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Artificial intelligence in orthodontics: Part 2 – Status quo

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Artificial intelligence is now involved in many aspects of our daily life. In digital orthodontic practice in particular, practitioners are constantly and mostly unknowingly confronted with different levels of implementations of artificial intelligence. The present article, the second in a three-part series, will seek to shed light on some of these algorithms using common examples from a standard orthodontic digital workflow.

Introduction

Artificial intelligence (AI), or assistant intelligence, is a widespread and constantly evolving phenomenon that is involved in different facets of our everyday life. It is concerned primarily with implementing regular human decisions and actions into computer-based algorithms.

As stated in the previous part of this series, AI algorithms perform three main tasks: classifying certain data, predicting certain values (e.g., treatment time), and generating synthetic data[1]. In digital orthodontics in particular, practitioners are confronted with different AI algorithms on a daily basis, even if unknowingly. These are mainly implemented to simplify certain diagnostic or treatment planning workflows and are developed constantly to improve their performance. Distinct examples of these algorithms can be found in CBCT 3D cephalometric analysis, CBCT autosegmentation, facial 3D analysis, telemedical orthodontic applications like Dental Monitoring (Paris, France), and sophisticated treatment planning for aligner sequencing[2-4]. In this article, we will present some examples of currently implemented AI algorithms based on standard orthodontic clinical applications.

AI algorithms in orthodontics

As previously stated, we are constantly confronted with AI algorithms, especially in the field of digital orthodontics. Let us take the example of in-office digital aligner treatment. This usually involves the acquisition, analysis and preparation of diagnostic records, treatment planning, and finally

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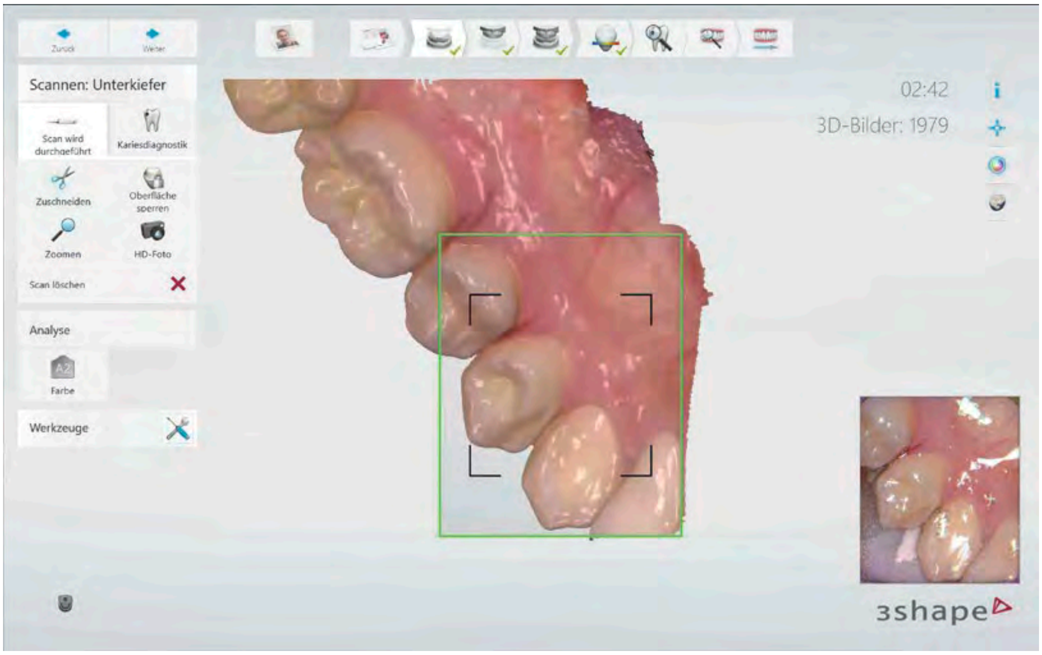


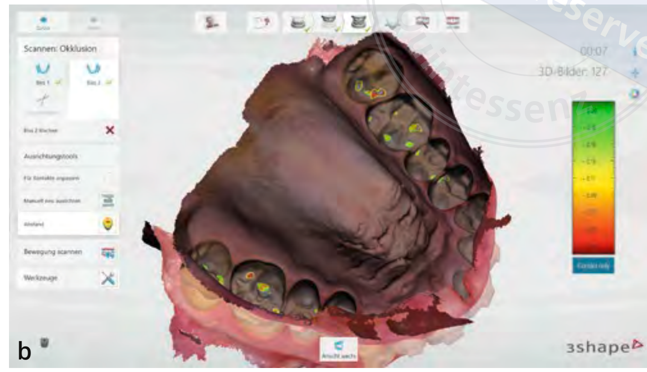
Fig 1 Intraoral scan screen showing the scan field (bottom right) and the merged 3D model during the scan process.

3D model preparation and printing. Interestingly, each of these components is packed with 'hidden' AI algorithms that aim to simplify, and sometimes even perform, standard actions required to complete each task successfully and efficiently. In the following sections, we will take a brief look at each of these tasks and provide a concise overview of the incorporated underlying AI algorithms. We will also try to examine a few drawbacks of the algorithms that are currently implemented; however, these are mainly based on the present versions of the software employed and might be improved in future versions.

Acquisition of diagnostic records

The first step in every orthodontic treatment procedure, including aligner treatment, is acquiring diagnostic records such as dental models and radiographic images. Nowadays, these steps are performed using digital radiography machines as well as model or intraoral scanners. The latter in particular use different AI algorithms for the different steps of the intraoral scan. The scan workflow normally begins with a single-arch scan. The scan tips, however, are usually reduced in size to enable intraoral usage. In this manner, the arch scan should be performed in smaller segments, with overlapping areas between each one. During the scan, however, we see a constantly growing 3D model of the arch without noticing the 'single' segment scans (Fig 1). Completion of this 3D model is usually performed in the background by sophisticated 3D AI algorithms that match the borders of each segment to the following one, align the single segments together and produce a single 3D arch model. When performing further scans from the same area, the scanner can automatically match the newly scanned surface to an existing 3D surface (e.g., the same tooth), merging the newly scanned area with the existing partial arch scan (Fig 1) and simultaneously realigning the existing segments and increasing the precision of the scan. Although these algorithms usually produce adequate results, they still require sufficient segments to provide higher dimensional accuracy[5,6].

Recent studies evaluating the accuracy of intraoral scans reported high accuracy of single tooth positions, and the total dimensional accuracy of the full-arch scan was higher in the sagittal dimension when compared to the transverse arch dimension[7,8]. This accuracy, however, was not equal for both arches, being higher for the maxillary scans than the mandibular scans[8]. The higher accuracy for the maxillary scans was justified by the additional palatal scan, which allowed for a more accurate transversal alignment of the right and left arch quadrants. Mandibular scans, in contrast, are extremely dependent on the align-



Figs 2a-c Screenshot from the intraoral scanner graphical user interface showing **(a)** the maxillary and mandibular models aligned to the vestibular scan, **(b)** the results of the alignment with no correction of the occlusal points, and **(c)** the alignment after 'automatically' reducing the overlapping for the occlusal model.

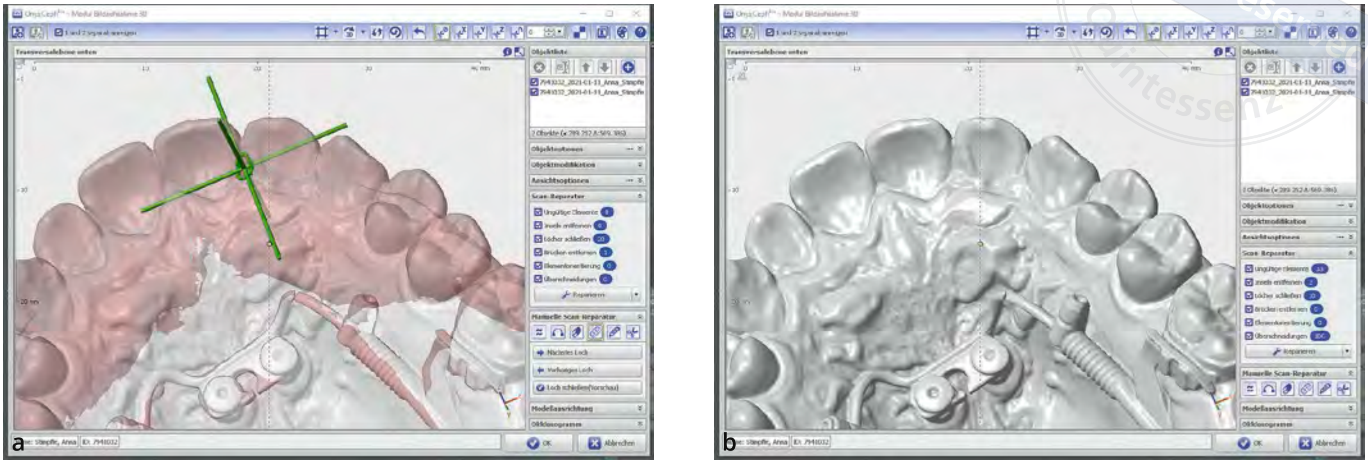
ment in the anterior segment of the 'horseshoe' scan. Further algorithms are also implemented during intraoral scanning, including hole-filling algorithms, which are usually applied for missing smaller areas of teeth as well as deep interdental areas that cannot be captured directly by the scanner. Furthermore, after single-arch scans have been performed, vestibular scans of both sides are required to align the models in occlusion. Although the latter step is usually performed using a surface aligning algorithm, a further algorithm is implemented in some scanners to adjust the occlusal alignment to avoid overlapping of the arch models. The accuracy of these algorithms, however, should be evaluated scientifically to avoid unintended manipulation of the actual occlusion (Fig 2).

With respect to radiographic records, similar fully automated and time-saving algorithms are currently implemented in web-based cephalometric analysis software. These AI algorithms show promising results for daily clinical applications[9,10].

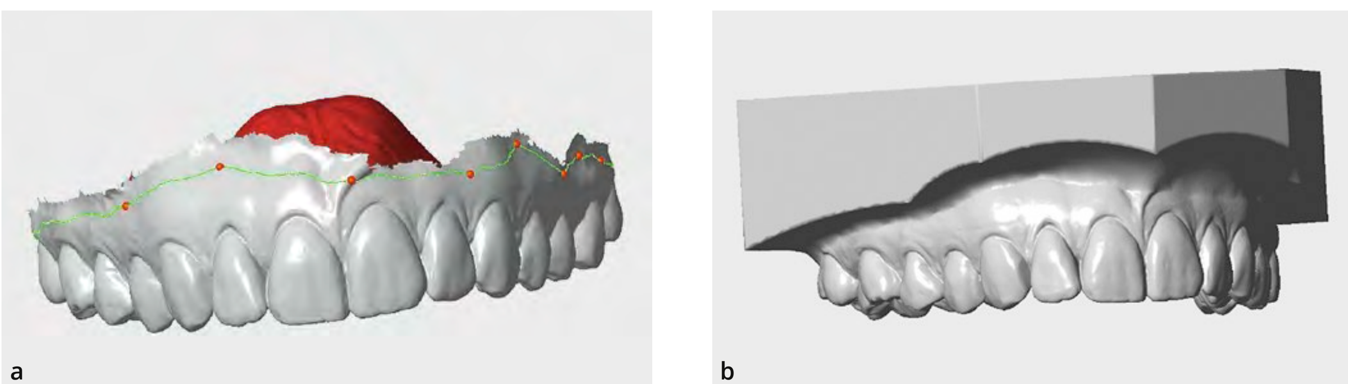
3D model preparation and tooth segmentation

After the 3D models have been acquired, they should usually be imported for further preparation and manipulation before beginning the treatment planning. These preparations generally include steps for model repair, removing unnecessary areas and checking the model surface for unsuitable areas. The first steps tend to be carried out using certain algorithms that check the integrity of the 3D model and orientation of the single model elements. The gap closing algorithms usually consider the curvature of the surface to create an even and smooth model surface. Some areas, however, especially interdentally, due to their complexity, frequently present a challenge for these algorithms, producing inaccurate results by flattening these areas, and manual adjustments by the operator are required to correct them (Fig 3).

Following the repair process, a model base should be added to produce a watertight model in preparation for



Figs 3a-b Model import and repair module. **(a)** After activating the model repair algorithm, the software will scan the model surface, automatically identifying and marking holes in the model, showing a preview of the hole filling result. **(b)** After accepting the previewed setting, the software will fill the hole. The result, however, is usually a flattened surface in the affected area.

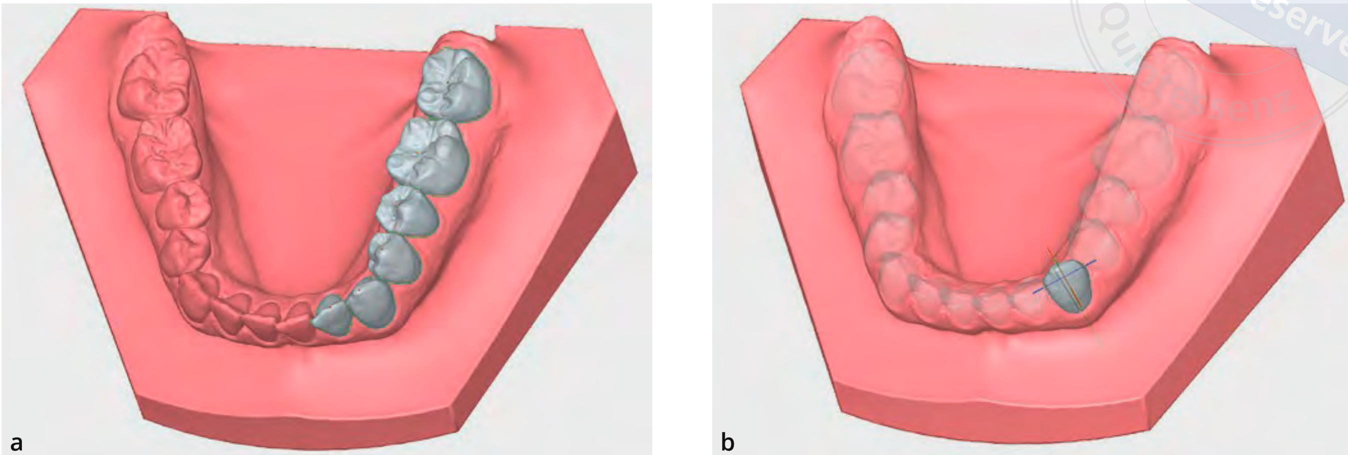


Figs 4a-b **(a)** Model trimming algorithm with the identified model boundaries, excluding all unnecessary margins of the model. **(b)** Result of the model trimming and model–base merging process.

further segmentation. This is usually done by certain AI algorithms that scan the model borders, marking unnecessary areas and indicating a cut line for the model at different preadjusted heights according to the needs of the operator (Fig 4a). Afterwards, a suitable model base can be selected from the program library and merged to the single models (Fig 4b). Even this step, despite its simplicity, might need complex calculations to be done by the AI algorithm to deliver reliable results; otherwise, an uneven surface might be created.

Another important step for model preparation is segmentation of the single teeth. This step is important to specify or recognise the crown of each tooth for further diagnostic or treatment planning tasks. Some programs currently available for everyday use generally need a single point to be placed on the model. The program then scans the whole surface surrounding this point to recognise the borders of each tooth. These borders are marked and highlighted so the operator can control the recognised tooth borders (Fig 5a). Once these borders fit the morphology of the tooth, the operator can confirm the highlighted regions, usually with a single click, and the program will separate the areas within the marked borders, creating and identifying a single 3D object for each tooth (Fig 5). During this process, the operator can compare the intraoral photos of the patient to confirm the segmentation results.

Once the previous steps have been completed, a further algorithm will scan the separated and identified 3D tooth shell and temporarily align a corresponding 3D tooth model from a preloaded library. When a suitable tooth crown has



Figs 5a-b Virtual tooth segmentation in OnyxCeph (version 3.2.169 [456]), showing **(a)** the placement of the single points identifying each tooth and the automatically identified crown boundaries for each tooth, and **(b)** the automatically orientated different anatomical landmarks and tooth axes.

been identified, it is aligned, scaled and morphed within the marked tooth shell, transferring all the corresponding points and tooth axes to the actual tooth crown. After transferring the points and axes to the corresponding crown, the segmented crown can be used for further manipulation and treatment planning. Moreover, the algorithm can identify distinct morphological features of the teeth, e.g., cusp tips, and position the points accordingly with relatively high accuracy[11] (Fig 5b). Further algorithms can add an estimated 'virtual' root to the segmented crowns for better visualisation during treatment planning. Nowadays, few proprietary packages are available that segment CBCT scans and merge intraoral scan data with CBCT data, including using true roots (as opposed to library roots) in the final tooth model in order to be used in treatment planning. By utilising such AI algorithms, the corresponding programs can save the operator time and effort by eliminating the need to mark each single point on each tooth crown. Moreover, the automatically segmented teeth, including the automatically placed points, can then be utilised easily during the further diagnostic and planning processes. Extensive research is currently being performed in this area to optimise the process for the automatic and unattended segmentation and recognition of single tooth crowns. These studies have shown promising results, with accuracy for tooth classification and segmentation of up to 89.81%[12,13].

Diagnosis and treatment planning

Orthodontic treatment planning is a relatively complicated, multifaceted process during which multiple physical records, i.e., diagnostic models, radiographs or extra-/intraoral photographs, need to be analysed. This analysis can be performed automatically or semi-automatically by dedicated AI algorithms to some extent. The final treatment plan, however, even if performed automatically, must be validated by the clinician.

Recent examples of the use of AI in orthodontics include AI algorithms for classifying and archiving orthodontic images, which in turn would facilitate the importation and organisation of patients' extra- and intraoral images and radiographs for employment in subsequent diagnostic steps[14]. Further diagnostic AI algorithms include evaluation of the lip morphology and nasolabial angle, which delivers valuable information efficiently during treatment planning, especially in extraction cases[15].

An important aspect during treatment planning for cases with impacted teeth is the space required to align these teeth in the dental arch. To date, this has been calculated manually by estimating the width of the unerupted teeth based on the width of the four mandibular incisors, but nowadays it can be done by a specifically designed AI algorithm based on the widths of the mandibular incisors and molars. This algorithm has shown a prediction accuracy of 49.5%, which was fairly accurate when compared to a Moyer analysis with an accuracy of only 45.0%[16].

Moreover, different algorithms are currently available for planning tooth movements and treatment outcomes. They can perform tasks like aligning the teeth in the dental arch or even settling the occlusion to optimise the occlusal tooth contacts. To perform these actions, however, these algorithms usually require a certain data input, which varies according to the complexity of the desired outcome. Examples of these algorithms are currently implemented in web-based applications or standalone software. Distinct examples of the latter are orthodontic diagnostic and treatment planning software like OnyxCeph (Image Instruments, Chemnitz, Germany). To perform the treatment planning process, certain data, so-called 'doctor's preferences', should be fed to the program. These usually involve defining the boundaries or maximum ranges for 3D tooth movements in dedicated input masks in the program's graphical user interface. Furthermore, different preadjusted or individual tooth angulation/inclination values can be defined and adjusted to the bracket system used by the clinician. These values, in addition to the tooth axes determined previously during the tooth segmentation process, are then utilised by the program to move the teeth into the desired position in the dental arch. During this process, the clinician can define an individual workflow for the virtual setup, indicating which manipulation tools (algorithms) should be used and in which sequence. Although this manual adjustment might sound time-consuming, it allows the clinician to adjust the program according to their own preferences.

A further example for automated virtual treatment planning is a commercially available software for automated orthodontic setups and bracket positioning (DIBS AI, OrthoSelect, American Fork, UT, USA). In this software, the teeth are identified and segmented automatically and the different axes are also identified automatically for each crown. Manual corrections, however, may be needed to adjust the borders of the crown and increase the accuracy of the bracket positioning. After the segmentation process is finished, the software will automatically align the teeth, levelling all their mesiodistal axes. This topic will be discussed extensively in the next part of this article series.

Aligner staging

In addition to the previously described AI tools for simulating treatment objectives, AI algorithms are deeply incorporated in the aligner planning and staging process. One of the main aspects to be considered during aligner staging is dividing the planned tooth movement into reasonable steps. This is a crucial stage, firstly to avoid overloading of the periodontal structures, and secondly to avoid compromising the aligner fit during clinical application. The amount of tooth movement in each setup increment also depends on the aligner material used, i.e., smaller steps should be used for stiffer aligner materials. Aligner planning software that is currently available usually allows the clinician to perform these staging steps either manually or automatically according to predefined movement limits. Automatic staging is generally performed by special AI algorithms that divide the planned movement linearly by the preadjusted increment size. Another important biomechanical aspect during aligner treatment is the anchorage situation. A classic example for this situation is distalisation of the premolars and molars and then retraction of the anterior teeth. To be able to perform this treatment without anchorage loss or undesirable protrusion of the incisors, the teeth should be moved sequentially, i.e., the molars should be distalised first, then the premolars and canines, and finally the front teeth can be retracted. This 'sequential' movement, despite its simplicity, is very time-consuming. Some aligner treatment software programs, however, include AI algorithms to perform the described sequential tooth movement automatically during aligner treatment planning. An example for the automated sequential movement can be found in the commercial aligner planning tool Archform (St Gallen, Switzerland). With the implemented tool, if a block of teeth, e.g., canines to second molars, are distalised, the program can move each tooth separately, beginning with the most posterior tooth, then moving the next tooth and so on, until they have all been moved to the desired position. Furthermore, the algorithm used creates single substages for each tooth within the programmed movement range (Fig 6).

A further step during aligner treatment planning and staging is the positioning of composite attachments on the teeth. This process is currently automated in some programs, but still requires further manual correction due to the complex geometry of the teeth and the lack of standard guidelines for the optimal positions of the different attachments for the different types of teeth and tooth movements. Furthermore, in cases of crowding and space deficit, the overlapping of the single crowns is identified after plan-

Fig 6 Sequential tooth movement in the aligner planning tool Archform. In this example, the buccal teeth, including the canines, are to be distalised. The movement stages are presented on the bottom slider with the final position (red dots) and substages (white dots) for each tooth.

ning of the target position of the teeth, which is then used to determine the amount of interproximal reduction required to achieve the planned results.

Exporting the 3D model and 3D printing

After planning the aligner treatment and creating the treatment stages, a virtual model for each stage should be exported and prepared for printing of the stereographic model. Even this process already involves many different AI algorithms for the different model preparation steps. In the orthodontic software OnyxCeph, for example, the clinician can apply different settings for the model preparation. These steps usually include trimming the model to the desired height, creating a horseshoe-shaped working model. A further algorithm can 'scan' the 3D model for undercuts in a predefined range and automatically block them out virtually to prevent the aligner from creating pressure points on the soft tissues. This allows the technician to use the stereographic model directly, without the need for further manual preparation. After performing the previous actions, the software generally utilises an additional algorithm to fuse the teeth with the model base, creating a completely closed model, a so-called 'watertight model' that can be printed directly without the need for further manipulation in the printing software. Some programs also include the ability to export 'hollow' models. This algorithm usually scans the surface of the model, adding a second layer in the inside part of the model with a predefined offset, corresponding to the model wall thickness that is desired at a later stage. During the final steps of exporting the model, these algorithms are usually 'fired' automatically in a serial manner until all the planned aligner stages have been exported.

After the models have been exported in the planning software, they can be imported directly into the printing software and prepared for printing. Usually, no further manipulations are required prior to stereographic printing; in some cases, however, the software checks the models for artefacts and repairs them to enable a smooth printing operation. In addition, the printing software can scan the 3D model after orientating the model on the printer platform virtually and evaluate the need for model supports to avoid printing failures due to the detachment of the model from the printing platform.

Conclusion

Digital orthodontic treatment planning can be assisted with AI algorithms, computational geometry techniques, biomechanical knowledge, 3D visualisation and human–computer interaction, and computer vision/image processing. AI algorithms play an ever-increasing role in digital orthodontics and are found in almost each step in the analysis and treatment planning process. In the present article, the authors focused on a few examples of AI algorithms implemented in currently available standalone and web-based orthodontic applications. Some of the algorithms described are focused on simple tasks, such as aligning and merging the single scan sections during an intraoral scan to create a full-arch scan, or defining the tooth boundaries during the segmentation process. Some algorithms also require manual data entry, e.g., setting tooth movement limits in aligner planning algorithms, an option that cannot be eliminated easily due to the lack of generally standardised aligner treatment guidelines. Nevertheless, these algorithms, despite their simplicity, save clinicians a great deal of time and effort that can be better invested elsewhere.

Current algorithms can only process data within certain boundaries and according to the amount and quality of information fed to the algorithm. The latter is crucial for training AI systems, especially data selection for neural networks, and its potential bias might affect the decisions made by the networks. In the medical field and particularly orthodontics, treatments are extremely individual. During treatment planning, various patient-related factors should be considered, e.g., medical history, treatment needs and compliance. Moreover, the individual nature of orthodontic treatment is not only patient-related but also clinician-related, depending on the preferred treatment systems or method of the latter, as well as their experience. To date, these factors have not been included in a single package that provides a global solution. A further limitation of algorithms is the lack of interconnectivity of those from different providers, which increases the need for manual data entry, and in some cases even duplicate entries of the same data in different applications. AI algorithms, however, are constantly developing and evolving; thus, these limitations may become obsolete with future applications.

Declaration

The authors declare that they have no competing interests.

References

1. Schupp W, Abu-Tarif A, Haubrich J, Elkholy F, Mah J, Krey KF. Artificial intelligence in orthodontics: Part 1. J Aligner Orthod 2021;5:251–258.
2. Chen Y, Du H, Yun Z, et al. Automatic segmentation of individual tooth in dental CBCT images from tooth surface map by a multi-task FCN. IEEE Access 2020;8:1–14.
3. Jang TJ, Kim KC, Cho HC, Seo JK. A fully automated method for 3D individual tooth identification and segmentation in dental CBCT [epub ahead of print 2 June 2021]. IEEE Trans Pattern Anal Mach Intell doi: 10.1109/TPAMI.2021.3086072.
4. Monill-González A, Rovira-Calatayud L, d'Oliveira NG, Ustrell-Torrent JM. Artificial intelligence in orthodontics: Where are we now? A scoping review. Orthod Craniofac Res 2021;24(suppl 2):6–15.
5. Kwon M, Cho Y, Kim DW, Kim M, Kim YJ, Chang M. Full-arch accuracy of five intraoral scanners: In vivo analysis of trueness and precision. Korean J Orthod 2021;51:95–104.
6. Nagy Z, Simon B, Mennito A, Evans Z, Renne W, Vág J. Comparing the trueness of seven intraoral scanners and a physical impression on dentate human maxilla by a novel method. BMC Oral Health 2020;20:1–10.
7. Radeke J, Vogel AB, Schmidt F, et al. Trueness of full-arch IO scans estimated based on 3D translational and rotational deviations of single teeth–An in vitro study. Clin Oral Investig 2022;26:3273–3286.
8. Vogel AB, Kilic F, Schmidt F, Rübel S, Lapatki BG. Dimensional accuracy of jaw scans performed on alginate impressions or stone models. J Orofac Orthop 2015;76: 351–365.
9. Kim H, Shim E, Park J, Kim YJ, Lee U, Kim Y. Web-based fully automated cephalometric analysis by deep learning. Comput Methods Programs Biomed 2020;194:105513.
10. Kunz F, Stellzig-Eisenhauer A, Zeman F, Boldt J. Artificial intelligence in orthodontics: Evaluation of a fully automated cephalometric analysis using a customized convolutional neural network. J Orofac Orthop 2020;81:52–68.
11. Stöckel K, Lapatki BG, Elkholy F. Genauigkeit und Zeitersparnis der automatischen Zahnbreitenmessung am digitalen 3D-Kiefermodell. J Orofac Orthop 2018:361–362.
12. Xu X, Liu C, Zheng Y. 3D tooth segmentation and labeling using deep convolutional neural networks. IEEE Trans Vis Comput Graph 2019;25: 2336–2348.
13. Tian S, Dai N, Zhang B, Yuan F, Yu Q, Cheng X. Automatic classification and segmentation of teeth on 3D dental model using hierarchical deep learning networks. IEEE Access 2019;7:84817–84828.
14. Li S, Guo Z, Lin J, Ying S. Artificial intelligence for classifying and archiving orthodontic images. Biomed Res Int 2022;2022:1473977.
15. Alam MK, Alfawzan AA, Akhter F, Alswairki HJ, Chaudhari PK. Evaluation of lip morphology and nasolabial angle in non-syndromic cleft lip and/palate and non-cleft individuals. Appl Sci 2022;12:1–11.
16. Camcı H, Salmanpour F. Estimating the size of unerupted teeth: Moyers vs deep learning. Am J Orthod Dentofacial Orthop 2022;161: 451–456.