Original Research

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Comparative analysis of the effectiveness of virtual and mechanical articulators in the functional diagnosis of temporomandibular joint disorders

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Abstract

INTRODUCTION. The study presents the results of a comparative evaluation of the effectiveness of mechanical and virtual articulators in the functional diagnosis of patients with temporomandibular joint (TMJ) disorders.
AIM. To assess the advantages and limitations of using mechanical and virtual articulators for analyzing dynamic occlusion in patients with internal TMJ pathology.
MATERIALS AND METHODS. A total of 52 patients (45 women and 7 men), aged 25 to 42 years, with occlusal disturbances caused by internal TMJ disorders, were examined. All patients underwent cone-beam computed tomography (CBCT) for TMJ assessment and axiographic recording (optical axiograph Dentograf Prosystom). The patients were divided into two groups: Group 1 ($n = 26$) was analyzed using a mechanical articulator, and Group 2 ($n = 26$) using a virtual articulator. CBCT and axiography data, as well as the results of dynamic occlusion evaluation (tooth contact in closure and opening, protrusion, and laterotrusion), were analyzed in both articulator types.
RESULTS. Mechanical articulators enabled the evaluation of dynamic occlusion with an effectiveness of 73.1%. Limitations were associated with their inability to accurately account for individual anatomical characteristics of the TMJs. Virtual articulators demonstrated higher effectiveness (92.3%) due to the integration of CBCT and axiography data, allowing detailed modeling of individual mandibular movements.
CONCLUSIONS. Virtual articulators show significant advantages over mechanical ones in assessing dynamic occlusion in patients with TMJ disorders, providing greater accuracy and personalization of the diagnostic process. Mechanical articulators demonstrated limited effectiveness and a considerable margin of error related to their non-individualized approach.

Keywords: articulation disorders, temporomandibular joint disorders (TMJ), mechanical articulator, virtual articulator, dynamic occlusion, individualized jaw relationship

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Сравнительный анализ эффективности применения виртуальных и механических артикуляторов в функциональной диагностике ВНЧС

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Резюме

ВВЕДЕНИЕ. В исследовании представлены результаты сравнения эффективности механических и виртуальных артикуляторов при функциональной диагностике пациентов с нарушениями височно-нижнечелюстных суставов (ВНЧС).
ЦЕЛЬ ИССЛЕДОВАНИЯ. Оценить преимущества и недостатки применения механических и виртуальных артикуляторов для анализа динамической окклюзии у пациентов с внутренней патологией ВНЧС.
МАТЕРИАЛЫ И МЕТОДЫ. Обследовано 52 пациента (45 женщин и 7 мужчин) в возрасте от 25 до 42 лет с нарушениями артикуляции, обусловленными внутренними нарушениями ВНЧС. Всем пациентам выполнено конусно-лучевую компьютерную томографию (КЛКТ) для оценки состояния ВНЧС и аксиогра-

фическое исследование (оптический аксиограф Dentograf Prosystom). Пациенты были разделены на две группы: в первой (*n* = 26) использовался механический артикулятор, во второй (*n* = 26) – виртуальный. Анализировались данные КЛКТ и аксиографии, а также результаты оценки динамической окклюзии (смыкание-размыкание зубов, протрузия, латеротрузия) в артикуляторах.
РЕЗУЛЬТАТЫ. Применение механических артикуляторов позволило оценить динамическую окклюзию с эффективностью 73,1%. Ограничения связаны с неспособностью точно учитывать индивидуальные анатомические особенности суставов. Виртуальные артикуляторы обеспечили более высокую эффективность (92,3%), благодаря интеграции данных КЛКТ и аксиографии, позволяя детально моделировать индивидуальные движения нижней челюсти.
ВЫВОДЫ. Виртуальные артикуляторы демонстрируют существенные преимущества перед механическими при оценке динамической окклюзии у пациентов с ВНЧС, обеспечивая более высокую точность и персонализацию диагностического процесса. Механические артикуляторы показали ограниченную эффективность и значительную погрешность измерений, связанную с неиндивидуальным подходом.

Ключевые слова: нарушения артикуляции, ВНЧС, механический артикулятор, виртуальный артикулятор, динамическая окклюзия, индивидуальное соотношение челюстей.

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INTRODUCTION

The development of modern medical technologies and their widespread implementation in dental practice have significantly expanded the possibilities and importance of functional diagnostics in the early detection of various diseases of the dentoalveolar system [1; 2]. The advancement of high-precision instrumental research methods enables the identification of pathological changes at the earliest stages of their formation [3; 4].

Currently, the diagnosis of dentoalveolar system diseases is based on a complex and comprehensive specialized examination using high-technology equipment [5; 6]. Some diagnostic procedures are performed with the direct participation of the patient, while others are carried out on models of the dentoalveolar system using articulators and specialized computer technologies [7; 8].

In recent years, there has been a significant increase in the number of patients with combined dental lesions and temporomandibular joint (TMJ) disorders, often accompanied by mandibular articulation dysfunction and involvement of the masticatory muscles. This trend highlights the increasing role of functional diagnostics in identifying such pathology [9; 10]. Timely application of functional diagnostic methods not only allows the detection of the causes and characteristics of the disease at its early stages, but also facilitates the development of an optimal treatment plan and the evaluation of its effectiveness.

At present, functional diagnostics of the dentoalveolar system employs a wide range of methods, including panoramic radiography, orthopantomography, and computed tomography [11; 12], which provides three-dimensional imaging of the jaws; magnetic resonance imaging (MRI), allowing the assessment of soft tissues and the temporomandibular joint (TMJ) [13; 14]; and optical axiography, which records joint trajectories and mandibular movements [15]. A crucial role in the functional diagnostics of dentoalveolar disorders is played by the creation of dental arch models using articulators [16; 17], as well as by electromyography, which enables the analysis of the bioelectrical activity of the masticatory muscles and their functional symmetry [18]. In addition, ultrasound imaging of the TMJ allows for both anatomical and functional assessment [19].

Within functional diagnostics, the evaluation of occlusion is of particular importance [20]. Occlusion is commonly classified into static and dynamic types. Dynamic occlusion refers to the interaction between the teeth during mandibular movements [20]. Under optimal, “physiological” conditions of the dentoalveolar system, immediate disclusion or loss of occlusal contacts occurs during mandibular movement from habitual occlusion. The presence of pathological changes or unwanted occlusal contacts – particularly those located close to the TMJ – may lead to impaired coordination of the masticatory muscles, altered joint position and function, pathological tooth wear, and structural changes [21]. The use of articulating foil or paper provides only limited information regarding occlusion [21]. The most effective method for evaluating dynamic occlusion is the application of individually adjusted articulators [22].

The assessment of dynamic occlusion is especially relevant in prosthetic dentistry for restoring masticatory function in full, in orthodontics for normalizing occlusal relationships, in maxillofacial surgery for evaluating TMJ function and treatment planning, in implantology for distributing occlusal loads when planning the number, localization, size, and form of implants, in periodontology for determining functional tooth loading – since excessive load contributes to periodontal disease – and in restorative dentistry, where control of both static and dynamic occlusal relationships is mandatory [23–25].

AIM

To evaluate the advantages and limitations of using mechanical and virtual articulators for the analysis of dynamic occlusion in patients with internal temporomandibular joint (TMJ) pathology.

MATERIALS AND METHODS

A total of 52 patients with pathological changes in mandibular articulation caused by internal temporomandibular joint (TMJ) disorders were examined. The gender distribution of the patients was as follows: 45 women (86.5%) and 7 men (13.5%), with a female-to-male ratio of 6.4:1. The age of the patients ranged from 25 to 42 years. The main complaints included TMJ pain (38 out of 52 patients; 73.1%), headaches (20 patients; 38.5%), and difficulty in mouth opening (41 patients; 78.8%). Clinical examination revealed joint sounds on palpation and during mandibular movements in 46 out of 52 patients (88.5%), while reduced mouth opening was observed in 47 out of 52 patients (90.4%).

All patients underwent cone-beam computed tomography (CBCT) to identify TMJ pathology. CBCT was also used to determine the individualized relationship between jaw models and the temporomandibular joints. The use of CBCT was of particular importance in the analysis of dynamic occlusion within the virtual articulator. In this subgroup, CBCT allowed for the acquisition of patient-specific parameters, which were subsequently transferred to the virtual articulator using a specialized CT module. The following parameters were evaluated: the position of the mandibular condyle in the articular fossa of the temporal bone, the width of the joint space, incisal points (upper and lower), prosthetic planes in the posterior teeth region (right and left), and condylar reference points (right and left).

In addition, all patients underwent axiographic examination using an optical axiograph (ProAxis, SdiMatrix, Russia), which enabled the registration and analysis of condylar trajectories of mandibular movements.

Visualization of the main mandibular movement parameters obtained through optical axiography is presented in Fig. 1–4.

Table 1. Complaints of patients with internal TMJ disorders

Таблица 1. Жалобы пациентов с внутренними нарушениями ВНЧС

Complaints	*n* (patients)	%
TMJ pain	38	73,1
Headaches	20	38,5
Difficulty in mouth opening	41	78,8
Joint sounds on palpation / motion	46	88,5
Reduced mouth opening	47	90,4

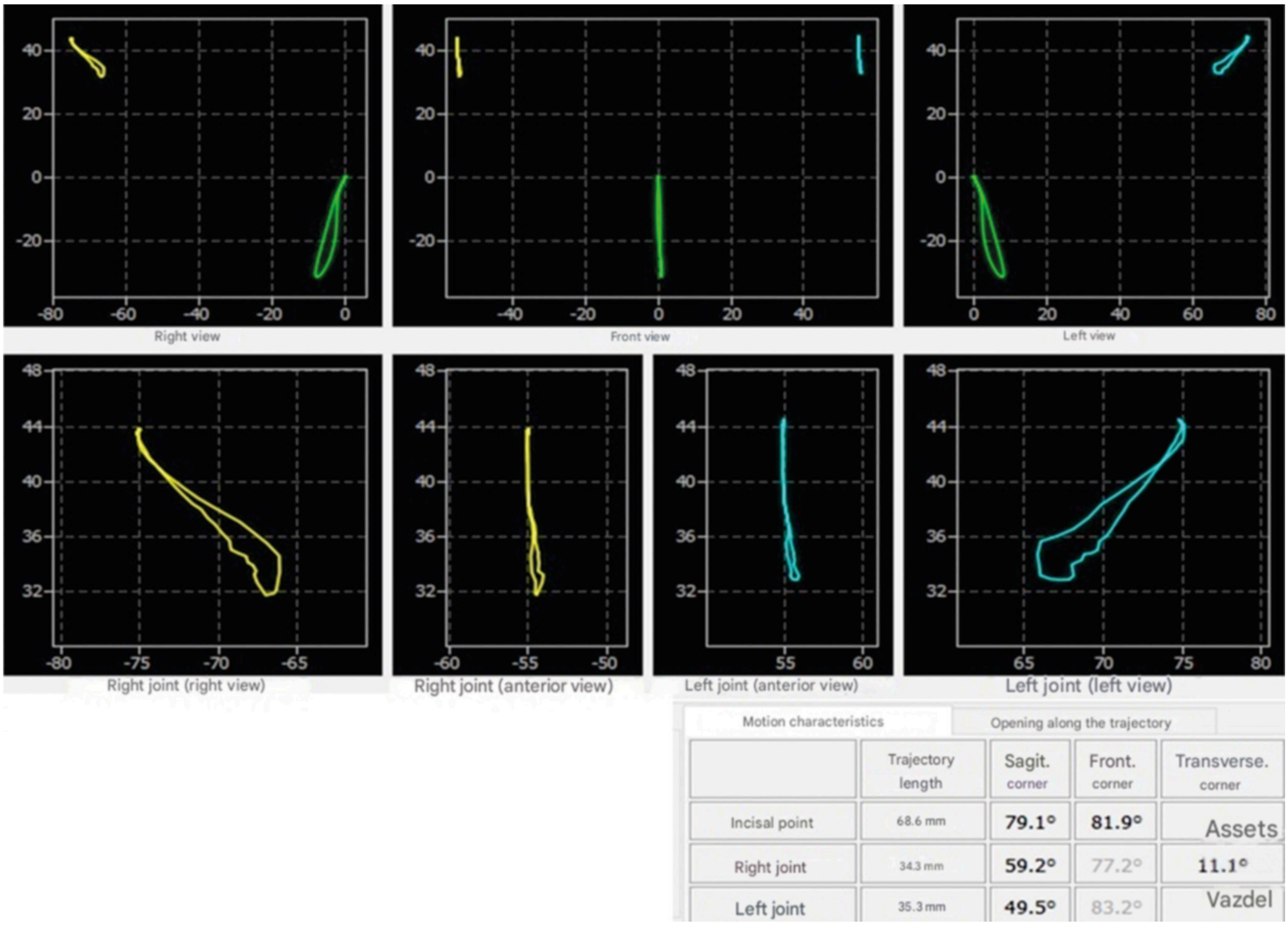


Fig. 1. Axiogram: opening / closing the mouth

Рис. 1. Аксиограмма: открывания / закрывания рта

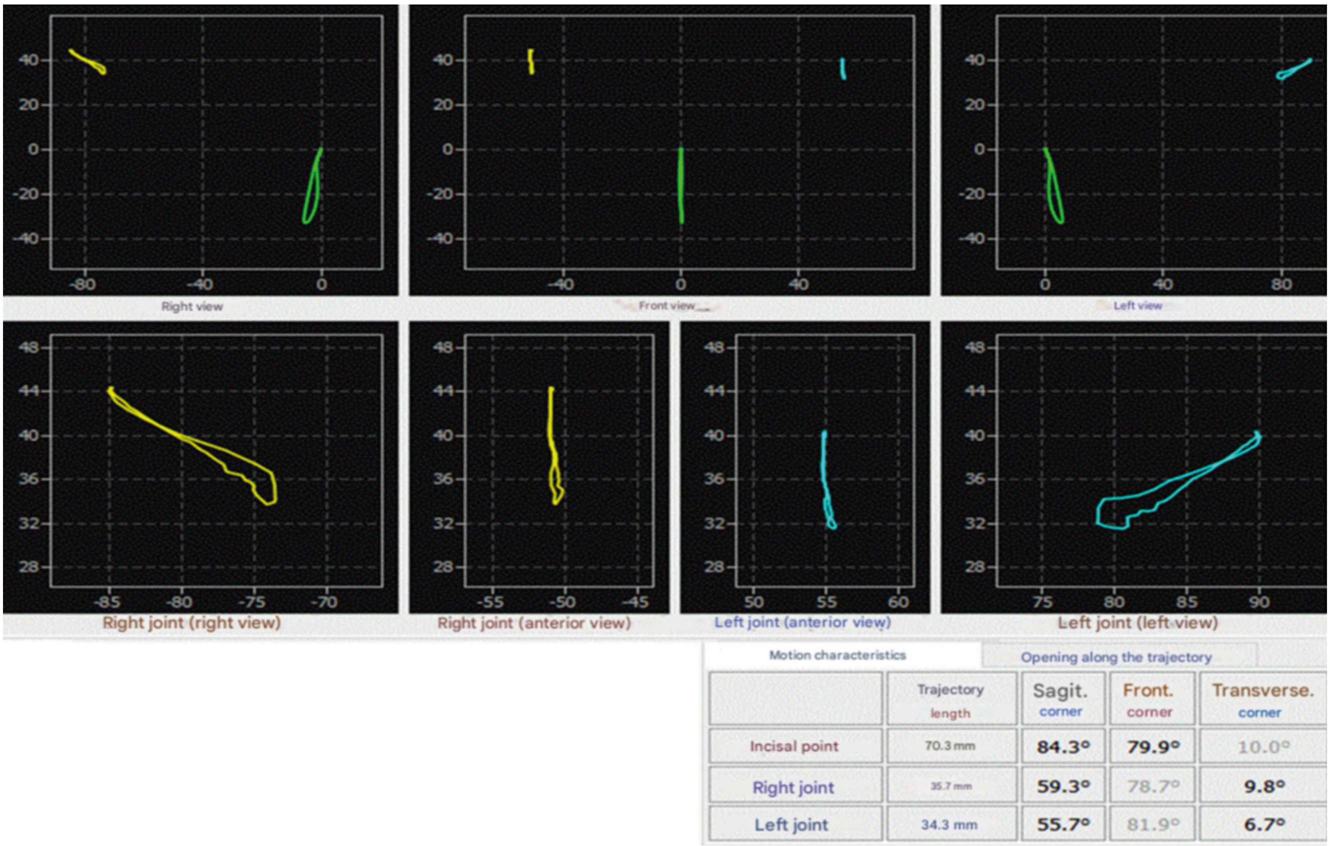


Fig. 2. Axiogram: deviation of the lower jaw from the midline during opening and closing of the mouth

Рис. 2. Аксиограмма: отклонение нижней челюсти от срединной линии при открывании и закрывание рта

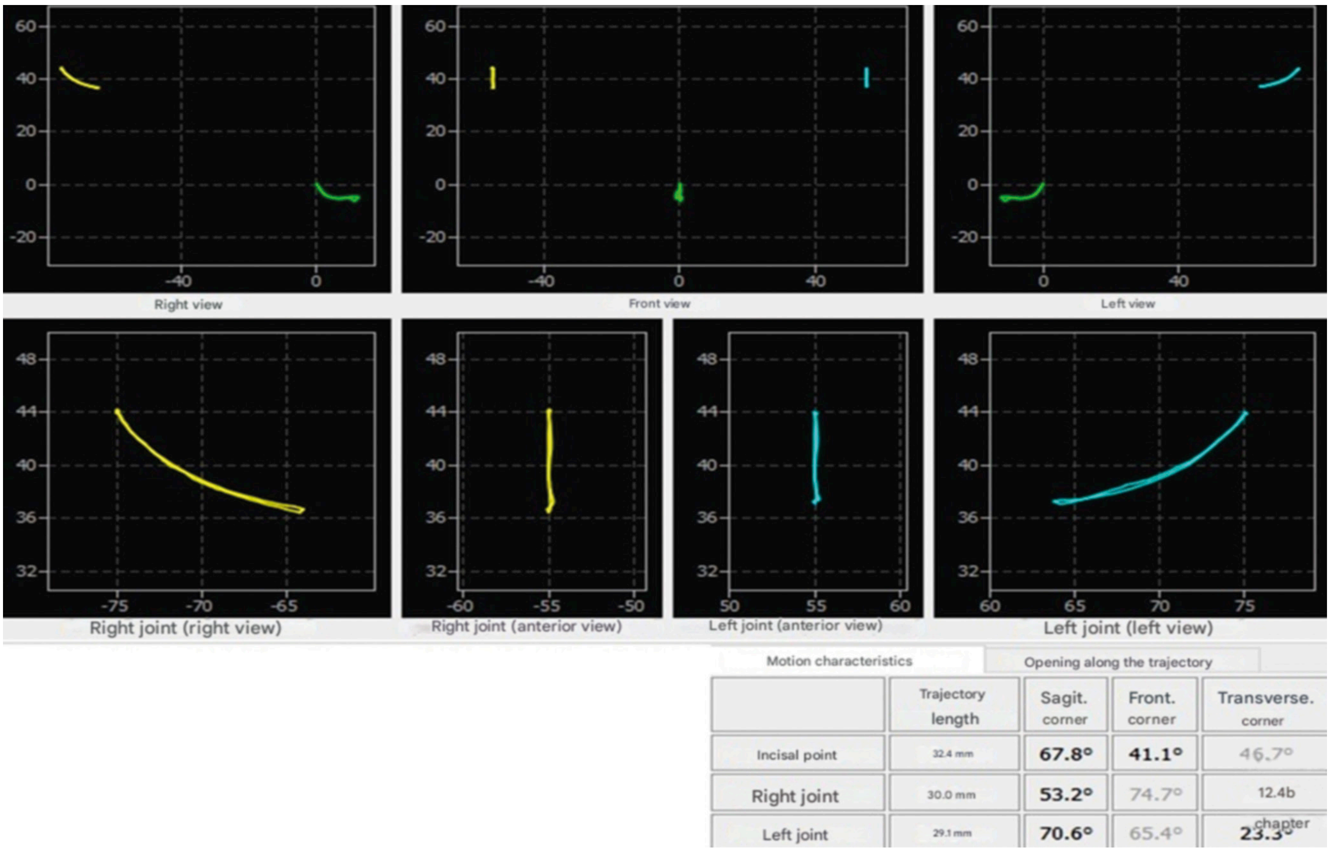


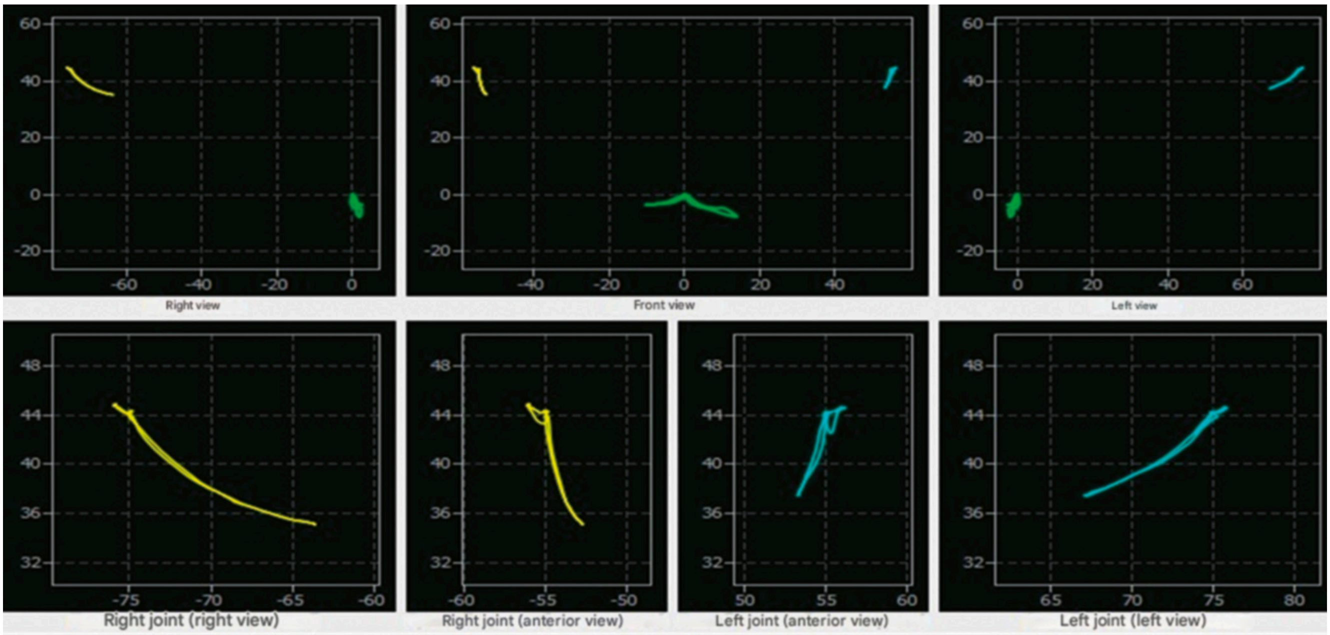
Fig. 3. Axiogram: deviation of the mandible from the midline during protrusion

Рис. 3. Аксиограмма: отклонение нижней челюсти от срединной линии при протрузии

In Group I, dynamic occlusion was evaluated in all 26 patients (50.0%) using a mechanical articulator (Fig. 5).

After taking two-layer silicone impressions, gypsum casts were mounted using a mechanical facebow, and mandibular movements were reproduced in the mechanical articulator through its condylar mechanisms. The articulator (condylar elements and programmable table) was adjusted according to the individual parameters obtained during optical axiography. The following factors were considered: the amplitude of mouth opening, synchronicity or asynchronicity of mandibular condyle movements, mandibular deviation from the midline during functional tests (mouth opening/closing, protrusion, laterotrusion), the nature and amplitude of condylar and incisal paths, and Bennett angles.

In 26 patients (50.0%) of Group II, dynamic occlusion was analyzed using a virtual articulator with virtual models (Fig. 6).



	Trajectory length	Sagit. corner	Front. corner	Transverse.. corner
Incisal point	60.9 mm	52.8°	75.0°	12.0°
Right joint	39.9 mm	86.2°	82.3°	7.7°
Left joint	32.7 mm	72.1°	68.6°	20.3 cases

Fig. 4. Axiogram: deviation of the mandible from the midline in lateral intrusion

Рис. 4. Аксиограмма: отклонение нижней челюсти от срединной линии при латеротрузии

Fig. 5. Mechanical articulator Artex CR (Girrbach)

Рис. 5. Механический артикулятор Artex CR (Girrbach)

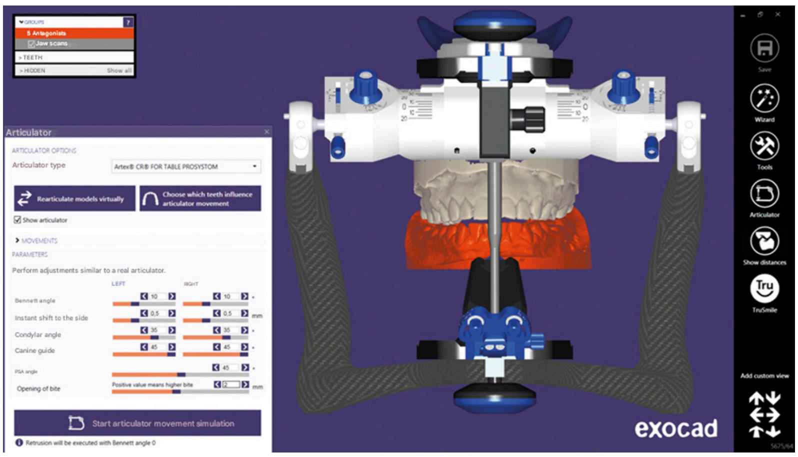


Fig. 6. Virtual articulator Artex Exocad

Рис. 6. Виртуальный артикулятор Artex в программе Exocad

After taking two-layer silicone impressions and casting gypsum models, the jaw models were optically scanned using the **ZIRKONZAHN** software. With the aid of an electronic facebow and CBCT data, the models were positioned within the virtual articulator, which enabled three-dimensional reproduction of the virtual dental arch in relation to the hinge axis and the incisal pin within the software environment.

To account for all individual parameters during virtual articulator mounting, an additional CT module (SdiMatrix) was used. This allowed measurement of the individualized distance from the upper central incisors to the TMJ condyles for subsequent transfer into the articulator. Three anatomical reference points were used: the interincisal point at the incisal edge of the maxillary central incisors, and the condylar reference points on the right and left TMJs.

Based on the CBCT data obtained, the virtual models were exported into the virtual articulator. Subsequently, the program was supplemented with individual mandibular movement trajectories that had previously been recorded using the axiograph.

The use of specialized computer software made it possible to integrate virtual jaw models with their movement trajectories, providing visualization within the virtual articulator. In addition, the spatial position of the mandible was determined.

Statistical criteria were selected based on the analysis of feature distribution and its comparison with the normal Gaussian distribution using the Kolmogorov–Smirnov test. The Wilcoxon matched pairs test was applied for comparison of repeated measurements. To assess the relationships between clinical parameters and the results of instrumental diagnostic methods, multivariate analysis of variance (MANOVA) and correlation analysis using Pearson's correlation coefficient were performed for quantitative indicators. Differences were considered statistically significant at $p < 0.05$.

All statistical analyses were performed on a personal computer running Windows 10 using **STATISTICA 12** software.

RESULTS

During the survey, 38 patients (73.1%) reported TMJ pain, while 20 patients (38.5%) experienced frequent headaches. Difficulty and discomfort during mouth opening were noted in 41 patients (78.8%). Among the 52 examined patients, 46 (88.5%) reported joint clicking or abnormal sounds such as crepitation during mandibular movements. Four patients (7.7%) did not perceive pathological joint sounds, although these were detected during clinical examination (palpation and auscultation of the TMJ area). Reduced mouth opening was observed in 47 patients (90.4%).

The distribution of patient complaints associated with internal TMJ disorders is presented in Fig. 7.

A comparative analysis of dynamic occlusion was carried out in all patients, focusing on mandibular movements across the dentition (mouth opening and closing, lateral movements, and protrusion with return to the initial position). Gypsum models of 26 patients (50.0%) were examined using a mechanical articulator, and 26 patients (50.0%) were analyzed with a virtual articulator.

In Group I, the Artex FaceBow (Girrbach) and the Artex CR mechanical articulator (Girrbach) were employed. Clinical examination of mandibular articulation was performed using Bausch 20 μm articulating paper and OKKLUSAL INDIKATOR WACHS SAM occlusal wax. The analysis included habitual occlusion closure as well as mandibular movements in protrusive and laterotrusive directions, and during mouth opening and closing.

Clinical and instrumental examinations with the mechanical articulator demonstrated an effectiveness of 73.1% in reproducing mandibular function during opening–closing, as well as protrusive and laterotrusive movements. During protrusion, the mandible advanced anteriorly without occlusal contacts on the posterior teeth. Under normal conditions, load distribution occurs between the TMJs and anterior teeth, with the primary load borne by the joint structures and minimal load applied to the incisors.

During lateral mandibular movements (laterotrusion), discrepancies were observed between in-mouth mandibular movements and those reproduced on gypsum models, due to significant differences in the morphology of the patient's condylar mechanisms and the fixed design of the mechanical articulator. This structural limitation significantly restricts the individualization of functional diagnostic data for specific clinical cases.

In Group II, the ProAxis electronic facebow (SdiMatrix) and the Artex virtual articulator within the Exocad software were used. A key feature of the virtual articulator is the ability to integrate all previously recorded condylar trajectories from axiographic studies, enabling precise reproduction of the patient's TMJ function. In this group, protrusive and laterotrusive mandibular movements were simulated within the virtual articulator. Clinical and instrumental analyses demonstrated an effectiveness of 92.3% for evaluating mouth opening–closing, as well as protrusive and laterotrusive movements (Fig. 8). In this case, the virtual mandibular model accurately reproduced all individual patient-specific movements.

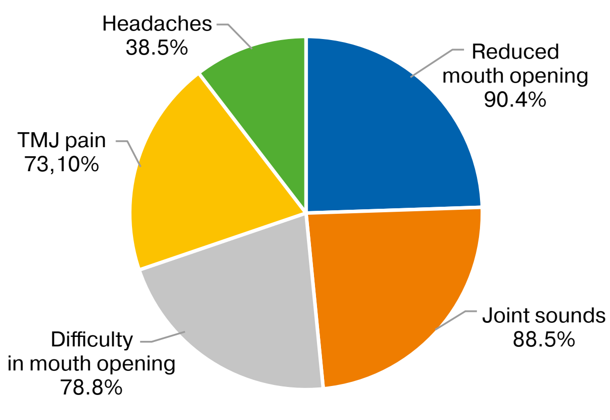


Fig. 7. Distribution of complaints from patients with internal TMJ disorders

Рис. 7. Распределение жалоб пациентов с внутренними нарушениями ВНЧС

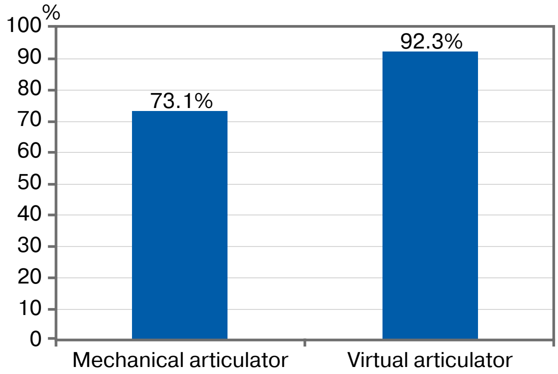


Fig. 8. The effectiveness of using mechanical and virtual articulators in diagnosing dynamic occlusion. The difference in effectiveness between the use of mechanical and virtual articulators in the diagnosis of dynamic occlusion was statistically significant ($p < 0.05$)

Рис. 8. Эффективность применения механических и виртуальных артикуляторов в диагностике динамической окклюзии. Различия между эффективностью применения механических и виртуальных артикуляторов в диагностике динамической окклюзии является статистически значимым ($p < 0,05$)

DISCUSSION

The present study is a continuation of our previous research on the comparative analysis of virtual and mechanical articulators in functional diagnostics. As is well known, occlusal analysis can be performed either directly in the patient's oral cavity or on jaw models. To simulate mandibular movements, special devices – articulators – are used. The hinge of the articulator functions as a mechanical model of the joint, which approximately reproduces the spatial movement of the patient's TMJ, thereby allowing for the simulation of physiological joint movements in terms of both amplitude and direction of displacement [25].

Mechanical articulators are widely applied for reproducing features of dynamic occlusion, particularly for tracking mandibular trajectories relative to the occlusal surfaces of the maxillary dentition. However, in some cases, mandibular movements simulated in the articulator do not correspond to the patient's individual physiological movements. This discrepancy is due to the fixed (nonadjustable) design of the articulator's condylar mechanisms, which cannot be adapted to the patient's specific anatomical characteristics. As a result, the accuracy of functional diagnostics of articulation disorders associated with TMJ dysfunction is compromised. It has been reported that errors in the adjustment of mechanical articulators account for up to 95% of inaccuracies during their use [26].

The use of mechanical facebows is also associated with frequent errors in model mounting. Such inaccuracies arise because, during mounting, the reference point is the upper frame of the articulator, whereas the distance between the condylar mechanisms and the mounted models may not coincide with the patient's individual anatomical parameters. Any vertical displacement of the models relative to the upper frame significantly affects the reliability of functional tests, since the distance between the condylar mechanism and the model changes [21]. These errors are particularly critical in TMJ diagnostics, in the fabrication of therapeutic occlusal splints for such patients, and in prosthodontic treatment. It is also important to note that mechanical facebows are positioned on the patient using extraoral reference planes, such as the Camper's or Frankfurt plane. However, extraoral and skeletal landmarks may not coincide, which leads to additional inaccuracies.

The technological limitations of mechanical articulators have a substantial impact on the accuracy of reproducing mandibular movements in dynamic occlusion [25]. The main sources of error include gaps in the fixation of registration impressions on plaster models, expansion of gypsum, and deformation of impressions. Furthermore, anatomical factors must also be considered, such as individual variations in the structure of the masticatory muscles, the elasticity and resilience of specific TMJ structures, periodontal tissue condition, individual tooth mobility, and mandibular flexion amplitude under functional load – parameters unique to each patient [21]. Accounting for all these variables is not feasible when using mechanical articulators for functional diagnostics.

The use of virtual articulators significantly reduces errors associated with anatomical variations and technical limitations [25]. In our study, the CT module (SdiMatrix) provided the ability to integrate virtual jaw models with mandibular movement trajectories obtained during axiographic examination, enabling visualization within the virtual articulator and thus improving the accuracy of functional assessment of articulation disorders.

Application of the virtual articulator in the functional diagnostics of dynamic occlusion allows for the simulation of mandibular movements that closely replicate actual mandibular function. The virtual articulator offers two approaches: mandibular movements can either be generated by condylar mechanisms or reproduced according to trajectories previously recorded through optical axiography. In this configuration, the maxilla is fixed according to cranial anatomical landmarks, while the mandible can move relative to it. Fixation of the maxilla within the virtual articulator enables real-time modeling of mandibular movements.

The use of mechanical articulators in the functional diagnostics of dynamic occlusion is associated with considerable limitations. In our study, their effectiveness was 73.1%, primarily due to design constraints that prevent acquisition of fully individualized patient-specific data.

In contrast, the virtual articulator made it possible to evaluate dynamic occlusion in multiple directions, including mouth opening and closing, protrusion, and right and left laterotrusion. The effectiveness of virtual articulators for dynamic occlusion diagnostics in our study reached 92.3%. Virtual modeling enabled continuous reproduction of mandibular movements with simultaneous registration of all possible occlusal contacts between the maxillary and mandibular arches.

The present investigation demonstrated clinically and statistically significant differences in the effectiveness of mechanical and virtual articulators (73.1% vs. 92.3%, respectively) in the functional diagnostics of dynamic occlusion ($p < 0.05$; 95% CI).

The potential influence of subjective factors during mandibular movement registration was minimized by employing the three-dimensional optical tracking system of the axiograph, which ensured precise monitoring of all movements and trajectories. The root-mean-square error of the optical system was less than 1 µm. To ensure maximum measurement accuracy, the system is capable of simultaneously tracking the position of more than 400 points.

Integration of CBCT head data with virtual jaw models in this study allowed highly accurate positioning of the models within the virtual articulator, in full accordance with individual patient-specific characteristics.

CONCLUSION

Virtual articulators demonstrate significant advantages over mechanical articulators in the assessment of dynamic occlusion in patients with temporomandibular joint (TMJ) disorders, providing greater accuracy and personalization of the diagnostic process. Mechanical articulators showed limited effectiveness and considerable measurement errors, primarily due to their non-individualized approach.

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