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Advanced Digital Technologies in Orthodontics

Theses of doctoral dissertation

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Original publications related to the Ph.D. thesis:

I. Tomášik, J**., Zsoldos, M**., Majdáková, K., Fleischmann, A., Oravcová, Ľ., Sónak Ballová, D., & Thurzo, A. (2024). The Potential of AI-Powered Face Enhancement Technologies in Face-Driven Orthodontic Treatment Planning. *Applied Sciences (Switzerland)*, *14*(17). https://doi.org/10.3390/app14177837
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II. Tomášik, J., **Zsoldos, M**., Oravcová, Ľ., Lifková, M., Pavleová, G., Strunga, M., & Thurzo, A. (2024). AI and Face-Driven Orthodontics: A Scoping Review of Digital Advances in Diagnosis and Treatment Planning. In *AI (Switzerland)* (Vol. 5, Issue 1, pp. 158–176). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/ai5010009
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III. Paľovčík M, Tomášik J, **Zsoldos M**, Thurzo A. 3D-Printed Accessories and Auxiliaries in Orthodontic Treatment. *Applied Sciences*. 2025; 15(1):78. https://doi.org/10.3390/app15010078
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[New guidelines in infective endocarditis and its dental and surgical aspects]
Orv Hetil. 2025 Feb 2;166(5):163-174. Hungarian. doi: 10.1556/650.2025.33219. PMID: 39893607.

Zsoldos, M.; Major, Á.; Kárpáti, K. Gyakorlati posztoperatív fájdalomcsillapítás a fogászatban KONZÍLIUM 2023: május pp. 15-17., 3 p. (2023)

Zsoldos M.; Major Á. A láthatatlan diszbiózis MEDICAL TRIBUNE (1589-1283): 2023 június pp 1-5 (2023)

Zsoldos M.; Angyal J. A nekrotizáló gingivitisz korszerű terápiája
Fábián Zs. A.; Matolay O. (szerk.) XII. Sántha Kálmán Tudományos Kerekasztal: Absztraktkötet 2019/2020 Debrecen: Debreceni Egyetem, pp 172-172 (2020)

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Magyar Fogorvos: (1216-2213): 29 1 pp 6-9 (2020)

1. Background of the topic

Digital technologies are a hallmark of our current era. They are both ubiquitous and often more and more indispensable. Although most digital technologies are applied across various medical and dental fields, some key digital advancements Artificial Intelligence (AI) and three-dimensional (3D) printing – had particular influence on orthodontics.

Initially conceptualized in 1955, AI has advanced through machine learning, deep learning, and neural networks, driven by Big Data. Its integration into medical imaging, diagnostics and treatment planning has expanded rapidly, enhancing daily workflows and providing tools that were inconceivable in the past, such as automated cephalometric analysis, 3D imaging, and predictive modelling.

On the other hand, orthodontics as a profession has evolved as well, shifting its focus from a solely occlusion-centred to a more "face-driven" approach, emphasizing aesthetics, not just function.

Beauty has been very important for humans for tens of thousands of years, it has been an integral part of human culture. What is beautiful has been described by certain rules, pertaining to symmetry and proportions, yet this idea remains subjective and somewhat elusive.

3D printing and related technologies enables planning and manufacturing highly customized orthodontic devices with improved precision and efficiency. There are a multitude of 3D-printing technologies, and their selection depends on the device to be fabricated. For example, directly printed aligners (DPAs) offer advantages over traditional methods, such as reducing environmental impact, improving individualization, and enhancing fit. However, challenges related to the material properties, high initial costs, and steep learning curves remain.

2. Aims

The aim of this Ph.D. thesis was to scrutinize modern digital technologies relevant to orthodontics, taking the paradigm shift – from occlusal to face-driven – into account. A comprehensive literature review was conducted to identify the most-studied digital technologies. Upon appreciating the breadth of contemporary scientific publications on the topic, our objective was to further discuss technologies that showed the most promise.

Based on our theoretical background, our next objective was to study the relationship between AI and facial aesthetics – whether deep learning-based algorithms can successfully handle the inherently challenging-to-quantify concept of human facial beauty, and how it changes faces to make them more beautiful. Consequently, our research project aimed to determine whether AI could effectively enhance the aesthetic appeal of human faces and whether AI-transformed ("beautified") images would indeed be judged as more aesthetically appealing by human evaluators. The goal of the study was to monitor the frequency of individual answers when choosing which picture is more attractive to the respondent (either original or AI-enhanced), as well as to monitor the frequency of point differences in the evaluation of the two versions for a given face.

Another objective of this thesis was to provide a detailed review of 3D printing and its use in orthodontics, stressing the need for technological advancement and education of practitioners in order to provide the most accurate and efficient *lege artis* treatment for the patients.

The aims and objectives can be summarized as follows:

1. To examine contemporary academic literature on digital technologies with a focus on facial aesthetics in orthodontics, and to assess prevailing trends, particularly those related to diagnosis and treatment planning.
2. To investigate whether specialized neural networks can successfully alter 50 facial images in alignment with human aesthetic perception, thereby addressing the broader question of AI's ability to conceptualize and modify beauty.
3. To explore the application of 3D printing technologies for orthodontic purposes within the landscape of modern digital orthodontic advancements, with particular emphasis on auxiliary devices, as reflected in contemporary scientific literature.

3. Materials and methods

Scoping Review of AI in Face-Driven Orthodontics

An organized scoping review was conducted using Scopus to identify the most cited articles on digital advances in orthodontics, as ranked by field-weighted citation impact

(FWCI). The search covered the period 2018–2023, including studies on AI, facial analysis, CBCT, 3D imaging, and treatment planning. Only English-language publications explicitly related to orthodontics were included. Using the FWCI metric, the 20 most-cited articles were identified and analyzed to determine emerging trends and technologies in AI-driven orthodontic diagnosis and treatment planning.

AI-Enhanced Facial Aesthetic Analysis

AI-based enhancement algorithm (FaceApp,ver. 11.10, FaceApp Technology Limited, Cyprus) was applied on a set of 25 male and 25 female standardized facial images to "beautify" them. Respondents evaluated the attractiveness of the original and enhanced images through an online survey, selecting the more appealing version and assigning attractiveness scores.

Further anthropometric analyses were conducted on the five image pairs with the most significant differences in before-and-after attractiveness. Using GIMP (ver. 2.10.36, Free Software Foundation, Inc.), key facial proportions were measured before and after enhancement. Additionally, AI (ChatGPT-4, OpenAI, USA) was used as a tool for further analysis. The areas of male and female faces with the most prominent changes were identified to explore whether they would match facial changes that can be achieved by means of orthodontic therapy

Literature Review on 3D-Printed Orthodontic Accessories

A literature search of PubMed and Google Scholar examined 3D-printed orthodontic accessories from 2020 to 2024, excluding those which concerned primarily aligners, brackets, and non-orthodontic applications. Case reports were included to highlight the novel use of 3D printing in customized orthodontic appliances. Studies were screened for methodological rigor and clinical relevance to provide an overview of how AI and additive manufacturing shape the future of orthodontics.

4. Results

AI and Face-Driven Orthodontics: Digital Advances in Diagnosis and Treatment Planning

A total of 147 publications were retrieved from Scopus, of which 133 met the inclusion criteria. The highest number of papers was published in 2022 (n = 36), with dentistry (25.5%), medicine (18.8%), and biochemistry/genetics (9.6%) as the most common subject areas, reflecting the interdisciplinary scope of this topic. The publications were primarily original research articles

(64.7%) and reviews (31.6%). After screening, 101 relevant articles remained, with 69 having Field-Weighted Citation Impact (FWCI) scores.

Among 20 articles with the highest FWCI scored, the dominant research areas were AI (n = 11, 55%), 3D printing (n = 3, 15%), facial scanning (n = 2, 10%), augmented reality (n = 2, 10%), and digital planning/CBCT integration (n = 2, 10%). Our results showed that AI and 3D printing were the most studied digital technologies in orthodontics.

AI-Based Facial Enhancement in Orthodontic Treatment Planning

The aesthetic evaluation surveys collected responses from 441 respondents in total. Of those, 159 and 282 participants evaluated the male and female faces, respectively. In 49 of 50 cases, AI-enhanced images were rated as more attractive, with an average attractiveness score increase of one point on a 1–10 scale. Respondents' age and gender had no significant effect on the results.

As identified by further anthropometric measurements, the most impactful AI-driven modifications involved lip fullness, eye size, and lower-face height. In male faces, enhancements were more prominent in lip volume, eye dimensions, nose width, and mouth shape, whereas in female faces, significant changes were observed in lip, eye, chin height, and midface proportions.

The analysis performed by AI identify modifications in hair and skin texture, chin width, smile, nose width, and facial shape, highlighting AI's ability to refine facial aesthetics in ways that could have potential implications for orthodontic treatment planning (especially smile and lower face third).

3D-Printed Orthodontic Accessories and Auxiliaries

A systematic review of PubMed and Google Scholar yielded 582 publications that were refined to 75 articles after screening. The studies included original research, clinical studies, case reports, reviews, and technical notes.

The most frequently used 3D printing technologies in orthodontics are stereolithography (SLA, n = 11) and digital light processing (DLP, n = 9) with resin-based materials (n = 27) and metal-based materials (n = 12).

The key advantages of 3D-printed orthodontic accessories according to the scientific literature include high precision (60%), improved patient safety (49%), increased efficiency (21%), and reduced chair-time (23%). However, high costs (61%), training complexity (45%), and extended production time (33%) were cited as the primary challenges. Additionally, material limitations (20%) and limited long-term clinical data (16%) were noted as concerns.

5. Discussion

It is clear that using novel digital technologies brings undisputable advantages in orthodontics. AI has been extensively applied in radiology, with studies demonstrating its ability to enhance imaging quality, detect pathologies, and improve landmark localization in cephalometry and CBCT analyses. Machine learning models have proven effective in automating skeletal classification, mandibular asymmetry assessments, and airway analysis. AI also plays a role in predicting treatment duration, monitoring patient progress, and assisting in decision making for extractions and orthognathic surgery.

AI shines especially in areas where there is a large amount of good quality (preferably labelled) data to teach the software. Its benefits are most pronounced when it comes to repetitive assignments or when there is a significant amount or variables to be considered. Novel application of AI-based algorithms pertains to complex 3D structures like faces their aesthetic analysis. Although AI offers a valuable tool for visualizing treatment objectives or outcomes, its limitations in predicting biologically achievable results must be considered. Ethical concerns regarding bias, privacy, and reinforcement of unrealistic beauty standards require further investigation. AI should be regarded as a decision support tool rather than a replacement for clinical expertise. While offering many advantages, AI faces challenges related to data dependency, algorithm transparency, bias, and clinical validation. The integration of AI into orthodontic education and practice requires further refinement to increase its accuracy, ensure its robustness, and gain professional trust.

Due to the medical field's special consideration, it is and likely to remain imperative to maintain expert oversight and control, not just for ethical, but also for safety concerns. A keystone of this is more transparent AI models.

Additive manufacturing has transformed orthodontics, implantology, prosthodontics, and maxillofacial surgery by offering customized appliances, surgical guides, aligners, and brackets. Key advantages include precision, efficiency, and reduced manual labour, while challenges include high costs, post-processing complexity, and biocompatibility concerns.AI-enhanced 3D printing is emerging as a promising approach for optimizing design, material selection, and manufacturing workflows.

Our literature review highlighted numerous applications of 3D printing in orthodontics, including:

- customized orthodontic appliances (e.g., distalizers, power arms, retainers),
- bone-anchored maxillary protraction (BAMP) devices,
- palatal expanders and space maintainers, and
- surgical guides for mini-implants (TADs) and bracket placement.

This manufacturing technique offers a number of benefits. 3D printing enhances treatment precision, patient comfort, and workflow efficiency; however, challenges such as cost, learning curves, and biocompatibility concerns persist. Some special consideration for example is the higher rigidity of 3D printed metal appliances, which has clinical relevance in expansion cases.

Future research should focus on AI-assisted design automation, material safety, cost reduction, accessibility improvement, and long-term clinical validation.

6. Summary

The integration of AI and 3D printing is driving a paradigm shift in orthodontics, enhancing diagnostic precision, treatment efficiency, and patient-centred care. AI-assisted orthodontics shows significant promise in diagnosis, treatment planning, and outcome prediction, although ethical and technical challenges, such as algorithmic opacity, bias, and data dependency, necessitate continued oversight by specialists. The rise of face-guided orthodontics further highlights AI's potential in treatment visualization, improving patient communication, while requiring safeguards against unrealistic expectations.

Similarly, 3D printing has revolutionized the fabrication of orthodontic devices, offering increased precision and efficiency. However, limitations such as high costs, extended manufacturing times, and material constraints must be addressed through further research. Advancements in AI-driven automation and biocompatibility could enhance its clinical applicability.

While these technologies promise transformative improvements, their successful integration requires a balance between innovation, ethical considerations, and regulatory frameworks. Future research should focus on optimizing AI models, refining 3D printing applications, and ensuring that these tools augment rather than replace clinical expertise, ultimately advancing personalized data-driven orthodontic care.

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