produced by experienced and trained practitioners in order to explore the aims. The results demonstrated that practitioners produced more recognisable reconstructions using skulls from their own race than skulls from other races, but that training and experience in recognising and reconstructing other race faces will reduce this 'cross-race effect' and promote the level of accuracy for the FFRs. The period between the previous and current study was about one and half years while the practitioner (WJL) was trained in PhD study. Therefore it was assumed that the degree of training/experience may contribute the improvement of the accuracy from this study.

The strengths of the 3D computer modelling system with haptic feedback utilised in this study are that muscles, layer by layer and skin can be visualized as separate units, with the 'transparency' tool - a process not available in the manual method, and the simultaneous visibility of multi-layers might allow alignment of two reference objects (the skull images in this study) in order to assess the accuracy. This method is also reproducible, quick and provides little or no damage to the original specimen. The additions of skin texture, eyelid position and hairstyle, as well as altering degrees of facial tissue depth are quicker and easier to integrate with animation or other computerised

programs. Consequently, it is assumed that this computerised facial reconstruction system in a series of studies including this study (6,12) could lead more accurate FFR.

However, the limitations demonstrated from this study must be stated. The prediction of the location, size and morphology of facial features - eyes, nose, mouth and ears - is critical to the level of the accuracy of FFR. The greater part of feature prediction is based on analysis of the relation between skull structures and soft tissue components, and a number of guidelines have been introduced. However, as there is a paucity of research into determining facial features of Koreans or other North-eastern Asians, this research applied guidelines derived from white European or black African populations. Although the deviation maps shows that all the facial features demonstrated relatively low error deviations to the subject, the distance between the eyes appeared too close especially for the subject D and E. The most inaccurate regions were found at nasal tips of all subjects. From these results, it can be concluded that the pre-existing guidelines derived from a specific ancestry group must be applied with cautions to other ancestry groups. Furthermore relevant research has to be performed utilising various ancestry groups to develop the reliability of prediction guidelines for FFR. Finally, the lesser deviation errors between the FFR and target subject are not necessarily mean the more accurate FFR as far as other accuracy tests will cross check the results from geometric surface comparison method such as face pool comparison test (6). Thus this quantitative study must be tested by other methods in future study to investigate the accuracy from surface comparison would have correlation to other accuracy investigations.

Conclusions

1. Application of updated average facial tissue depth data can facilitate the reliability of FFR in terms of geometric surface accuracy.
2. The results from this study demonstrate that the computerised 3D modelling method can produce reliable FFR in good level of resemblance.

3. The pre-existing prediction guidelines studied from White European ancestry groups for the determination of facial components appeared to be applicable to reconstruct the faces of adult Koreans. However, it will be required further studies into prediction guidelines derived from their own ancestry groups for more reliable FFR.

4. Subsequent studies are required to assess the accuracy of FFRs using other quantitative methods such as face pool comparison for the purpose of establishment of the results from this study.

Acknowledgements

Authors would like to show our gratitude to the subjects who provided their facial photographs and CT images of the faces and skulls.

References

1. Wilkinson CM. Forensic facial reconstruction. Cambridge: Cambridge University Press, 2004;200-19.

2. Helmer RP, Röhrich S, Petersen D, Möhr F. Assessment of the reliability of facial reconstruction. In: İşcan MY, Helmer RP, editors. Forensic analysis of the skull: craniofacial analysis, reconstruction, and identification. New York: Wiley Liss publishers, 1993;229-46.

3. Wilkinson CM. Facial reconstruction: anatomical art or artistic anatomy? J Anat 2010;216(2):235-50.

4. Stephan, C.N. and Cicolini, J. The reproducibility of facial approximation accuracy results generated from photo-spread tests. Forensic Sci Int 2010;201(1-3):133-7.

5. Bruce V, Young A. In the Eye of the Beholder: The Science of Face Perception. New York, Oxford University Press, 1998.
6. Wilkinson CM, Rynn C, Peters H, Taister M, Kau CH, Richmond S. A blind accuracy assessment of computer-modeled forensic facial reconstruction using computed tomography data from live subjects. *Forensic Sci Med Pathol* 2006;2(3):179-88.
7. Wilder HH, Wentwoith B. *Personal Identification*. Boston, MA: Gormon Press, 1918.
8. Krogman WM. The reconstruction of the living head from the skull. *FBI Law Enforcement Bulletin*, 1946;11-8.
9. Gerasimov MM. *The face finder*. New York: Lippincott, 1971.
10. Wilkinson CM, Whittaker DK. Juvenile forensic facial reconstruction: A detailed accuracy study. *Proceedings of the 10th conference of the International Association of Craniofacial Identification*; 2002 Sep 11-14; Bari. Italy: International Association of Craniofacial Identification, 2002;11-4.
11. Tillotson A. *Could craniofacial analysis have a role to play in disaster victim identification?* [dissertation]. Dundee: Univ. of Dundee, 2011.
12. Lee WJ, Wilkinson CM, Hwang HS. An accuracy assessment of forensic computerized facial reconstruction employing Cone-Beam Computed Tomography from live subjects. *J Forensic Sci* 2012;57(2):318-27.
13. Lebedinskaya GV, Balueva TS, Veselovaskaya VS. Principles of facial reconstruction. In: İşcan MY, Helmer RP. editors. *Forensic analysis of the skull: craniofacial analysis, reconstruction and identification*. New York: Wiley Liss publishers, 1993;183-98.
14. Hwang HS, Park MK, Lee WJ, Cho JH, Kim BK, Wilkinson CM. Facial soft tissue thickness

database for craniofacial reconstruction in Korean adults. *J Forensic Sci* 2012;57(6):1442-7.

15. Prag J, Neave RAH. *Making faces*. London: British Museum Press, 1997.
16. Von Eggeling H. Die leistungsfähigkeit physiognomischerrekon-struktionsversuche auf grundlage des schädels. *Arch Anthro* 1913;12:44-7.
17. Haglund WD, Reay DT. Use of facial approximation techniques in identification of Green River Serial Murder victims. *Am J Forensic Med Pathol* 1991;12(2):132-42.
18. Snow CC, Gatliff BP, McWilliams KR. Reconstruction of facial features from the skull: an evaluation of its usefulness in forensic anthropology. *Am J Phys Anthropol* 1970;33(2):221-8.
19. Stephan CN, Henneberg M. Recognition by forensic facial approximation: Case specific examples and empirical tests. *Forensic Sci Int* 2005;156(2-3):182-91.
20. Van Rensburg MSJ Accuracy of recognition of three-dimensional plastic reconstruction of faces from skulls. *Proceedings of Anatomical Society South Africa, 23rd Annual Congress 20* (abstract), 1993.
21. Claes P, Vandermeulen D, De Greef S, Willems G, Suetens P. Craniofacial reconstruction using a combined statistical model of face shape and soft tissue depths: methodology and validation. *Forensic Sci Int* 2006;159(Suppl):S147-58.
22. Hwang HS, Kim K, Moon DN, Kim JH., Wilkinson CM. Reproducibility of facial soft tissue thicknesses for craniofacial reconstruction using Cone-Beam CT images. *J Forensic Sci* 2012;57(2):443-8.
23. Lee WJ. Cross-race effect on forensic facial reconstruction and recognition of reconstructed faces [dissertation]. Dundee: Univ. of Dundee, 2012.

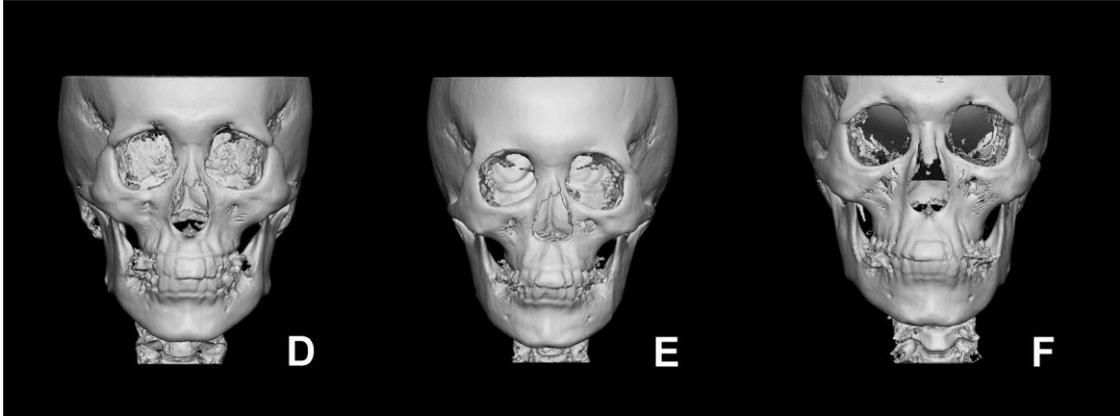


Figure 1. CT scanned three skull images used in this study.

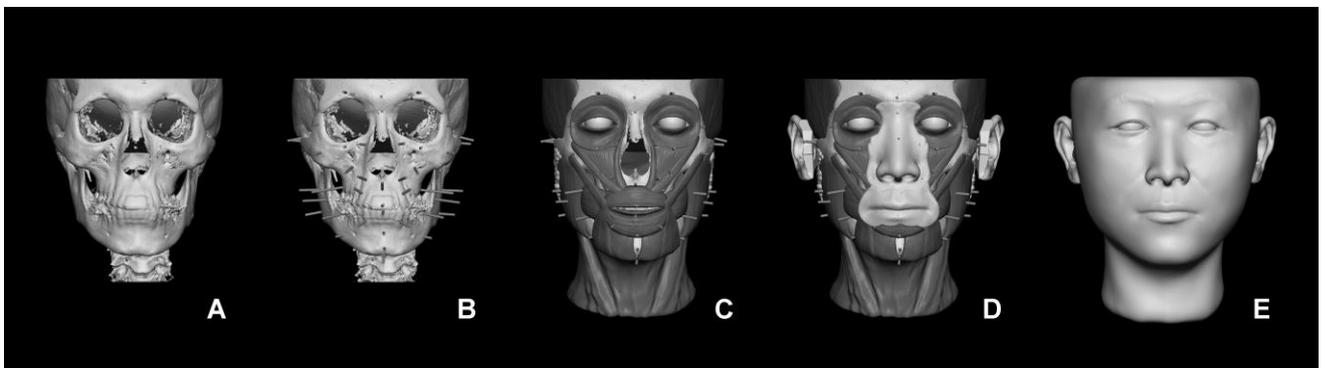


Figure 2. 3D computerised FFR procedure following the combination method.

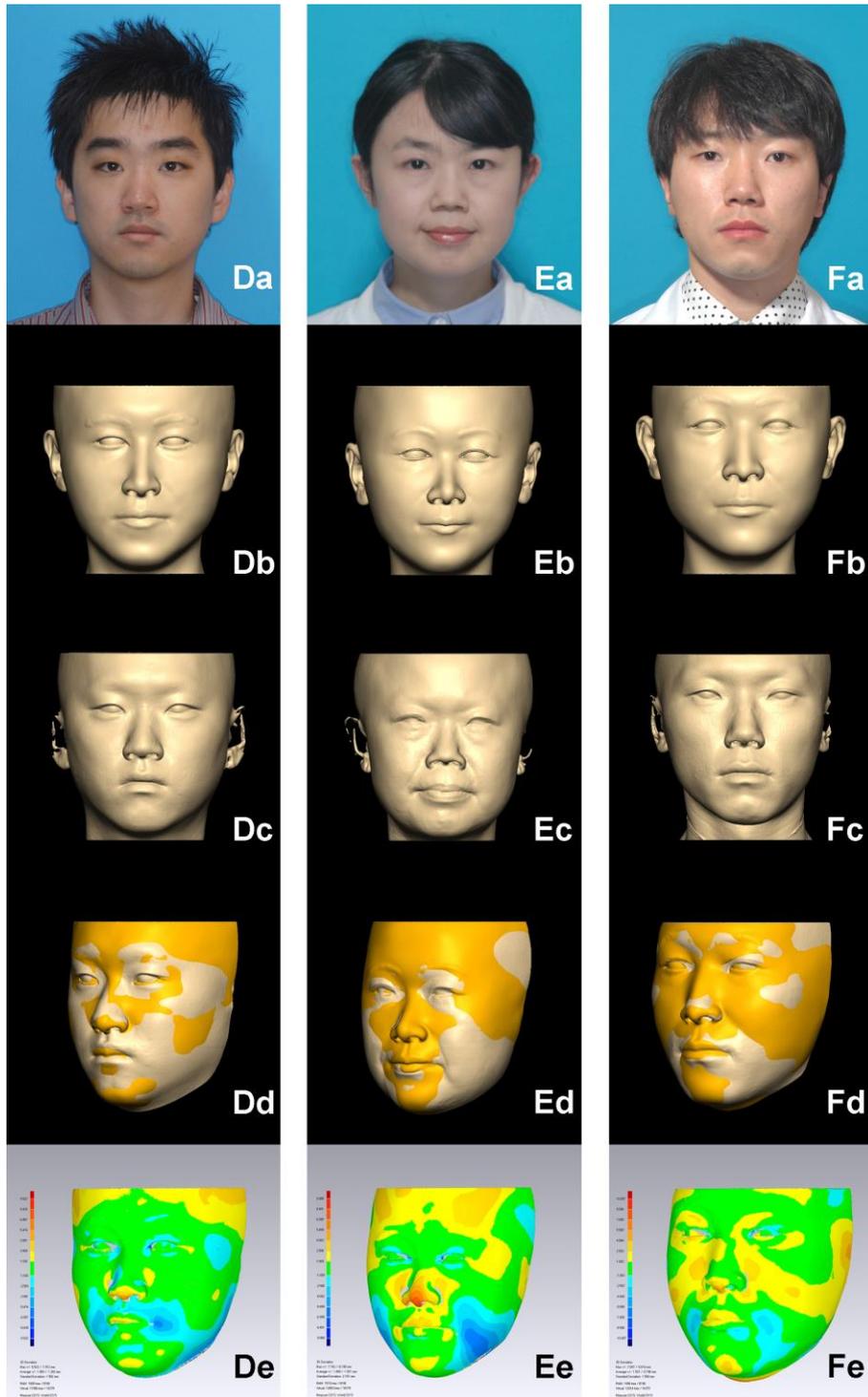


Figure 3. From the top row: Facial photographs of subjects D, E and F (Da, Ea and Fa), reconstructed faces (Db, Eb and Fb), scanned facial surfaces (Dc, Ec and Fc), alignments each of the facial reconstruction and corresponding scanned face (Dd, Ed and Fd; gold-coloured for the scanned faces, orange-coloured for the reconstructions), deviation maps (De, Ee and Fe).

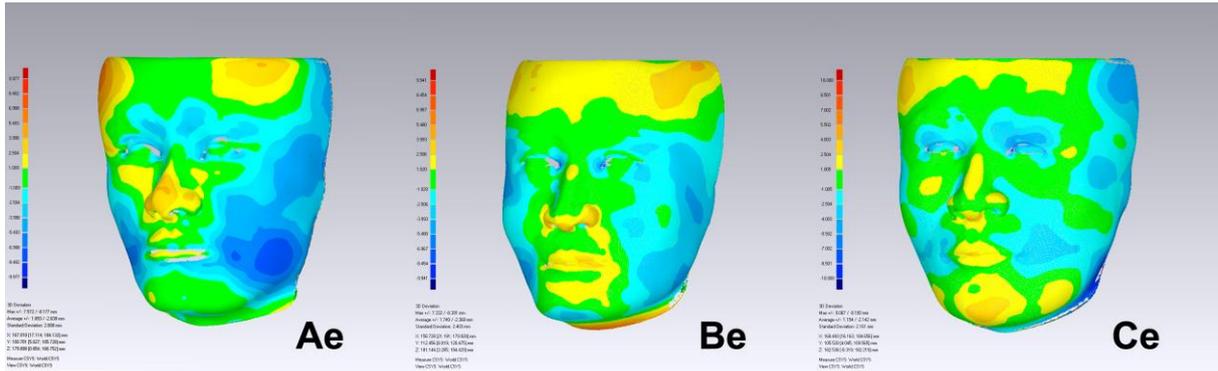


Figure 4. From left to right: deviation maps for subject A, B and C from the previous study (12).

Table 1. Average and standard deviation of the discrepancy between the facial surface of the FFR and corresponding subject.

Study	Previous study (Lee et al. 2012)			This study		
	A	B	C	D	E	F
Average (mm)	-0.47	-0.31	-0.49	-0.09	-0.18	0.37
Standard Deviation (mm)	2.808	2.403	2.161	1.580	2.094	1.501

Table 2. Distribution (%) of the deviation error between the surfaces of the reconstruction and the subject within each defined error range (minimum range within ± 2 mm).

Study	Previous study (Lee et al. 2012)			This study		
Subject	A	B	C	D	E	F
-10.0 \leq X < -5.0	10.12	2.24	4.59	0.30	2.33	0.01
-5.0 \leq X < -2.0	33.25	32.63	24.93	10.98	12.14	2.09
Deviation range -2.0 \leq X \leq 2.0	44.63	50.43	66.18	80.74	68.78	78.82
2.0 < X \leq 5.0	10.39	14.12	4.21	7.97	16.16	17.84
5.0 < X \leq 10.0	1.61	0.58	0.09	0.01	0.59	1.24
Total (%)	100	100	100	100	100	100

Table 3. Distribution (%) of the deviation error between the surfaces of the reconstruction and the subject within each defined range (minimum range within ± 2.5 mm).

Study	Previous study (Lee et al. 2012)			This study		
Subject	A	B	C	D	E	F
-10.0 \leq X < -5.0	10.12	2.24	4.59	0.30	2.33	0.01
-5.0 \leq X < -2.5	26.53	25.58	16.41	7.42	9.86	0.91
Deviation range -2.5 \leq X \leq 2.5	54.30	64.55	76.74	87.53	79.30	86.77
2.5 < X \leq 5.0	7.44	7.25	2.17	4.74	7.92	11.07
5.0 < X \leq 10.0	1.61	0.58	0.09	0.01	0.59	1.24
Total (%)	100	100	100	100	100	100