Computational Intelligence in Metric Analysis of the Skull in the Context of Maxillofacial Surgery

ALEŠ PROCHÁZKA1,2, (Life Senior Member, IEEE), TATJANA DOSTÁLOVÁ3,
OLDŘICH VYŠATA1,4, (Member, IEEE), PAVEL CEJNAR01,
VLADIMÍR MAŘÍK2, (Life Fellow, IEEE), AND HANA ELIÁŠOVÁ3

1Department of Computing and Control Engineering, University of Chemistry and Technology at Prague, 160 00 Prague, Czech Republic
2Czech Institute of Informatics, Robotics and Cybernetics, Czech Technical University in Prague, 160 00 Prague, Czech Republic
3Department of Stomatology, 2nd Medical Faculty, Charles University at Prague and Motol University Hospital, 150 06 Prague, Czech Republic
4Department of Neurology, Faculty of Medicine in Hradec Králové, Charles University at Prague, 500 05 Hradec Králové, Czech Republic

Corresponding author: Aleš Procházka (A.Prochazka@ieee.org)

This work was supported by the Development of Advanced Computational Algorithms for Evaluating Post-Surgery Rehabilitation under Project 00064203 (FN MOTOL) and Grant LTAIN19007.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethics Committee of the Charles University at Prague under Approval No. EK-973IGA 1.12/11, and performed in line with the Declaration of Helsinki.

ABSTRACT Anthropometric studies focusing on facial metrics and their proportions form an important research area devoted to observations of the appearance of the human skull. Many different applications include the use of craniometry for maxillofacial reconstruction and surgery. This paper explores the possibility of using selected craniometric points and associated metric to observe spatial changes during the maxillofacial surgery treatment. The experimental dataset includes observations of 27 individuals. The proposed method is associated with the processing of measurements by selected methods of signal processing and computational intelligence. The statistical results point to changes of facial measures before and after the maxillofacial surgery. The proposed method conclusively demonstrates that the area of the mean upper law triangle after surgical treatment is decreased by 8.5%, at the 5% significance level of the two-sample t-test. The classification of selected measurements by a neural network model reached an accuracy of 84.9%.

INDEX TERMS Craniometry, skull identification, maxillofacial surgery, computational intelligence, machine learning.

I. INTRODUCTION Anthropometric studies [1] form a research area devoted to observations of the appearance of the human skull. Facial measures, proportions, and symmetry [2], [3], [4] are very important in dentistry, orthodontics, plastic surgery, recognition of different diseases and their therapy, anthropological skull analysis [5], [6], and forensic identification [7]. An investigation of the mechanical properties of human skull bone and its geometry [8] form an associated research area. The dentofacial deformity, its early diagnosis [9], monitoring, and the following treatment are then closely related to the maxillofacial surgery [10], appropriate computational strategies, and clinical validations.

Specific methods applied in forensic anthropology and forensic medicine allow the identification of an individual by their skull [11] on the basis of craniofacial comparison and subsequent superposition [12] using the relation between the skull and the soft tissues of the face [13]. Similar research is related to the measurement of skull sizes, shapes, and skull triangles [14] for the proposal of a systematic method in archaeology and in studies of evolutionary development. Specific methods are used for the correlation of external skull landmarks, the identification of regions of the brain, and intracranial measurements [15], [16].

Data processing methods are based on the values obtained by standard measurement techniques including
The correction of the facial profile presenting the situation of selected measures and areas of the following triangles before and after the maxillofacial surgery:

- **A1**: ZyDx-ZySin-Subsp - the middle face area,
- **A2**: MxDx-MxSin-Subsp - the upper jaw area,
- **A3**: GoDx-GoSin-Pog - the lower jaw area.

The evaluation of maxillofacial surgery includes changes of selected measures and areas of the following triangles before and after the treatment:

- A1: ZyDx-ZySin-Subsp - the middle face area,
- A2: MxDx-MxSin-Subsp - the upper jaw area,
- A3: GoDx-GoSin-Pog - the lower jaw area.

The data processing goals are in the study of the effect of the maxillofacial surgery on selected measures. The observed measures have been processed by selected statistical methods, the two-sample *t*-test to detect the relation of specific features, and neural networks to test classification abilities for selected signal features.

The classification of selected features for the separation of measures before and after the maxillofacial surgery was performed by a two-layer neural network with sigmoidal and softmax transfer functions in the first and the second layer, respectively.

**III. RESULTS**

The visual monitoring of the treatment progress was combined with the application of computational intelligence for the assessment of data recorded by computed tomography. The correction of the facial profile presenting the situation of selected measures before and after the surgery to analyze the result of the treatment and to allow the study of the long-term stability. For each individual, pre-treatment and post-treatment cone beam computed tomography data were acquired. The mean age of the patients prior to treatment was 18–44 years. The timespan between pre- and post-treatment imagery ranged from 1 to 40 months. This study was conducted according to the recommendations of the American Dental Association (ADA). In accordance with the Declaration of Helsinki, patients were requested to provide informed consent to the clinical examination by means of an informed consent form. The anonymity of the data obtained was strictly respected.

Ethical approval for the study was obtained from the Ethics Committee (EK-973IGA 1.12/ 11).

The LeFort 1 osteotomy allows for the movement in all three planes and its monitoring needs analysis of specific facial locations. The position of the craniometric landmarks [13], [37] in the 3D model of the skulls before and after therapy were determined by the Invivo Anatomage software. All cone beam computed tomography examinations were indicated for surgical and orthodontic treatment.

Figure 1 presents the positions of selected craniometric landmarks used for further processing. They include:

- Pogonion (Pog) – the most anterior point on the mandible in the midline,
- Gonion (Go) – the outer point on either side of the lower jaw at which the jawbone angles upwar,
- Maxilla (Mx) – the closest points on the lateral contour of the maxilla,
- Subspinale (Subsp) – the deepest anterior point in the concavity of the maxilla,
- Zygion (Zy) - the most lateral point on the contour of each zygomatic arch.

The evaluation of maxillofacial surgery includes changes of selected measures and areas of the following triangles before and after the treatment:
FIGURE 2. The correction of the facial profile presenting the situation before and after the treatment of a selected individual with orthognathic surgery results for LeFort 1 technique allowing maxilla movement forward.

TABLE 1. Selected measurements between cranometric landmarks on the skull before (A) and after (B) the surgery for a selected individual for 10 experiments with their mean values (Mean), standard deviations (STD), and their differences (D).

| Distance       | A    | B    | D    | A    | B    | D    |
|----------------|------|------|------|------|------|------|
| D1:ZyDx-ZySin | 128.2| 127.9| 0.3  | 0.5  | 0.4  | 0.1  |
| D2:MxDx-MxSin | 63.1 | 62.0 | 1.1  | 0.8  | 0.5  | 0.3  |
| D3:GoDx-GoSin | 89.8 | 90.1 | -0.3 | 0.5  | 0.3  | 0.2  |

FIGURE 3. The main skull distances of one individual presenting repeated observations of (a) D1:ZyDx-ZySin, (b) D2:MxDx-MxSin, (c) D3:GoDx-GoSin, and (d) D4:Subsp-Pog measures with their mean values and multiples of standard deviations before and after the surgery.

Repeating observations of D1:ZyDx-ZySin, D2:MxDx-MxSin, D3:GoDx-GoSin, and D4:Subsp-Pog on the skull were analysed at first. Table 1 presents statistics of these measures before and after the maxillofacial surgery for a selected individual and 10 experiments with their mean values, standard deviations, and their differences. Figure 3 presents the distributions of these observations with their mean values during the dental, orthodontic, and maxillofacial treatment.

Mean distances acquired before and after the surgery for the set of 15 males and 12 females were studied in the following step. Figure 4 presents the fundamental evaluations of the results including the distances D1:ZyDx-ZySin and D2:MxDx-MxSin after the surgery vs. these distances before the treatment.

The pair comparison of selected distances with their mean values and c multiples of standard deviation for c = 0.5, 1, 2 before and after the maxillofacial surgery is presented in Figure 5.

Figure 6 presents the areas of triangles A3:GoDx-GoSin-Pog vs. A2:MxDx-MxSin-Subsp and in the facial region before and after the surgery with the mean values for 15 males and 12 females before and after the maxillofacial surgery. The two-sample t-test was evaluated to test the decision for the null hypothesis that the data of the triangle area for males and females comes from independent random samples with
equal means. This hypothesis was accepted for triangles A2 and A3 and rejected for triangle A1 at the 5% significance level both for the initial and final area.

Selected measures between craniometric landmarks before and after the maxillofacial surgery for 27 individuals are presented in Table 2 together with their mean values and standard deviations.

**Table 2.** Selected measures between craniometric landmarks before and after the maxillofacial surgery for 27 individuals with their mean values (Mean) and standard deviations (STD).

| Distance | Initial Mean (STD) | Final Mean (STD) |
|----------|--------------------|------------------|
| D1: ZyDx-ZySin | 123.8 (6.7) | 123.8 (6.7) |
| D2: MxDx-MxSin | 60.7 (3.8) | 60.8 (3.9) |
| D3: GoDx-GoSin | 93.9 (6.2) | 96.5 (6.5) |

Table 3 presents the area S and standard deviation (STD) of the three main triangles in the facial region for 15 males and 12 females before and after the surgery for triangles A1:ZyDx-ZySin-Subsp, A2:MxDx-MxSin-Subsp, and A3:GoDx-GoSin-Pog. Figure 7 presents the changes in the areas of these triangles in the facial region before and after maxillofacial surgery, not taking gender into account. The two-sample t-test was evaluated to test the decision for the null hypothesis that the data of the areas of the triangles before and after maxillofacial surgery come from independent random samples with equal means. This hypothesis is accepted only for triangle A2, at the 5% significance level.

The areas of the second and the third triangles were used as features for the classification of skull measures before and after maxillofacial surgery. The results of the classification by the support vector machine (SVM) and the two-layer neural network neural network with 10 neurons in the first layer are presented in Fig. 8 together with the class boundaries. Table 4 presents the classification results of selected methods with the highest accuracy of 84.9% (in bold) and the 10-fold cross-validation error of 0.17 achieved by the neural network method.

The complete dataset is stored at the IEEE DataPort (https://dx.doi.org/10.21227/n78r-xd27) for further investigation. This repository includes also the Matlab 2022b (MathWorks, Massachusetts, USA) source code for data analysis before and after the treatment.

**IV. DISCUSSION**

Facial appearance and facial features are traditionally employed in orthodontic, maxillofacial treatment plans, and...
TABLE 4. Accuracy (ACC) and cross-validation errors (CV) for the classification of craniometric data into two classes by the support vector machine (SVM), Bayesian method, three-nearest neighbour method, and two-layer NN.

| Method           | ACC [%] | CV   |
|------------------|---------|------|
| SVM method       | 81.1    | 0.264|
| Bayesian method  | 71.7    | 0.377|
| 3-nearest neighbour | 74.7    | 0.358|
| 2-layer NN       | 84.9    | 0.170|

spatial therapy image tasks. The results can establish a person’s new appearance based on an examination of craniofacial traits. The proposed therapy must be based on sound scientific principles to yield accurate and reliable results.

This paper investigates the influence of maxillofacial surgery on specific anthropological skull measures for 27 patients with dentoalveolar deformities: hypoplasia of the upper jaw, hypoplasia of the lower jaw, or both. LeFort I osteotomy (horizontal maxillary fracture, separating the teeth from the upper face) was used for correction of those midface deformities.

Evaluation of computed tomography and analysis of measures between craniometric landmarks include the following results for the given set of patients:

- The distribution of observation measurement errors presented in Fig. 3 that occur during repeated measurements of a single individual,
- Changes of mean skull measures before and after the surgery presented in Table 1 that point to: (i) a reduction of $D1:ZyDx-ZySin$ by 0.3 mm, (ii) a reduction of $D2:MxDx-MxSin$ by 0.1 mm, (iii) an increase of $D3:GoDx-GoSin$ by 0.3 mm. The trend of these changes is confirmed by 27 individuals as presented in Table 2,
- Standard deviations of selected measures presented in Table 1 that point to a reduction of their mean values evaluated before and after the surgery by 0.2 mm in average,
- The effect of the maxillofacial surgery on the main triangular areas in the skull presented in Fig. 1 with similar results of the treatment both for the set of males and females showing that (i) area A1 is slightly enlarged, (ii) area A2 is reduced, (iii) area A3 is enlarged (as presented in Fig. 6 and Table 3),
- The comparison of areas A3 vs. A2 showing that mean values for females are lower than for males both before and after the treatment as presented in Fig. 6,
- The possibility of classification of skull measures affected by maxillofacial surgery using machine learning tools as presented in Fig. 8.

While distances between craniometric landmarks are studied in different papers [38], [39], the present study includes the analysis of additional features estimated as selected triangular facial areas. Results point to differences of these measures for males and females during the treatment. The most significant difference was observed for triangle A2:MxDx-MxSin-Subsp in the given set of patients.

The classification of skull measures before and after maxillofacial surgery by the two-layer neural network model was achieved with an accuracy of 84.9%. A slightly lower classification accuracy was achieved by the support vector machine (81.1%), the 3-nearest neighbours method (77.4%), and a Bayesian classification method (71.7%).

V. CONCLUSION

The paper forms a contribution to the increasing role of the computational intelligence and visualization tools in surgery. The direct consequence of the very fast technological progress is the more extensive use of the three-dimensional treatment planning with 3D reconstruction, especially in connection with 3D printing and experimental robotic-assisted surgery [40], [41].

It is expected that further research will be devoted to the evaluation of facial measures for more extensive datasets, different types of maxillofacial surgery, and to the use of deep learning methods for more complex analysis of skull shapes to contribute to the multidisciplinary area of biomedical engineering.

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OLDŘICH VYŠATA (Member, IEEE) received the M.D. and Ph.D. degrees in technical cybernetics from the Institute of Chemical Technology in Prague, Czech Republic, in 1985 and 2011, respectively. He is currently a member of the Digital Signal and Image Processing Research Group, Department of Computing and Control Engineering, UCT Prague, the European Neurological Society, the Czech Society of Clinical Neurophysiology, the Czech League Against Epilepsy, and the Czech Medical Association of J. E. Purkyně. He is oriented toward computational medicine, analysis of motion disorders, and machine learning. He is also associated with the Neurological Department, University Hospital, Charles University at Hradec Králové, Czech Republic. He serves as a reviewer for different Springer, Elsevier, and MDPI journals.

PAVEL CEJNAR received the M.S. degree in computer science, in 2004, an extension of the M.S. degree in theoretical computer science, in 2009, the B.S. degree in food chemistry and technology, in 2010, and the Ph.D. degree in plant protection (biochemical methods), in 2021. He is currently a member of the Digital Signal and Image Processing Research Group, Department of Computing and Control Engineering, UCT Prague. His research interests include multidimensional statistical analysis, data processing with the support of artificial intelligence methods, algorithmic optimization and parallelization, complex search methods, and advanced signal processing with a focus on data from biochemistry and medicine. He is a reviewer of Springer, Elsevier, and MDPI journals.

VLADIMÍR MAŘÍK (Life Fellow, IEEE) received the M.Sc. and Ph.D. degrees in control engineering from the Czech Technical University in Prague. He is currently the Scientific Director with the Czech Institute of Informatics, Robotics and Cybernetics, Czech Technical University in Prague, and the Head of the Intelligent Systems Research Group with a focus on artificial intelligence, machine learning, large-scale parallel computations, distributed multiagent systems, and theories of complex problems. His research interests include devoted to soft-computing, dynamic optimizations, environmental informatics, and computer-integrated manufacturing. Applications include the development of smart cities, proposals of intelligent transportation systems, and implementation of advanced systems for education.

HANA ELIÁŠOVÁ received the RNDr. and Ph.D. degrees. She is currently a Doctor of Natural Sciences and Forensic Expert in the field of forensic anthropology. She also works as an External Pedagogue at Charles University in Prague and Masaryk University, Brno. She publishes in professional journals and forensic book publications. She actively participates at international conferences. Her scientific research interests include anthropological identification of human remains, forensic odontology, portrait identification, and trichology. She has received awards for presentations in the field of forensic anthropology. She has also received the prize of the Director of the Institute of Criminalistics for expert and research activities and the Minister of the Interior for extraordinary results in the field of security research.

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