ISSN 1392 - 1207. MECHANIKA. 2012 Volume 18(4): 447-452

Numerical modelling of human masticatory organ kinematics

D. Gąska*, E. Kijak, T. Lipski***, J. Margielewicz******
**Silesian University of Technology, Krasińskiego 8,40-019 Katowice, Poland, E-mail: damian.gaska@polsl.pl*
***Pomeranian Medical University, Rybacka 1, 70-204 Szczecin, Poland*
****Medical University of Silesia, Poniatowskiego 15, 40-055 Katowice, Poland*
*****Silesian University of Technology, Krasińskiego 8,40-019 Katowice, Poland, E-mail: jerzy.margielewicz@polsl.pl*

crossref http://dx.doi.org/10.5755/j01.mech.18.4.2327

1. Introduction

Application of mechanics during motion analysis of living organisms led to the development of a new branch of science called biomechanics. Answering how the organisms move demands a multidisciplinary approach and knowledge of mechanics, anatomy and physiology. Biomechanics area of interest is very broad and includes mechanical effects on the body and biomechanical analysis of the phenomena associated with its physical activity. In general, the biomechanics is divided into: clinical biomechanics, sport biomechanics and engineering biomechanics [1-3]. In view of the division relied on biomechanics, this work should be counted among the clinical biomechanics of the masticatory organ. Modern dentistry for the evaluation of masticatory organ uses a variety of diagnostic techniques such as radiography, computed tomography, magnetic resonance imaging, electromyography, and a whole set of methods to study masticatory muscles. These methods, beyond the undeniable advantages, have also defined limits, which could for example include: the possibility of tangential visualization of morphological structures, are invasive and cumbersome for the patient. The diagnosis formulated on the basis of clinical studies and information provided by the patient during his medical history, is the result of subjective doctors judgment, which is significantly influenced by experience and intuition. To eliminate subjective judgments, new methods, that provide the dentist objective and new qualitative and quantitative information about the real state of the patient's masticatory organ are looked for. Complete view of the states, and biomechanical conditions of masticatory organ function, are possible to be obtained, thanks to the application of modeling studies. Biomechanical models that depict the changes occuring during movement of the mandible [4-9], provide an indication of the causes responsible for the masticatory organ dysfunctions. In this place it should be made clear that a biomechanical model's formulated also with a view to increasing knowledge, explains or predicts new events in a way that is faster, cheaper and safer for the patient. One of the basic studies of masticatory organ is the mandible kinematic analysis, which is responsible for the strict mathematical representation of the mandible and masticatory muscles movement system. Such studies enable understanding biomechanisms responsible for the conduct of events occurring within the masticatory organ. There are in literature publications related to the masticatory organ kinematics, but their results have not been validated with clinical trials [2]. In addition, the use of averaged models, in terms of diagnosis masticatory organ dysfunction, is simply unacceptable.

This paper presents a model of the mandible kinematics, on the base of which it is possible to precisely determine the moments of time, where movement disorders appear. Basis for identification of the time moments in which the mandible movement is disturbed are kinematic values, which are obtained as a result of solving the inverse kinematics problem [10]. On the basis of numerically calculated kinematic values mapping the mandible movement the spatial amplitude-frequency spectrums (STFT) are still determined [1].

A characteristic feature of the spatial spectra is that at the time of the mandible movement disorders, an increase of harmonics amplitude is shown. Frequency analysis in clinical masticatory organs diagnosis have been so far used only to evaluate the acoustic effects occurring within the temporomandibular joints [11-13], and for this reason it is advisable and reasonable to undertake the work associated with their analysis in the frequency domain. It should be mentioned that the frequency analysis shows a high effectiveness in identifying defects of working machines, so you can ask why not to use proven in technique methodology, to identify the masticatory organ disorders. The results of modeling studies were carried out on the recorded measurement data, which were performed in Pomeranian Medical University.

2. Formulation of spatial model of the mandible kinematics

In computer simulations of the human body, in mathematical description of its motion, kinematic chains with open structure are commonly used. In general, movement of the biomechanism that maps masticatory organ function can be modeled using any number of variables. At the same time as in the case of technical systems, location and orientation of the organisms is being described in terms of stationary reference frame. From a mechanical point of view the kinematics equations define the orientation and position in any moments of time. Therefore, for exact description, it is necessary to introduce a useful mathematical tools, which should be characterized by the efficiency of numerical calculations.

From a theoretical point of view kinematics of masticatory organ can be considered in two ways. The first is to calculate the trajectories of selected points with given coordinates of the mandible configuration, such an approach is called an easy task of kinematics. Inverse problem of kinematics is to calculate the configuration coordinates for the registered motion trajectory of the mandible.

Regardless of which task of kinematics is the aim of model researches, it must have a properly defined kinematic chain.

In this paper, a spatial model of the mandible was built using open kinematic chain with a configuration variable in time and 6 degrees of freedom (Fig. 1). In the adopted numerical research model, three coordinates define the orientation of the mandible (φ_3, φ_4, φ_5), the other three image lifting motion (q, φ_1, φ_2).

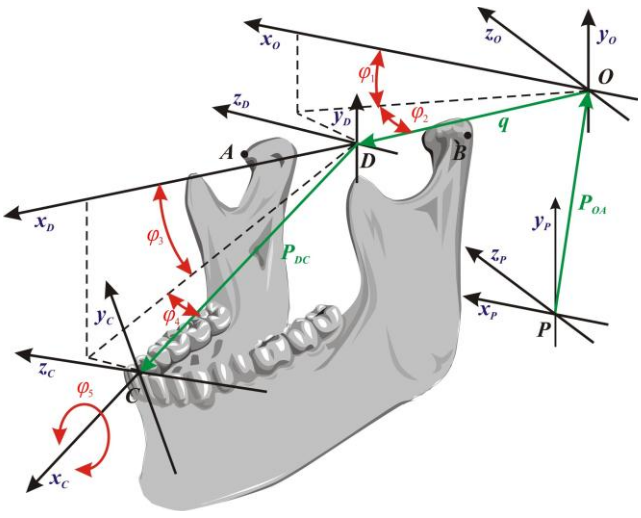

Fig. 1 Spatial model of the mandible kinematics

Based on the model of mandible kinematics (Fig. 1) equations describing the position of measuring points of the mandible in selected moments of time were derived, but the location and orientation of the mandible is calculated relative to the stationary reference frame $x_P y_P z_P$

$$\begin{cases} \boldsymbol{P_D} = \begin{bmatrix} x_0 + q\cos\varphi_1\cos\varphi_2 \\ y_0 + q\sin\varphi_1\cos\varphi_2 \\ z_0 - q\sin\varphi_2 \end{bmatrix} \\ \boldsymbol{P_A} = \begin{bmatrix} x_D + l_2\left(\sin\varphi_3\sin\varphi_5 + \cos\varphi_3\sin\varphi_4\cos\varphi_5\right) \\ y_D + l_2\left(\sin\varphi_3\sin\varphi_4\cos\varphi_5 - \cos\varphi_3\sin\varphi_5\right) \\ z_D + l_2\cos\varphi_4\cos\varphi_5 \end{bmatrix} \\ \boldsymbol{P_B} = \begin{bmatrix} x_D - l_3\left(\sin\varphi_3\sin\varphi_5 + \cos\varphi_3\sin\varphi_4\cos\varphi_5\right) \\ y_D - l_3\left(\sin\varphi_3\sin\varphi_4\cos\varphi_5 - \cos\varphi_3\sin\varphi_5\right) \\ z_D - l_3\cos\varphi_4\cos\varphi_5 \end{bmatrix} \\ \boldsymbol{P_C} = \begin{bmatrix} x_D + l_1\cos\varphi_3\cos\varphi_4 \\ y_D + l_1\sin\varphi_3\cos\varphi_4 \\ z_D - l_1\sin\varphi_4 \end{bmatrix} \end{cases} \quad (1)$$

These Eqs. (1) continue to be the basis for deriving formulas on the configuration coordinates. Medical devices used in clinical studies (Zebris JMA), allow simultaneous recording of the condyle (A and B, Fig. 1) and incisors (C, Fig. 1) trajectory, therefore – to calculate the exact configuration coordinates – it is possible to use analytical inverse kinematics methods of spatial mechanisms. Due to the limited number of publication pages only the final equations, without a detailed derivation are shown

$$\begin{cases} q = \sqrt{\left(x_D - x_0\right)^2 + \left(y_D - y_0\right)^2 + \left(z_D - z_0\right)^2} \\ \varphi_1 = arctg\left(\dfrac{y_D - y_0}{x_D - x_0}\right) \\ \varphi_2 = arctg\left(-\dfrac{\left(z_D - z_0\right)\left(\cos\varphi_1 + \sin\varphi_1\right)}{\left(x_D - x_0\right) + \left(y_D - y_0\right)}\right) \\ \varphi_3 = arctg\left(\dfrac{y_C - y_D}{x_C - x_D}\right) \\ \varphi_4 = arctg\left(-\dfrac{\left(z_C - z_D\right)\left(\cos\varphi_3 + \sin\varphi_3\right)}{\left(x_C - x_D\right) + \left(y_C - y_D\right)}\right) \\ \varphi_5 = arctg\left(\begin{array}{l} \dfrac{\left(\left(x_A - x_D\right) + \left(y_A - y_D\right)\right)\cos\varphi_4}{\left(z_A - z_D\right)\left(\sin\varphi_3 - \cos\varphi_3\right)} + \\ + \left(-\dfrac{\sin\varphi_4\left(\cos\varphi_3 + \sin\varphi_3\right)}{\left(\sin\varphi_3 - \cos\varphi_3\right)}\right) \end{array}\right) \end{cases} \quad (2)$$

In this place it should be noted that the point C (Fig. 1) during clinical research is not always located in the medial plane of the mandible, and for this reason the equation on the configuration coordinate φ_4 must be corrected. When the correction is not taken into account, then the calculated Cartesian coordinates of point C trajectory would not match with the recorded measurement data

$$\varphi_4 = arctg\left(-\frac{\left(z_C - z_D\right)\left(\cos\varphi_3 + \sin\varphi_3\right)}{\left(x_C - x_D\right) + \left(y_C - y_D\right)}\right) - \varphi_4\left(0\right) \quad (3)$$

The usability and effectiveness of each model is determined by its verification. The criterion for verifying the spatial model of the mandible kinematics, which was formulated in this study, was defined as compliance with the numerically calculated trajectories and trajectories recorded in clinical trials. Sample results of the model verification are shown in Fig. 2 and Fig. 3.

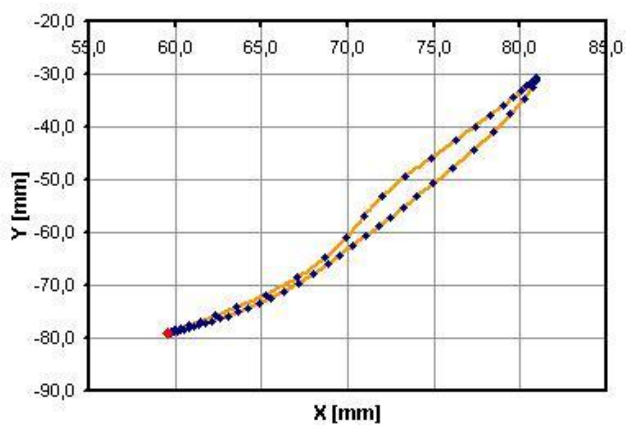

Fig. 2 Verification of numerically calculated trajectories and trajectories recorded in clinical trials on incisor in sagittal plane trajectory

Dark spots (Figs. 2 and 3) represent moments of time in which Cartesian coordinates were recorded by the Zebris JMA, however the continuous light curve imitates the result of numerical calculations. The derived kinematic causal relationships, which incorporate the relationship between Cartesian coordinates and configuration coordinates are the basis to carry out any analysis of masticatory organ kinematics. Furthermore, knowledge of these volumes is crucial in numerical research aimed at assessing the activity of masticatory muscles.

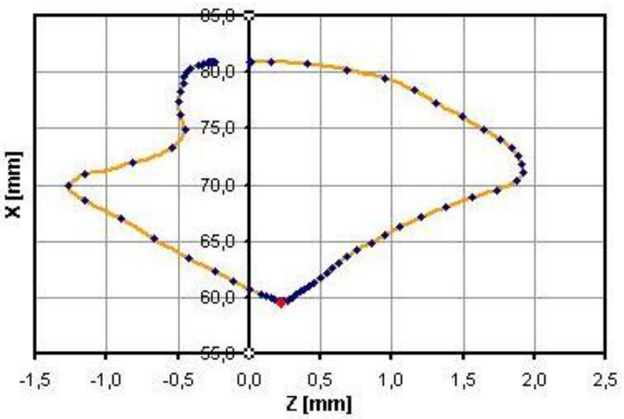

Fig. 3 Verification of numerically calculated trajectories and trajectories recorded in clinical trials on incisor in horizontal plane trajectory

3. Modelling research

Modelling studies of the human masticatory organ, were performed on the basis of recorded data mapping spatial mandible movement of the patient, aged 37, who was referred to Pomeranian Medical University, after reposition of a dislocated mandible. In clinical interview the patient reported that during dental surgery he was injured and "something" jumped in the joints, which made the mouth closing impossible. The symptoms shown at clinical research of noise in the form of glitches and skipping around the two temporomandibular joints, and the sound effects appeared in the final phase of abduction motion. Tests results recorded by Zebris JMA system are shown in Figs. 4 and 5.

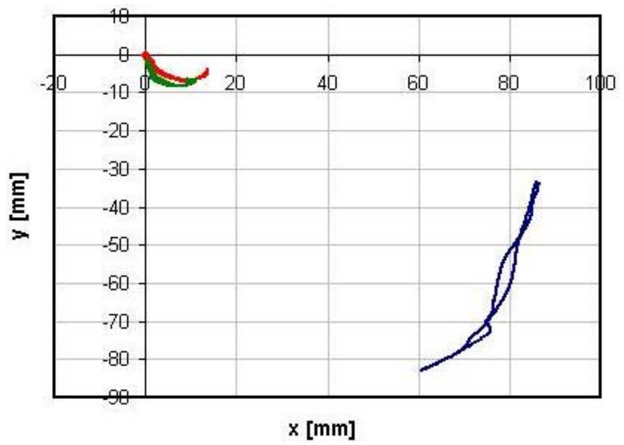

Fig. 4 Incisor in sagittal plane trajectory

Trajectories of characteristic points of the mandible, which are graphically illustrated in Figs. 4 and 5 represent a solid basis for a dentist to formulate a diagnosis on the degree of dysfunction of the masticatory organ. On its basis it can be formulated that the trajectories plotted by moving mandibles head show a slight asymmetry of temporomandibular joints motion (Fig. 4). Moreover, the ranges of movements of the condylar process heads also show asymmetric motion. The displacement of the left condyle head in the forward direction is 13.5 mm, while the right is 11 mm. Moreover, in the frontal plane the measuring points, that depict motion of the heads of the condyle, move along curved trajectories (Fig. 5). The degree of opening of dental arches measured between the edges of the incisors is approximately equal to 56mm. Graphical record of the trajectory of incisors in the frontal plane is characterized by s-letter shape with clearly visible intersection of the abduction and adduction track. Much more information is obtained if data registered in a clinical measurement (Figs. 4 and 5) will be subject to the numerical processing. As a result of such processing the clinician obtains a complete image of the kinematics of the mandible.

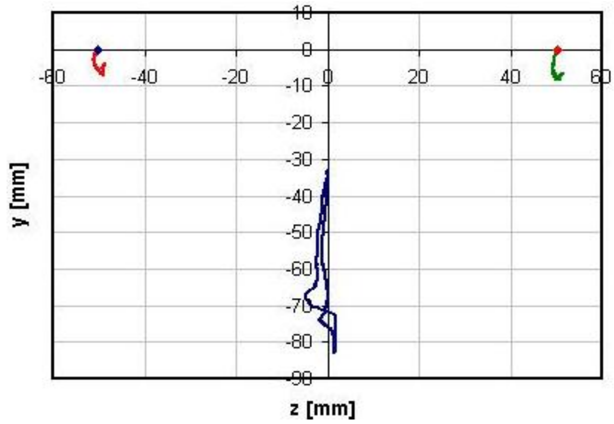

Fig. 5 Incisor in horizontal plane trajectory

The configuration coordinates (2), calculated on the basis of the trajectory recorded during clinical trials (Figs. 4 and 5), clearly describe the orientation and position of the mandible in any moments of time. In the view of small variation in time of configuration coordinates they were subjected to twice differentiation relative to time. In this way calculated new representation of signals characterizing the kinematics of the mandible, was the basis for undertaking research in the field of frequency. From the diagnostic point of view, most of the data are obtained by analyzing the evolution of each harmonic as a function of time on the basis of which it is possible to determine the time and duration of disorder. The spatial amplitude-frequency spectrum was used for this reason, because the characteristics calculated using the fast Fourier transform is characterized by a high sensitivity due to the speed of abduction and adduction of the mandible. High sensitivity of the harmonic spectrum of FFT on the speed of mandibles movement makes it difficult to identify moments of time in which it comes to its disorder. Moments of time in which there are disorders of mandibles movement are determined by the largest amplitude values occurring in the spectrograms. The calculated spectrograms characterizing the kinematics of the patients mandible are shown in Figs. 6 to 11.

On the basis of modeling studies it was found that the precise description of the mandible movement is sufficient when acceleration spectrograms of the configuration coordinates φ_2, φ_3, φ_4, and φ_5 (Figs. 8 to 11) as examined. Detailed analysis of the spectrograms appearing in Figs. 6 and 7 is not required because the information contained in them is also found in other spectrograms, moreover, these values represent the result of events occurring in both temporomandibular joints.

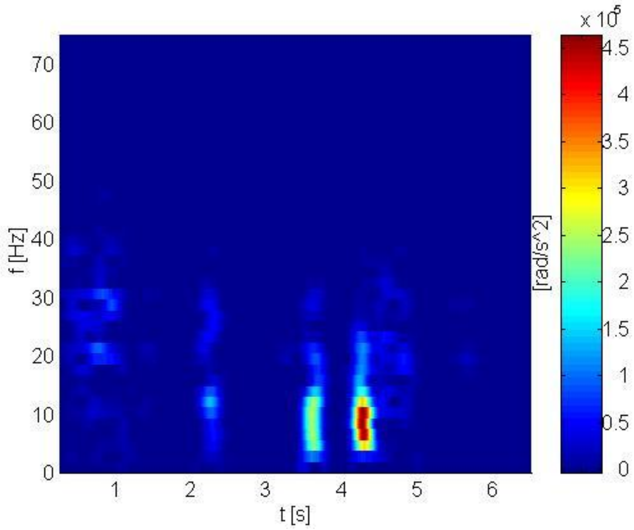

Fig. 6 Spectrograms calculated on the basis of q coordinate acceleration

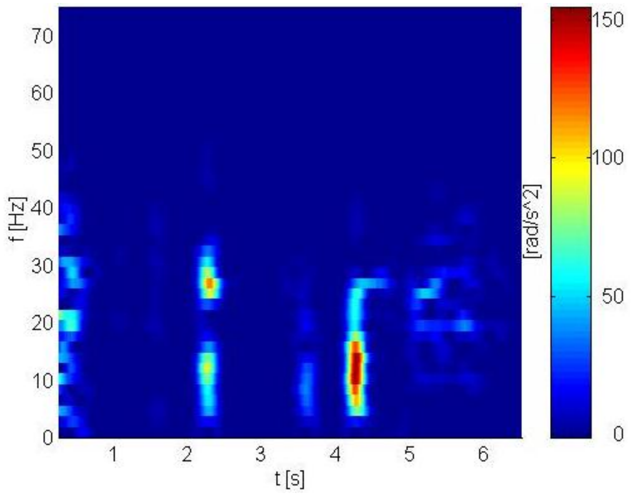

Fig. 7 Spectrograms calculated on the basis of φ_1 coordinate acceleration

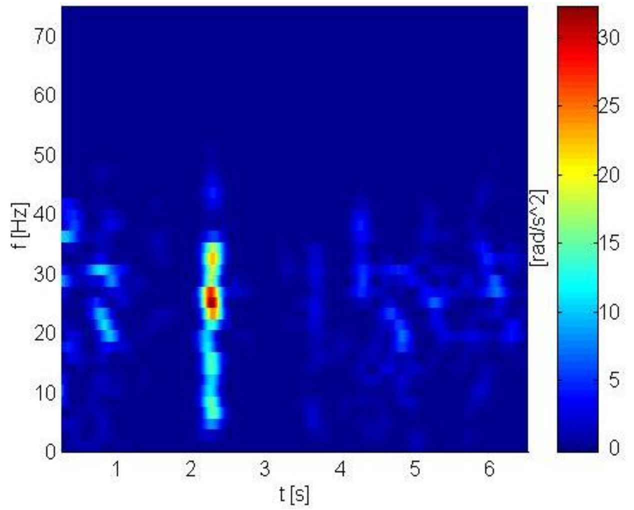

Fig. 8 Spectrograms calculated on the basis of φ_2 coordinate acceleration

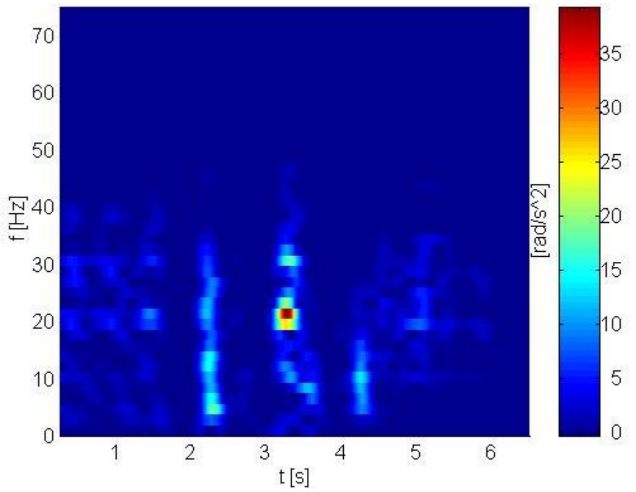

Fig. 9 Spectrograms calculated on the basis of φ_3 coordinate acceleration

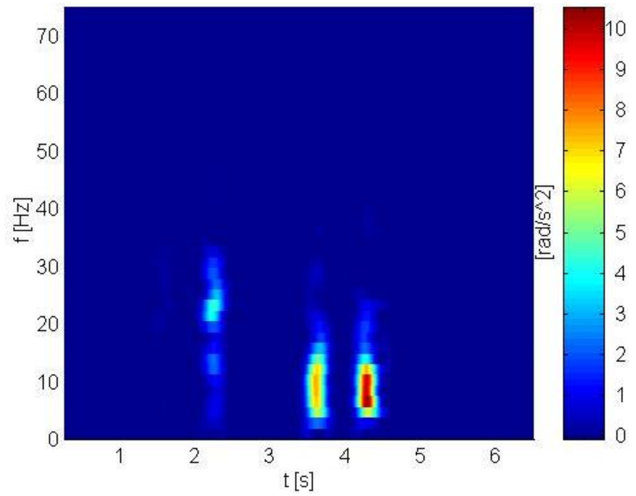

Fig. 10 Spectrograms calculated on the basis of φ_4 coordinate acceleration

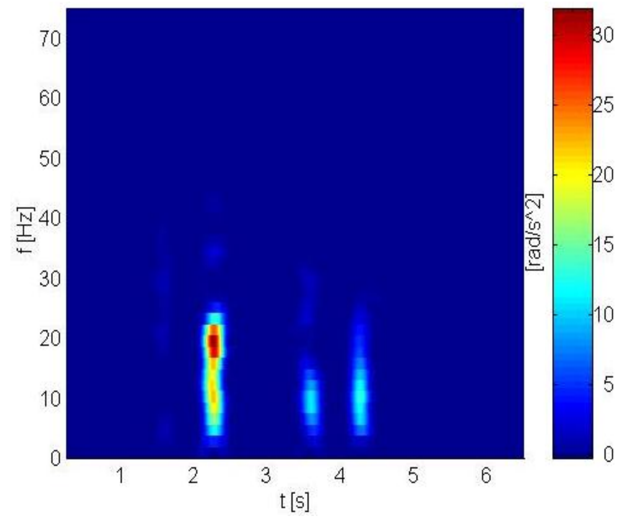

Fig. 11 Spectrograms calculated on the basis of φ_5 coordinate acceleration

Harmonic activity seen in the spectrograms (Figs. 6 to 9) which takes place outside the interval from 2 to 2.5 s and from 3.5 to 4.5 s, may be caused by adjusting articular discs to the volume of joint space. In this place it should be noted that the load exerted on the disc during its deformation causes the flow of fluids through the interstitial areas of the disc, although these flows may emerge as a short-term slowing down of the mandible.

On the basis of analysis of the spectrograms the moments of time where there is a movement disorder of the mandible have been identified. The first event is visible on the spectrograms appearing in Figs. 10 and 11 and takes place after about 1.5 s, when the distance between the incisal edges is about 40 mm. At the time of disorders condyle heads in the temporomandibular joints movement is as follows: left condyle head stops, and then goes back only slightly by about 1 mm and over that time the right condyle head moves in the forward direction of the mandible. Right condyle movement is carried out until the second event takes place after about 2 s. At the second event right of the mandible condyle head stops, then goes back in the pond by about 2 mm, at the same time left of the mandible the condyle head rapidly moves toward mandibles forward direction, until it reaches maximum aperture of dental arches.

In the adduction movement two events disrupting movement of the mandible are taking place, the first occurs after about 3.5 s, when the distance between the edges of the incisors is about 40 mm. The second event during the adduction movement takes place after about 4.2 s. In this place it should be noted that movement of the condyle head during movement of adduction takes place in reverse order in relation to the abduction movement. The moments of time, which have been identified on the basis of spectrograms Figs. 10 and 11, as well as the nature of the movement of the condyle heads indicate moments when it comes to hops around the temporomandibular joints. These hops are the source of acoustic symptoms observed during clinical trials. Based on clinical and modelling studies a diagnosis model, which found excessive mobility of the mandible predisposing to recurrent dislocations was formulated.

4. Conclusions

The paper presents a mathematical approach to spatial kinematics modeling of the human mandible. Analytical relationships describing configuration coordinates are given in general form, which allows to perform model studies of the mandible kinematics realizing movements: abduction and adduction, laterotruzal (lateral movements) and protruzal (ejecting and reversing the mandible). Formulated in the paper spatial model of the mandible kinematics provides a dentist the qualitatively new information about the disorder having its source within the masticatory organ and about stomatognathic system functioning. Proposed in this paper a spatial model of the human masticatory organ kinematics can be modified. This modification should imitate changing the length of the masseters, as a result it will be possible to evaluate their work during the performance of physiological functions. In this place it should be noted that information on the spatial orientation of muscle fibers are needed to determine the directions of the forces generated by muscles. With an estimated muscle forces, tests to determine the loads acting on the temporomandibular joints can be taken.

On the basis of the model studies and clinical trials, it is possible to draw the following general conclusions

- „A priori" knowledge in the field of clinical trials do not provide clear data on biomechanical masticatory organ states. In addition, common models of the mandible kinematics do not contain information in relation to the verification of used biomechanical models. Therefore, this paper proposes a spatial kinematics model, which was verified with the results obtained in clinical trials.
- The configuration coordinates as a result of solving the inverse kinematics problem are the basis for testing model to assess the activity of masticatory muscles. Kinematics of the masticatory muscles can be analyzed when taken into account Cartesian coordinates defining the location of insertion of the jaw muscles and bones of the skull.
- Numerically calculated time course of configuration coordinates, which reflects the patient's masticatory organ function can be interpreted as diagnostic signals. These signals are further subjected to digital processing in time domain and frequency domain.
- Digital signal processing in diagnostic of masticatory organ creates new opportunities for the interpretation of the results obtained during clinical trials.
- Use of the methods commonly used in technical diagnostics, allows in such a way to process the signals of masticatory organ, that it is possible to identify the precise moment of time where there is a movement disorder of the mandible.
- Time course of diagnostic signals of masticatory organ shows similarity, however, the calculated on its basis spectrograms highlight significant differences that have not been observable without the use of short-time frequency analysis. For this reason, short-time frequency analysis should be a primary research tool used in clinical diagnosis of masticatory organ.
- Determination of the moments where there is a movement disorder of the condyle, allows a precise description of motion in the temporomandibular joints.
- It should be noted that the proposed paper showing an analysis of masticatory organ diagnostic signals in the frequency domain is one of the first such attempts, made to assess dysfunction. In the clinical diagnostics frequency analysis has only been applied in the evaluation of acoustic symptoms, having its source within the temporomandibular joints.

In this place it should be made clear that the presented spatial model of mandible kinematics, brings a new information qualitatively as well as enrich the knowledge about functioning of the masticatory organ. The results obtained by the model tests indicate that numerical modeling of the masticatory organ is an effective tool to assist the dentist when formulating a diagnosis.

Acknowledgements

The research has been performed within the research project N N 518 384237 financed by the Ministry of Science and Higher Education (Poland).

References

1. **Margielewicz, J.** 2010. Numerical Modeling in the

Diagnosis of Biomechanical Conditions of the Stomatognathic System, Polskie Towarzystwo Inżynierii Biomedycznej, 210p (in Polish).
2. **Daumas, B.; Xu, W.L.; Bronlund, J.** 2005. Jaw mechanism modeling and simulation, Mechanism and Machine Theory 40: 821-833. http://dx.doi.org/10.1016/j.mechmachtheory.2004.12.011.
3. **Kizilova, N.; Krpinsky, M.; Griskkevicius J.; Daunoraviciene K.** 2009. Posturographic study of the human body vibrations for clinical diagnostics of the spine and joint pathology, Mechanika 6(80): 37-41.
4. **Leader, J.K.; Boston, J.R.; Debski, R.E.; Rudy T.E.** 2003. Mandibular kinematics represented by a nonorthogonal floating axis joint coordinate system, Journal of Biomechanics 36: 275-281. http://dx.doi.org/10.1016/S0021-9290(02)00337-8.
5. **Peck, Ch.C.; Murray, G.M.; Johnson, Ch.W.L.; Comp, M.; Klineberg, I.J.** 1999. Trajectories of condylar points during nonworking side and protrusive movements of the mandible, Journal of Prosthetic Dentistry 82(3): 322-331. http://dx.doi.org/10.1016/S0022-3913(99)70088-0.
6. **Sawicki, J.; Mickiewicz, W.; Biedka, A.; Woźniak, K.; Faluta, Ł.; Wiśniewski, K.** 2004. A comprehensive assessment of functional status of masticatory organ using different measurement techniques (in polish), Acta bio-Optica et Informatica Medica 14(2): 254-257.
7. **Zhang, X.; Ashton-Miller, J.A.; Stohler, Ch.S.** 1995. Three-dimensional unilateral method for the bilateral measurement of condylar movements, Journal of Biomechanics 28: 1007-1011. http://dx.doi.org/10.1016/0021-9290(94)00117-M.
8. **Zuccari, A.G.; Andres, C.J.; Simpson, G.W.** 1996. A color-enhanced aid for location of the transverse horizontal opening and closing axis of the mandible, The Journal of Prosthetic Dentistry 76(2): 181-186. http://dx.doi.org/10.1016/S0022-3913(96)90304-2.
9. **Pileičikienė, G.; Šurna, A.; Skirbutis, G.; Barauskas, R.; Šurna R**. 2010. Influence of guiding tooth geometry on contact forces distribution in the human masticatory system: a FEM study, Mechanika 3(83): 34-39.
10. **Margielewicz, J.; Chladek, W.; Lipski, T.** 2008. Kinematical analysis of mandibular morion in the sagittal plane, Acta of Bioengineering and Biomechanics 10(1): 9-19.
11. **Motoyoshi, M.; Matsumoto, Y.; Ohnuma, M.; Arimoto, M.; Takahashi, K.; Namura, S.** 1995. A study of temporomandibular joint sounds. Part 2. Caustic characteristics of joint sounds, Journal of Nihon University School of Dentistry 37(1): 47-54. http://dx.doi.org/10.2334/josnusd1959.37.47.
12. **Prinz J.F.** 1998. Autocorrelation of acoustic signals from the temporomandibular joint, Journal of Oral Rehabilitation 25(8): 635-639. http://dx.doi.org/10.1046/j.1365-2842.1998.00275.x.
13. **Zimmer B.** 1993. Correlations between the loss of acoustic TMJ symptoms and alterations in mandibular mobility after surgical mandibular advancement, European Journal of Orthodontics 15(3): 229-234.

D. Gąska, E. Kijak, T. Lipski, J. Margielewicz

ŽMOGAUS KRAMTYMO ORGANŲ KINEMATIKOS SKAITINIS MODELIAVIMAS

R e z i u m ė

Kratymo organų funkciniai sutrikimai yra grupė visas amžiaus grupes pažeidžiančių ligų, kurias vis dažniau diagnozuoja gydymo įstaigos. Technologijų pažanga ir speciali medicininė įranga palengvina stebėti judėjimo organų ligas. Įvertinant apribojimus, susijusius su klinikinėmis studijomis, buvo sukurtas apatinio žandikaulio erdvinis kinematinis modelis. Šis modelis sudarytas naudojant tikslią klinikinėse studijose surinktų duomenų interpretaciją. Straipsnyje parodytas modelis palengvina reiškinių, atsirandančių fiziologinių žandikaulio judesių metu supratimą, taigi modeliavimo rezultatai suteikia naujos informacijos, kuri iki šiol nebuvo įvertinta analizuojant kramtymo funkcijos sutrikimo priežastis.

D. Gąska, E. Kijak, T. Lipski, J. Margielewicz

NUMERICAL MODELLING OF HUMAN MASTICATORY ORGAN KINEMATICS

S u m m a r y

Functional disorders of the masticatory organ is a group of diseases characterized by the increasing frequency of instances whereby these disorders affect all age groups. Advances in technology and the application of specialized medical equipment facilitates the observation of masticatory organ disorders. Having regard to limitations associated with the use of clinical studies, a spatial model of the mandible kinematics was developed. Results of such model are obtained to enable accurate interpretation of data collected during clinical studies. The model formulated in the paper facilitates our understanding of the phenomena occurring during physiological mandible movements, also the results of modeling studies provide new information that has not yet been taken into account when analyzing the causes of dysfunction.

Keywords: numerical modelling, human masticatory organ kinematics.

Received February 25, 2011
Accepted June 13, 2012