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ACCURACY ASSESSMENT OF SHAPE MAPPING USING COMPUTER TOMOGRAPHY

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Abstract

Diagnosis and therapy of human diseases is often associated with an analysis of the geometry of internal organs or their pathological conditions. That is why the problem of accuracy assessment of shape mapping using computer tomography and the latest imaging techniques became very important. Therefore, in the paper the accuracy assessment of mapping was proposed using the real shape of the synthetic indices. Two test cases were presented – a reference sphere and the cartilage surface of the knee condyle. The results of tomography research and analysis of accuracy of shape mapping using the "best fit" method and the program Reshaper, in the form of synthetic indicators are presented.

1. Introduction

Computer tomography is one of the latest techniques of diagnostic and therapeutic mapping, and is particularly important because of the increasingly common use of this method in medical and technical applications. It allows not only an assessment of external surface geometry, but also the penetration into the internal structure of the test organ.

The problem of the accuracy assessment of shape mapping of bioelements, particularly cartilages and bone tissues and their internal structures is extremely important. Scientists are fascinated by this problem for many years, in various fields. Recent mapping techniques such as spiral computer tomography (STK) and magnetic resonance (MR) solve that problem partially, but still geometry designation creates many problems. These techniques do not allow, at a specified measurement uncertainty, the simultaneous appointment of the geometry of bone and cartilage structures in the whole research area. This issue is particularly important for assessment of the size and diagnosis with osteoarthritis.

Hypothesis may be that the provision of shape mapping of the joint surfaces with sufficient accuracy, allows for evaluation of a small loss of cartilage, chondromalacia, and for designation of the spatial shape of the buccal cartilage and assessment of its impact on the operating conditions of the biobearing.

In technical applications computer tomography allows to control not only the geometrical parameters of products, but also allows to penetrate into the interior of the test object and to evaluate its internal structures [1, 5].

Therefore, the accuracy assessment of shape mapping using the methods of spiral computer tomography (STK) and magnetic resonance imaging (MRI) is so essential [8, 9].

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2. Assessment of shape mapping

The accuracy assessment of shape mapping using synthetic indicators, which are the functional combination of the errors of selected groups of evaluated device or characteristic points, was proposed.

Error values were determined as the difference between the vectors defining the location of characteristic points of the artifact and the resulting model in the adopted reference system. In the case of determining the accuracy of the mapping of working surfaces of joints using STK or MRI, which in principle are the areas of irregular shape, an algorithm procedure was developed which allows for a direct comparison of a 3D image of the test area and the numerical model (where there is a mathematical description) or negative model obtained from other measurement techniques. The main units of the system are blocks: blocks of visualization and data collection and blocks of analysis of vector error comparison [5].

The block of visualization allows to record the measurement or production process during which the measurements were carried out. In the case of using a measuring instrument that has no interface to enable direct cooperation with a computer, the block provides the function of direct recording of the measurements.

The block of analysis is intended to perform a statistical evaluation of measurement results, to develop a matrix characteristic of the breakdown dominant, influential and complementary characteristics, to develop a matrix of deviations of controlled parameters, to determine the functional dependence between the dominant characteristics and to define synthetic indices incorporating the selected properties of products and their graphical or tabular presentation.

For purposes of analysis the following assumptions were adopted:

$$\mathbf{A} = \{A_{i,} \quad i = 1,2,\ldots n\}, \tag{1}$$

where:

- **A** – means the controlled device;
- $A_1, A_2, A_3, \quad A_n$, – mean the units or components of the controlled device.

$$\mathbf{U(A)} = \{U_j, \quad j = 1,2,\ldots k\}, \tag{2}$$

where: **U(A)** mean the properties of the individual teams of device **A** due to the characteristic U_j.

Based on these assumptions, sets of technical and performance characteristics of the device (product) A can be specified, composed of teams A_i $(1\ldots n)$, for different properties or characteristics of the criteria resulting from the characteristics **U** expressed by the characteristics U_j $(1\ldots k)$.

$$\mathbf{U}(\mathrm{A_i}) = \{U_j, (A_i), \quad j = 1,2,\ldots k\}, \tag{3}$$

where: $U_j, (A_i)$ is the state of the team A_i due to the property U_j.

Analyzing the devices **A** consisting of teams A_i, with properties U_j, the characteristics describing all the teams and features can be can be written as:

$$\begin{array}{cccc}
U_1, (A_1), & U_2, (A_1), & U_j, (A_1), & U_k, (A_1), \\
U_1, (A_2), & U_2, (A_2), & U_j, (A_2), & U_k, (A_2), \\
. & . & . & \\
U_1, (A_i), & U_2, (A_i), & U_j, (A_i), & U_k, (A_i), \\
. & . & . & . \\
U_1, (A_n), & U_2, (A_n), & U_j, (A_n), & U_k, (A_n),
\end{array} \tag{4}$$

Each row of this matrix corresponds to a specific group of A_i and each column corresponds to the specific characteristics of U_j.

Properties of individual groups should meet the criteria established by the constructor K_r:

$$\mathbf{K(A)} = \{K_r, (A_i), \quad r = 1,2,\ldots m\} \tag{5}$$

and the whole device main criterion **K(A)**.

It can therefore be concluded that the whole device **A,** meeting the criteria **K**, will have certain properties **G** :

$$\mathbf{G(K,A)} = \{G_d, G_s, \quad s = 1,2 \quad r\}, \tag{6}$$

where:

- G_d – is the dominant feature of the device **A**;
- G_s – are the analyzed characteristics of the device **A**.

It was found that the entire unit will have established characteristics where the properties **G(K,A)** are satisfied and if there is an appropriate relationship between the properties **U**(A) of different teams of device, and the characteristics **G(K,A)** of the device, which was adopted to save as:

$$\mathbf{W} = \mathbf{U}(A) \;\; F(Q) \;\; \mathbf{G(K,A)}, \tag{7}$$

where: $F(Q)$ is the relation between the properties **U**(A) of individual teams of device and the characteristics **G(K,A)** of the device to meet the performance characteristics of Q.

Record (7) "W" was defined as a synthetic indicator describing the degree of compliance by the device **A** performance characteristics of a **Q** determining the degree of precision mapping of the shape [4, 5].

For the diagnosis of internal organs such an approach to the description of measurement error allows to take into account the anisotropy of matter.

3. Analysis of the accuracy of shape mapping using ceramic balls

The analysis of accuracy of the shape mapping using helical computer tomography (CT, parameters: P-pitch factor = 1, SC-slice collimation = 0.6) was performed for two cases: based on a ceramic reference ball (Fig. 1) and the natural artifact – the knee joint (Fig.11).

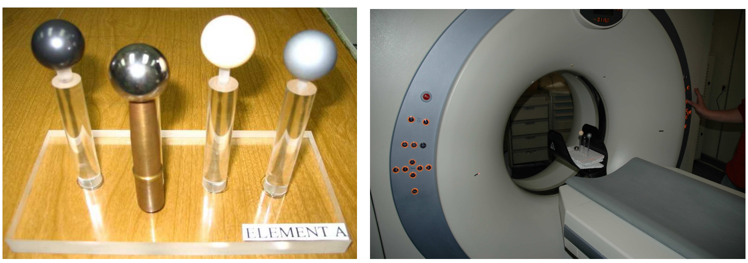

Fig. 1. Reference balls and their test using computer tomography.

Measurement strategy included a series of 3 cycles of measurement, and for balls in addition to the two perpendicular orientations.

In the case of reference balls, measurements were performed on the CT (Fig. 1). The accuracy assessment of the shape mapping of the sphere was carried out based on the ball numerical artifact [2, 5, 7, 8].

In the case of a natural artifact, measurements were performed on a Siemens tomograph and on the coordinate measuring machine (CMM). In the accuracy assessment of the mapping of a knee joint using the technique of CT, a reference element was developed on the basis of the results of measurements performed on the CMM [MPE = (0.8 x l/400)um]. The results of tomography research and analysis of accuracy of the shape mapping were obtained using the "best fit" method and the program 3D Reshaper. The measurement results were presented as: the mapping deviations of the surface of a ceramic reference ball resulting from the errors of measurement performed by computer tomography in the side view in Figs 2 and 3, the mapping deviations of the surface of a ceramic reference ball resulting from the errors of measurement of the radius performed by computer tomography – a view in the polar axis of the CT computer and a mapping deviation of the surface of ceramic reference ball resulting from the errors of measurement performed on computer tomography (Fig. 4). A wavy surface on the 3D model was obtained in the vicinity of the pole CT (Fig. 5).

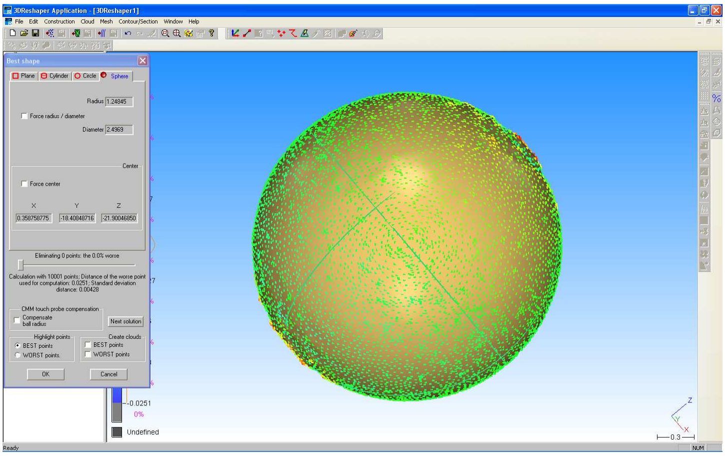

Fig. 2. Mapping deviations of the surface of a ceramic reference ball resulting from the errors of measurement performed on computer tomography in the side view.

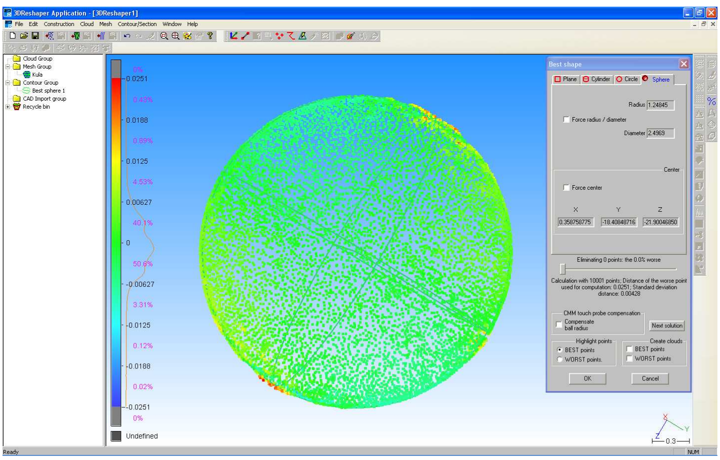

Fig. 3. Mapping deviations of the surface of a ceramic reference ball resulting from the errors of measurement performed on computer tomography in the transparent view.

Fig. 6 is the histogram of the distribution of errors of radius measurements of ceramic reference balls resulting from measurement on CT.

The map of the distribution of measurement points and their distance from the equatorial plane of the reference ball is shown in Fig. 7.

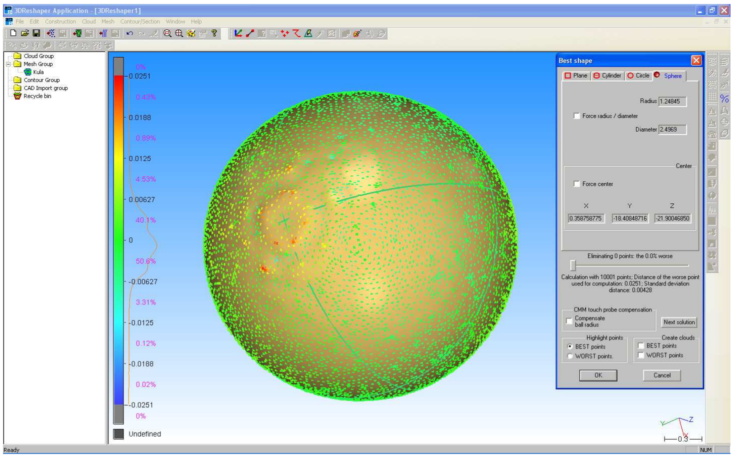

Fig. 4. Mapping deviations of the surface of a ceramic reference ball resulting from the errors of measurement of the radius performed on computer tomography – a view in the polar axis of the CT.

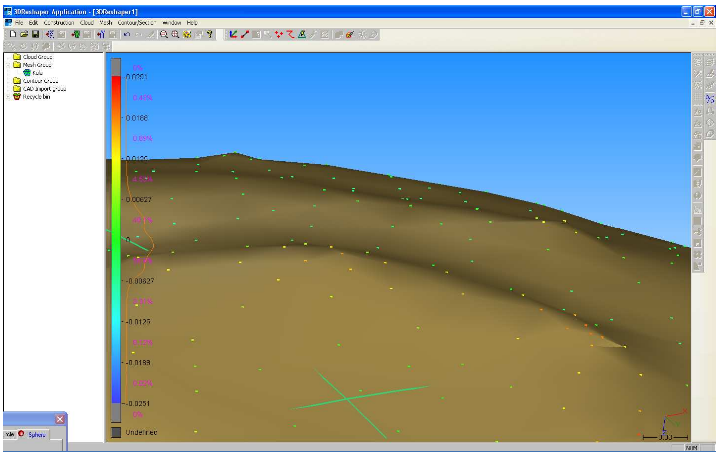

Fig. 5. Wavy surface on the 3D model in the vicinity of the pole CT.

The histogram of errors of the radius measurements of the reference ball was based on 10,000 measurements. The studies allow the conclusion that for 90.7% of the results the error of radius measurement of the ball using CT is located in the range of ± 0.063mm, and for 98.5% falls within ± 0.125mm. The standard deviation is 0.0428mm and the average value of the ball diameter is 24.969mm.

Based on the map of distribution of the measurement points and their distance from the equator plane of the reference ball (Fig. 7) and the histogram of the distribution of the measurement results of the distance of measurement points from the plane of the equator (Fig. 8) an asymmetric distribution of the errors in the upper and lower sphere of the balls was found.

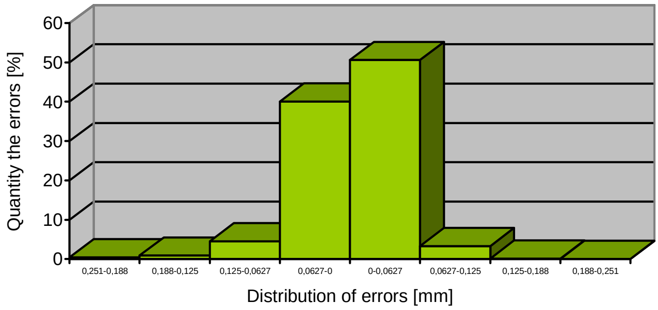

Fig. 6. Histogram of the distribution of errors of the radius measurements of ceramic reference balls resulting from measurement on CT.

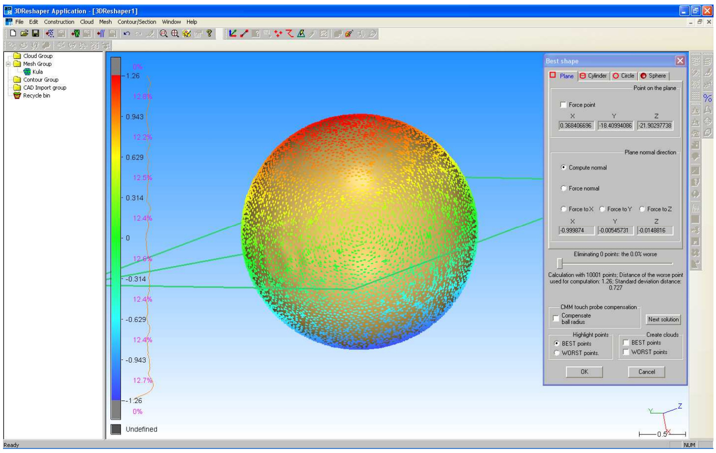

Fig. 7. Map of the distribution of measurement points and their distance from the equatorial plane of the reference ball as the result of measurement on CT.

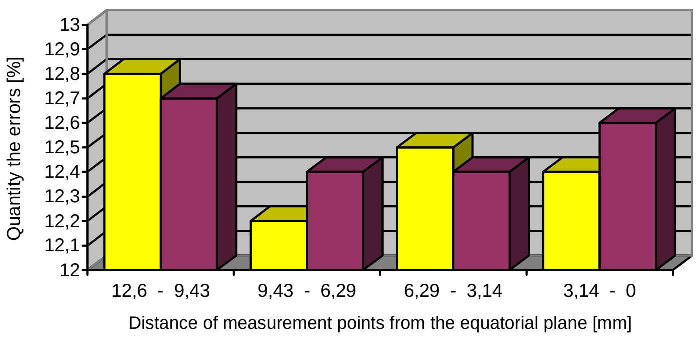

Fig. 8. Histogram of the distribution of the measuring results on CT at some distance of measurement points from the equatorial plane.

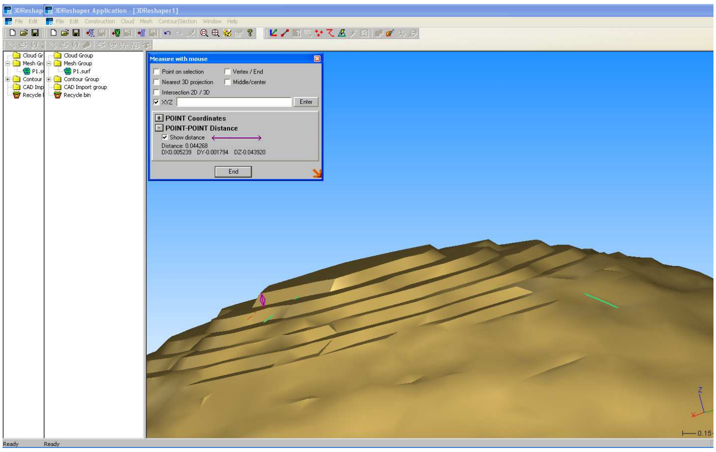

Fig. 9. Tomography poles in the resulting 3D model of the reference ball.

Image analysis of CT poles demonstrates the distortions of the ball surface resulting from a change in the angle of the ball surface with the scanning plane (Fig. 9), with the possibility of determining the width of the scan.

4. Analysis of the accuracy of shape mapping of the surface of cartilaginous knuckle of a knee joint

In analyzing the accuracy assessment of the surface mapping of CT diagnosis, it was found that the best research strategy should take into account natural phantoms devoted to tomographic diagnosis. Therefore it was decided to undertake a study of the natural shape of the knee, taking the surfaces of the knee condyles as a model to study. Due to the specific nature of the research and the lack of numerical description of the area, a slightly different research strategy was planned, which included:

- determination of the research area;
- determination of a reference 3D model (scatter and surface) of the studied area based on the results obtained from studies on a coordinate measuring machine (CMM);
- tomographic sequential and spiral studies;
- creation of a 3D model based on CT research results;
- creation of a solid model of a stretch of knee.

Accuracy assessment of shape mapping of articular surfaces of the knee consisted of comparing the reference 3D model with the solid model and determining the mismatch deviations using the “best fit” method. In this work the software Amira, 3D Reshaper and an authoring program were used, which allows the creation of point clouds and surfaces of the CT scans.

In Fig. 10 results are presented of measurements on the CMM in the form of the points being control lines and the created surface representing the reference 3D model of the knee condyles.

Having the artifact shape, measurements of the condyles were initiated with the use of CT [4]. Based on CT scans, a solid model was developed, and then the created model of knee condyles was presented in the Amira program (Fig. 11) in order to verify the possibility of its further processing *e.g.* in the Femap ANSYS program.

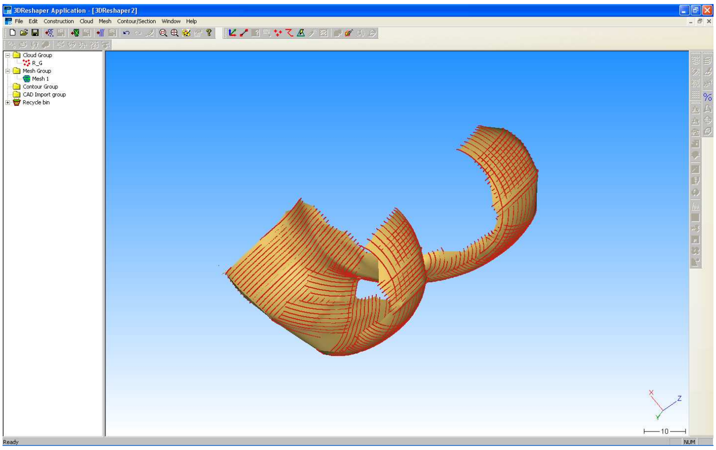

Fig. 10. Measuring points performed on the CMM and the surface of knee condyles.

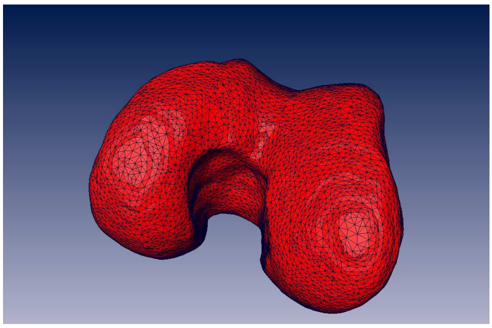

Fig. 11. Surface of the knee divided into parts according to the method of finite from the Amir program received from the results of tests on CT.

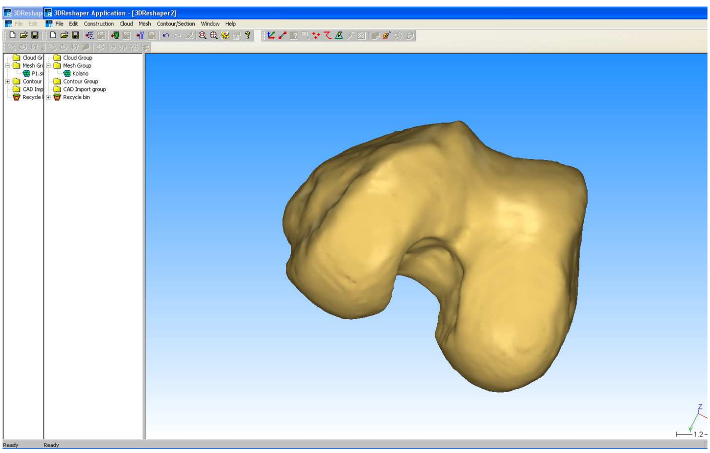

Fig. 12. Model of the knee-joint obtained on the basis of studies on CT from the 3D Reshaper program.

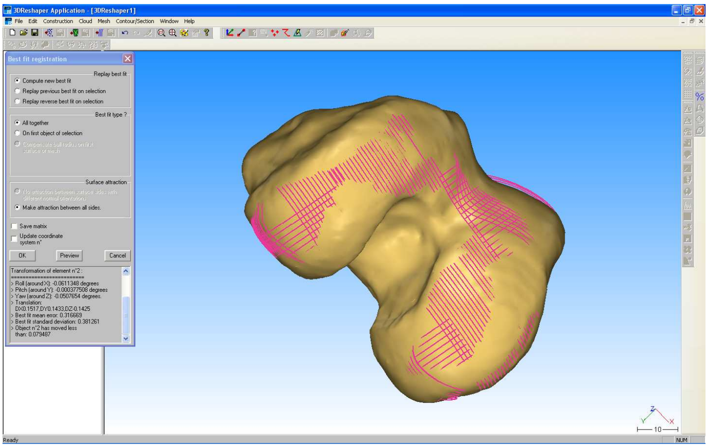

Fig. 13. Knee-joint - the imposition of measuring points from CMM on the surface obtained from measurements on CT using the "best fit" method.

a) b)

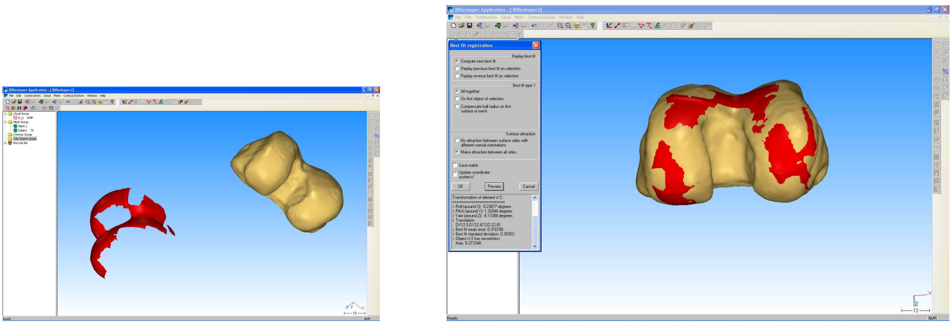

Fig. 14. Accuracy analysis of the of surface mapping of the knee condyles: a) reference surface model (left), model from CT test (right side); b) the results of the imposition of the model and artifact.

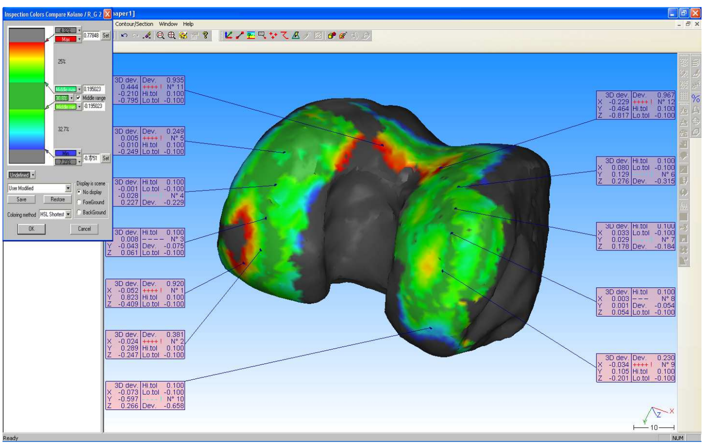

Fig. 15. Knee-joint – the map of deviations of shape mapping as the comparison of the imposition of the surface derived from the CT studies with the surface obtained from studies on CMM.

At the same time on the basis of the CT scans, the solid model of knee condyles was developed in the 3D Reshaper program (Fig. 12).

Accuracy assessment of the actual shape mapping of the knee condyles diagnosed by the CT technique was carried out by numerical comparison of scans obtained on the basis of CT of a 3D model with the spatial reference model derived from studies on a CMM [5].

Fig. 13 presents a comparison of the surface shape of the knee condyles obtained from CT studies with the model reference point, using the best fit.

Fig. 14 shows the mismatch results related to the reference surface.

The map of accuracy deviations of shape mapping on CT is shown in Fig. 15. It was found that 80% of the deviation of the mismatch does not exceed ± 0.5mm. Maximum values (up to ± 3 mm) occurred in the area of the junction of both surfaces of condyles and on the tips of the condyles.

There were positive deviations (65%) and negative (35%).

5. Conclusions

The developed procedure allows the evaluation of devices based on CT and to determine the quality of the entire device based on the dominant parameters or characteristics with respect to their function or according to some groups. At the same time the system can be used to compare the number of functionally similar devices from the perspective of selected properties or performance characteristics.

Determination of synthetic indicators allows the designation of the influence of selected parameters (geometric or kinematic) on the analyzed characteristics of utility.

The system has a modular construction, it can work with any measuring device equipped with an interface allowing data transfer to computer control and evaluate the device. The block of visualization and monitoring allows continuous tracking of the diagnostic process, including the measuring process. The studies carried out using reference ceramic balls and the knee allowed to designate the overall error of radius measurement of the ball and the accuracy of shape mapping of the selected area of the knee.

Acknowledgements

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References

[1] G. Bentley, T. Minas: "Treating joint damage in young people – Science, Medicine and the Future – Statistical Data Included". *British Medical Journal*, no. 6, 2000, pp. 311–312.

[2] T. Flohr *et al.*: "Perfofmance evoluation of a 64 slice CT system with z-flying focal spot". *Fortschr. Rbntgenstr*, no. 176, 2004, pp. 1803–1820.

[3] M. Hofer: *Teaching Manual of color duplex tomography*. 2nd ed., Tieme, New York 2004.

[4] A. Ryniewicz: *Analiza dokładności odwzorowania kształtu powierzchni roboczych biołożysk z zastosowaniem wzorców przestrzennych i modeli odwrotnych*. Projekt badawczy KBN, no. 4083/B/T02/2008/34, 2008–2010. (in Polish)

[5] A. Ryniewicz: "Traceability needs for geometrical identification of form of biobearing working surface and defect of joint cartilage". *Elesevier Measurement*, vol. 42, no.10, 2009, pp. 1463–1469.

[6] J. Sładek: "Modelowanie i ocena dokładności maszyn oraz pomiarów współrzędno-ściowych". *Zeszyty Naukowe MECHANIKA*, Politechnika Krakowska, no. 87, 2001. (in Polish)

[7] Genauigkeit von Koordinatenmessgeräten Kenngrößen und deren PrüfungLeitfaden zur Anwendung von DIN EN ISO 10360 für Koordinatenmessgeräte mit CT-SensorenVDI/VDE 2617 Blatt 13.

[8] Computertomografie in der dimensionellen Messtechnik Leitfaden zur Anwendung von DIN EN ISO 10360 für Koordinatenmessgeräte mit CT-SensorenVDI/VDE 2630 Blatt 1.3.

[9] M. Bartscher, U. Hilpert, J. Goebbels, G. Weidemann: "Enhancement and Proof of Accuracy of Industrial Computed Tomography (CT) Measurements – CIRP". *Annals – Manufacturing Technology*, vol. 56, no. 1, 2007, pp. 495–498.