Keywords
Digital orthodontics; fixed orthodontic therapy; digital treatment planning; clinical outcomes; prosthodontic integration; CAD/CAM.

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Received: 01.04.2026
Revised: 22.04.2026
Accepted: 12.05.2025
Doi: 10.1922/ejprd.v34i1s.1400

European Journal of Prosthodontics and Restorative Dentistry (2026) 34(1S),146–156

Impact of Digital Treatment Planning on Clinical Outcomes in Fixed Orthodontic Therapy: A Prospective Clinical Study

Abstract
Digital treatment planning has transformed fixed orthodontic therapy by replacing conventional analog methods with integrated digital workflows based on intraoral scanning, cone-beam computed tomography, digital models, virtual setup, and CAD/CAM-supported appliance fabrication. This narrative review aimed to evaluate the impact of digital treatment planning on clinical outcomes in fixed orthodontic therapy and to highlight its relevance to prosthodontics and restorative dentistry. Current evidence indicates that digital workflows improve diagnostic visualization, treatment simulation, and interdisciplinary communication. Clinically, digital planning contributes to more accurate bracket positioning, improved anchorage control, enhanced treatment predictability, and reduced procedural errors. It also improves treatment efficiency by minimizing mid-course corrections and optimizing clinical workflows. Patient-centered outcomes are positively influenced, with increased comfort, better communication, and higher satisfaction due to improved visualization of treatment objectives. Furthermore, digital treatment planning facilitates restorative-driven orthodontics, pre-prosthetic alignment, smile design, and implant coordination, thereby strengthening interdisciplinary care. Despite these advantages, challenges such as cost, learning curve, software variability, data accuracy, and data privacy concerns remain. Overall, digital treatment planning represents a significant advancement in fixed orthodontic therapy, offering improved clinical outcomes, greater efficiency, and enhanced integration with restorative and prosthodontic disciplines. Continued advancements in artificial intelligence, materials, and digital manufacturing are expected to further refine its clinical applications.

1. Introduction
The planning of orthodontic treatment has witnessed a paradigm shift during the last 20 years as it shifted to the traditional analog systems to the advanced digital systems. Conventionally, diagnosis and planning used depended on models of plaster studies, two-dimensional radiographs, and manual measures which despite being clinically effective were usually constrained by variability of operators, loss of visualization and inability to predict the results of treatment with sufficient accuracy. With the rise of digital technologies, a paradigm shift has become possible as it offers three-dimensional (3D) visualization, virtual simulations, and the use of data to make decisions. Digital orthodontics combines intraoral scanning, cone-beam computed tomography (CBCT) with sophisticated software platforms and thus increases the accuracy in diagnosis and enables custom-tailored treatment planning.[1]
Digitization of the traditional workflows in orthodontics has greatly enhanced the efficiency and accuracy of the traditional workflow. Digital models do not need physical storage and can easily share dates among clinicians and virtual setups will give the clinician an opportunity to simulate the movement of teeth and identify possible challenges before they can commence the treatment. Moreover, with the help of digital tools, there is a better possibility of visualization and both clinicians and patients may gain a clearer picture of the

treatment goals and anticipated results.[2] This technological and conceptual change is not a new one but it advocates a more predictive and patient centered orthodontic treatment. The use of artificial intelligence (AI) and machine learning algorithms also contributes to automated diagnostics and treatment planning that could help decrease the level of human error and enhance consistency.[3]

Over the last several years, digital dentistry has become one of the key elements of multidisciplinary dental practice. Orthodontics is no longer an isolated practice but rather it is greatly combined with prosthodontics, restorative dentistry, periodontics and implantology. Digital workflows provide the effective interaction between the various specialties due to the ability to share the standardized digital records and treatment simulations. As an example, digital smile design and virtual articulators enable clinicians to match the movement of the orthodontic teeth with restoration objectives to provide the best esthetics and functional results.[4] Such integration is especially applicable in complicated cases which demand coordinated planning whereby orthodontic treatment is a preparatory step to a prosthetic rehabilitation.

Of particular importance to prosthodontics and restorative dentistry is the applicability of digital orthodontic planning. Modern philosophies of treatment have focused on the use of restorative oriented orthodontics, in which tooth placement is controlled by the ultimate prosthetic outcome and not merely by occlusal factors. Digital tools can also be used to allow clinicians to use virtual wax-ups and test final restorations prior to the start of orthodontic treatment, resulting in better predictability of the treatment outcome and reducing the need of post-orthodontic adjustments.[5] In addition, CBCT and digital impressions contribute to a higher quality of the planning of implant location and the design of the prosthetics, which once again emphasizes the role of combined digital processes in the preparation of successful clinical outcomes in the long term.[6]

Regardless of these improvements, there are also critical aspects to be considered in the implementation of a digital orthodontic planning, in terms of accuracy, cost and clinical applicability. Although digital systems provide better visualization and data management, their quality is highlighted by the accuracy of information collection and algorithms in the software. Moreover, the implementation of digital workflows into the everyday clinical practice presupposes both equipment and training investments and can restrict its availability in some environments. However, the increasing amount of evidence indicates that digital technologies can be used to improve treatment outcomes and optimize clinical processes.[7]

The growing use of digital technologies in dental practice has also affected material sciences and production technologies. The CAD/CAM and additive manufacturing methods have facilitated the fabrication of orthodontic devices and prosthetic parts, which are very precise and customized. It has been shown that digital fabrication techniques can be as accurate as conventional techniques, or more so, in places where precision is needed, such as prosthodontics.[8] Equally, the digital impression techniques have demonstrated higher trueness and accuracy over the conventional procedures in as far as better fitting restorations and appliances are concerned.[9]

There is, therefore, an increased need to critically assess the clinical effects of digital treatment planning in orthodontics, especially in the fixed appliance therapy. Although there are several studies that investigate individual elements of digital workflows, a synthesis of their impact on clinical outcomes has not been fully researched. As such, the current review will address the effects of digital treatment planning on clinical outcomes of fixed orthodontic therapy, specifically its effects on the efficiency of treatment outcomes, precision, patient-centered outcomes, and the interdisciplinary context. This review aims at equipping clinicians with a more accurate idea of the advantages, shortcomings, and future possibilities of digital orthodontic planning in modern dentistry through the consolidation of existing evidence.

2. Methodology

This review was done as a narrative review and through a structured literature search. The keywords that were used to identify relevant studies included digital orthodontics, fixed appliance therapy, and clinical outcomes. Articles addressing digital treatment planning in fixed orthodontics with clinical outcomes reported were incorporated and those that were non-clinical, irrelevant or duplicate were removed. The basis of the selection was the screening of titles, abstracts and full texts so that only the ones that would be relevant to the aim of the review are selected.

3. Overview of Digital Treatment Planning in Orthodontics

Digital orthodontic treatment planning Digital orthodontic treatment planning is an umbrella move whereby classic analog orthodontic treatment planning has been supplanted by an entirely IT-based workflow. This change is defined by the complex of the use of high-quality imaging modalities, digital models, and the special software, all of which will improve the diagnostic accuracy, predictability of treatment, and interdisciplinary coordination.

3.1 Components of Digital Workflow

The intraoral scanning is the basis of the new digital orthodontic since it allows taking precise three-dimensional (3D) dental impressions. Intraoral scanners are better patient-friendly, shorter chairside time, and have better reproducibility compared to conventional impressions. Research has found that digital impressions are very accurate and reliable in terms of orthodontic diagnosis and treatment planning.[10] Also, the development of scanning technologies and protocols has also streamlined precision, even in complicated clinical situations.[11] The diagnostic uses of intraoral scanners are not limited to model acquisition, it is also used to help to analyze occlusion and tooth structure in detail.[12] New evidence also emphasizes the role of operator technique and scanning strategies in the enhancement of accuracy

and reducing errors.[13] In addition, such patient-centered outcomes as decreased discomfort and enhanced acceptance have been repeatedly reported in clinical practice.[14]

CBCT imaging is important in offering three dimensional images of craniofacial structures such as root of teeth, alveolar bone and other anatomical landmarks in the vicinity. CBCT is a supplement to digital models, which amplifies the diagnostic potential of the system especially in complicated cases that need accurate determination of the position of roots and bone morphology.[15] Moreover, CBCT has also been used more and more in the overall assessment of orthodontics and provides useful information in the treatment planning and risk analysis.[16]

Digital models have mostly substituted the traditional plaster casts because of their convenience to store, access, and allow detailed measurements and analyses. Digital models empower clinicians to conduct virtual examinations, track treatment progress, and exchange information effectively among multidisciplinary groups. There is some evidence that digital models are not only comparable to traditional casts in the accuracy but also offer other benefits in the workflow and the management of data.[17]

Digital orthodontic planning requires the use of software platforms, including ClinCheck and OrthoAnalyzer, which allow the use of virtual configurations, simulation of tooth movement, and prediction of the outcome of the treatment. Such platforms enable therapeutic clinicians to see the course of treatment and implement the required changes prior to therapy. Arguments in favor of digital setup fabrication accuracy and reliability have been discussed proving the significance of expert operator and software abilities in finding the best result.[18] Also, the use of digital superimposition tools helps to more accurately quantify the movement of the teeth, which improves the planning of the treatment and its assessment.[19] It has also seen the recent advancements in digital orthodontic setups which have focused more on enhanced predictability and precision in complex treatment situations.[20]

3.2 Technologies Involved

The CAD/CAM systems have transformed the process of manufacturing orthodontic appliances because it allows the use of customized brackets, archwires, and indirect bonding trays that are highly precise. These systems improve their treatment efficiency and consistency as well as minimize manual errors that are involved in the traditional fabrication processes.[21] Moreover, both accuracy and precision of digital impressions in CAD/CAM processes have been demonstrated to be high and corroborate their extensive use in the clinic.[22]

The artificial intelligence (AI)-assisted planning is a relatively new area that has already had a substantial influence on the diagnosis and treatment planning in the field of orthodontics. With the help of AIs, it becomes possible to examine extensive data, make treatment choices, and anticipate the results with greater precision. Recent research illustrated the possibilities of AI to improve the efficiency of diagnostics and help in the individual treatment strategy.[23] Besides, there remains a continuing growth in AI applications in the field of dentistry, which provide new opportunities in terms of automation and better clinical outcomes.[24] The fact that AI can be incorporated into digital workflows also enables the use of advanced data analysis and decision support systems[25], and the fact that it can also be applied to biomaterials and dental studies also leads to emphasizing the fact that AI can be used across the fields. [26]

Among the main characteristics of the digital orthodontic planning are virtual set-up and simulation, providing clinicians with the opportunity to simulate the movement of the teeth and visualize the ultimate results before the start of the treatment. These devices are able to enhance predictability of the treatment and provide the possibility to plan orthodontic mechanics more accurately. Potential clinical evidence has shown that digital set ups are accurate in controlling moderate crowding when using fixed appliances[27], which has been used to support their clinical usefulness in modern orthodontics.

3.3 Comparison with Conventional Planning

Digital approaches are more advantageous than traditional methods of planning in terms of diagnostics, visualization, and communication. Digital technology allows making accurate measurements and analysis and minimizes the error rate related to manual methods. Clinical trials comparing digital bonding and planning systems have shown that there is better precision in bracket placement and general treatment planning.[28]

Another important advantage is improved visualization, since three dimensional representations enable clinicians to comprehend the spatial relationship more and also to simulate the outcomes of the treatment. Not only does it facilitate clinical decision-making but patient understanding and engagement are also improved.

Digital workflows will enable smooth transfer of information among clinicians, laboratories, and patients in regard to communication. It is easy to share digital impressions and simulations of treatment, which facilitates interdisciplinary collaboration and enhances the overall coordination of treatment. Also, patient-reported outcomes report that patients prefer digital methods because they feel more comfortable and communicate better when planning their treatment.[29]

All in all, digital treatment planning is a more accurate, efficient, and patient-centered alternative to the traditional orthodontic workflow and it contributes to its increasing popularity in the contemporary clinical practice. Table 1 summarizes the key elements of the digital orthodontic workflow, clinical applications of them, and their impact on treatment outcomes. The general digital workflow and its effect on clinical outcomes were summarized in Figure 1.

Table 1. Components of digital workflow and their clinical applications in fixed orthodontic therapy

Digital Component	Clinical Application	Advantage over Conventional Methods	Impact on Clinical Outcomes	References
Intraoral scanning	Digital impressions, occlusal analysis	Improved patient comfort, reduced distortion, better reproducibility	Enhanced accuracy and reduced chairside time	[10–14]
CBCT imaging	Three-dimensional assessment of roots, bone, and anatomical structures	Superior visualization of craniofacial anatomy	Improved diagnosis and anchorage planning	[15,16]
Digital models	Virtual study models and treatment monitoring	Easier storage, retrieval, and data sharing	Increased efficiency and reproducibility	[17]
Software platforms (e.g., ClinCheck, OrthoAnalyzer)	Virtual setup, simulation, and superimposition	Better pre-treatment visualization and planning control	Improved predictability and treatment planning	[18–20]
CAD/CAM systems	Customized brackets and appliance fabrication	Greater precision and standardization	Reduced fabrication errors and improved appliance fit	[21,22]
AI-assisted planning	Diagnostic support and treatment prediction	Automated and data-driven decision-making	Increased consistency and planning efficiency	[23–26]
Digital indirect bonding	Virtual bracket positioning and tray-guided bonding	Reduced operator variability	Improved bracket placement accuracy and fewer bonding errors	[30,31]
3D printing	Production of models, trays, and orthodontic components	Rapid and customizable fabrication	Enhanced workflow efficiency	[60]

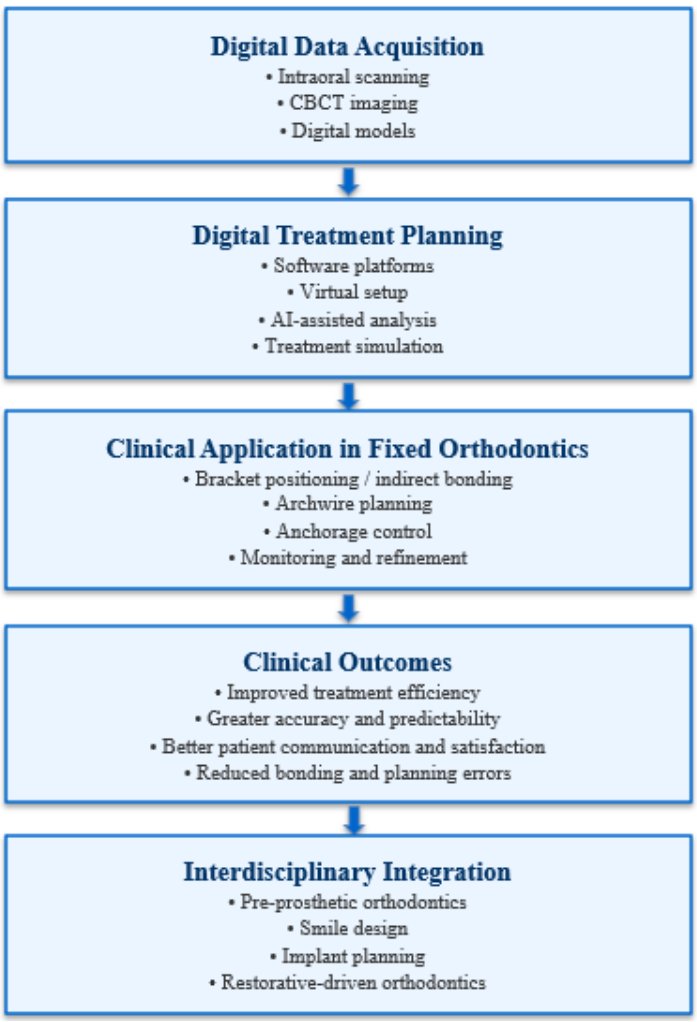

Figure 1. Digital workflow in fixed orthodontic therapy and its impact on clinical outcomes.

4. Clinical Applications in Fixed Orthodontic Therapy

Digital treatment planning has demonstrated a great impact on the clinical implementation of fixed orthodontic therapy by raising precision, efficiency, and predictability in different stages of the treatment. The adoption of digital tools in everyday practice of orthodontics enables practitioners to streamline the overall mechanics of treatment and attain more predictable results.

One of the most notable uses of digital orthodontics is the so-called bracket positioning (indirect bonding). According to digital workflows, the brackets can be virtualized on 3D models and then single-use transfer trays are fabricated to perform specific intraoral bonding. This method reduces errors that are operator-specific, and the precision of the positioning of the brackets is more accurate than traditional methods of direct bonding.[30] Besides, the digital indirect bonding systems have been reported to be more efficient in the clinic and have less chairside time without compromising accuracy. [31]

Digital developments have also enabled archwire planning to be used with greater precision of customizing archwires with reference to virtual configurations. Digital treatment planning allows the clinicians to predefine tooth movements and choose correct archwire sequences based on these. This helps in better force application and control of tooth movement thus leading to better results of treatment.

The other important issue of fixed orthodontic therapy, which has been enhanced by digital planning, is anchorage control. Modern imaging and simulation can enable clinicians to assess bone quality, anatomy constraints, and an ideal position of temporary anchorage devices (TADs). Clinical trials have shown that mini-screws placement with guidance via digitally can lessen patient agony and enhance the accuracy of the procedures.[32] Also, it is necessary to comprehend anatomic variations, bone thickness, and bone density, which are critical to effective anchorage planning, which has been effectively reported in the previous studies.[33]

One of the biggest improvements in digital orthodontics is treatment simulation and prediction. Virtual systems allow clinicians to test movement of the teeth, assess treatment options, and determine the final results prior to administering treatment. The simulations enhance the accuracy of the treatment planning and enable easier communication with the patients. The use of machine learning models also contributes to the predictor abilities, enabling the use of data to make decisions in complicated situations.[34] This type of technologies encourages personalized treatment methods and leads to enhanced clinical efficiency and predictability.

The general effect of the digital treatment planning on the fixed orthodontic therapy is that it has resulted in the improved biomechanics, more accurate bracket positioning, greater management of anchorage and better predictability of the treatment. Such developments reaffirm the increasing relevance of digital processes towards the delivery of high-quality orthodontic results.

5. Impact on Clinical Outcomes

Digital treatment planning as a part of fixed orthodontic therapy has proven to impact the clinical outcomes significantly. They are especially noticeable in the efficiency of treatment, accuracy and predictability, patient-related outcomes and decreased error in the procedures. All these digital workflows have helped to make the orthodontic practice easier, refined, and patient-centric.

5.1 Treatment Efficiency

The enhancement of efficiency of treatment is probably one of the most obvious benefits of digital orthodontic planning. Digital workflows allow an accurate diagnosis, virtual simulation of treatment, and optimal appliance design, which reduces unnecessary correction in the treatment process. This will lead to a quantifiable decrease in the total treatment time and better clinical workflow. There is a systematic evidence that systematic evidence can be used to impact treatment time during fixed orthodontics due to better planning and reduced mid-course treatments.[35]

Moreover, digital systems will help to reduce the number of clinical appointments through the decrease of mistakes during placing brackets and having an order of treatments. A pre-planning and simulation capability enables clinicians to deliver treatment in an efficient manner, which saves time on the chairside and increases the productivity. The presence of external factors that influence the duration of treatment, including the lack of care disruptions, only emphasizes the need to have an efficient and well-designed treatment planning.[36]

5.2 Accuracy and Predictability

Digital orthodontic planning greatly improves accuracy and prediction especially in the movement of teeth and the treatment result. The virtual systems and simulation technologies enable clinicians to predict the movement of the tooth and modify the treatment regime. Nevertheless, even though computerized systems increase accuracy, there is still a degree of variability when it comes to the movement of the teeth because of biological aspects. The initial research on orthodontics using aligners proved that the planned and actual movements can be different, which underlines the need to carefully plan.[37]

Recent developments have also enhanced the concept of orthodontic biomechanics by showing better control of the movement of teeth by using digitally guided planning.[38] The results of the studies which analyzed the outcomes of treatment among the various groups of patients have indicated that the use of digital planning is associated with more accurate and predictable outcomes.[39] It has also been found through the use of finite element analyses into biomechanical responses in tooth movement supporting the use of digital tools in optimizing force systems.[40] Also, three-dimensional assessments established effectiveness of digitized systems in the attainment of the planned teeth motions and correction of the occlusal discrepancies.[41]

In relation to occlusal outcomes, digital planning is helping to achieve better alignment and functional occlusion owing to the ability to control the vertical and sagittal relationship. The findings of clinical suggestions

grounded on digital and conventional frameworks indicate that digital workflows have the capability of aiding effective treatment planning and decision-making in orthodontics.[42] Moreover, digital-assisted orthodontic therapy has shown positive results in terms of using the 3D outcome measure of positive changes in occlusiveness.[41]

5.3 Patient-Centered Outcomes

Patient-centered outcomes such as comfort, compliance, and general satisfaction also have been improved with digital orthodontics. Digital tools, including intraoral scanners and guided placement systems, make the procedure less uncomfortable to the patient and improve the experience. The clinical research has indicated that advanced techniques such as digitally guided anchorage placement correlate with the reduction of pain and enhancement of tolerance in the treatment course.[43]

Digital and modern orthodontic methods proved to be more acceptable and compliant especially among pediatric populations as opposed to conventional appliances.[44] In the same light, the comparison of various orthodontic modalities suggests that digital modalities are capable of enhancing oral health-related quality of life and comfort to patients.[45]

Another important outcome that is affected by digital workflows is patient satisfaction. The evaluations made over long terms have revealed that patients say that they are highly satisfied with orthodontic treatment especially where they find it efficient and their results are predictable.[46] The fact that the results of the treatment may be visualized in digital simulations increases the level of patient comprehension and involvement even further and leads to the improvement of the clinician-patient communication process.

Communication and visualization are also improved with the help of digital tools that enable patients to understand the treatment plans and the results expected in a better way. It enhances patient education, informed consent and strengthens clinician patient relationship using three dimensional simulation and visual aids.

5.4 Reduction in Errors

One of the main positive effects of the digital treatment planning is the decrease in the number of clinical errors, especially with bracket bonding. Digital indirect bonding methods permit accurate placement of bracket reducing placement errors and enhancing accuracy of treatments. It has been proved that the digital bonding systems are capable of greatly decreasing the errors related to the manual methods.[30]

Furthermore, the digital workflows are associated with a reduced level of refinements necessary during treatment. Digital planning minimizes the chances of remedial intervention in the middle of the course by allowing the correct prediction of tooth movement and accurate positioning of appliances. Future research has indicated that online arrangements enhance predictability of treatment and minimize the further adaptations in treatment.[27]

Altogether, digital treatment planning can be characterized as a method leading to better clinical outcomes due to its efficiency, accuracy, better patient experience, and the reduction of mistakes. These benefits favor the increasing use of digital workflows in fixed orthodontic therapy and emphasize the importance of them in the modern orthodontic practice development.

6. Integration with Prosthodontics and Restorative Dentistry

The digital orthodontic planning system and the incorporation of digital orthodontic planning with prosthodontics and restorative dentistry is a critical breakthrough in the overall dental care. The current treatment style is less oriented on unilateral treatment and more on interdisciplinary cooperation, in which the orthodontic movement of teeth is directed towards restorative and prosthetic goals. Such integration is possible through the use of digital workflows, which allow visualization, simulation, and coordination of the various dental specialties accurately.

Pre-prosthetic orthodontics is also important in setting teeth positions in the most effective way before the restorative procedures which include crowns, bridges and implants. Digital treatment planning enables clinicians to consider the distribution of space, root position, and occlusal relationships beforehand so that the conditions could be perfect to rehabilitate with prosthetic. Digital workflows are demonstrated to promote the alignment of orthodontic and restorative stages contributing to the improved results in terms of function and esthetics.[47] Moreover, digital technology in the field of prosthodontics helps to take a more predictive approach to the organization of treatment, which is based on the necessity to coordinate the orthodontic procedures with the final restorative outcomes.[48]

The other important use of digital orthodontics in restorative dentistry is smile design integration. Digital smile design (DSD) tools provide clinicians with the ability to see the resultant final esthetic look prior to starting the treatment, so the orthodontic movements could be arranged to be in balance with the facially and dentally aesthetic look. This practice improves communication with patients and makes sure that the results of the treatment process satisfy not only functional but also esthetic requirements. As reported in the clinical practice, digital workflows have proven efficient in an esthetic rehabilitation effort, especially in more complicated scenarios where periodontal or structural compromise is involved.[49]

Digital orthodontic and prosthodontic workflows have been used to enhance the coordination of implant planning. CBCT and intra oral scans, which are part of digital imaging, enable the accurate evaluation of the bone volume, implant placement and prosthetic needs. The efficient planning and execution of the workflow in the field of implant dentistry can be supported by fully digital workflows and helps to reduce the risk of issues and follow the positive outcome in the long-term.[50] Moreover, the digital impressions and models are also used to achieve greater precision in the implant-supported restorations, which once again promote the importance of the digital integration in multidisciplinary care.[51]

The interdisciplinary approach towards work is of paramount importance in the current dental practice especially cases that demand the cooperation between orthodontists, prosthodontists, and restorative dentists. Digital solutions allow clinicians to share and communicate data seamlessly, which is why coordinating treatment plans and their execution becomes a possibility. Integration of orthodontic and restorative treatment using digital processes has been demonstrated to enhance effectiveness and predictability in treatment.[52] The efficacy of digital restorative workflows in dealing with the developmental defects and complex rehabilitation cases is also emphasized in case series and clinical reports.[53] In addition, the interdisciplinary integration has been strengthened by the fact that comprehensive digital approaches have proven to be more precise and predictable when used in fixed prosthodontic treatments.[54] New technologies in digital fabrication and prosthetic design also aid in the achievement of better results when both orthodontic and restorative treatment is intended to be performed.[55]

Digital wax-ups and restorative-based orthodontics is a paradigm shift in treatment preparations where the ultimate prosthetic result determines the orthodontic tooth movements. Digital wax-ups enable clinicians to design the final restoration they want and calculate the orthodontic adjustments they need to make. Virtual articulators and computerized restorative planning processes have been demonstrated to increase precision and predictability in the planning of treatment.[56] The strategy will make sure that the orthodontic treatment is not done in a vacuum but is coordinated with the restorative strategy, which will eventually lead to more functional and esthetic outcome.

To conclude, the combination of digital orthodontics and prosthodontics and restorative dentistry allows creating a more complex, accurate, and patient-centered treatment. Digital workflows are essential to enhance clinical outcomes and advance the modern dental practice by making interdisciplinary collaboration and alignment of orthodontic planning and restorative goals possible.

7. Role of Dental Materials and Technology

The success of digital orthodontic working processes is concentrated around dental materials and newly developed technologies. Under the fixed orthodontic therapy, the developments in material design, surface engineering, and digital manufacturing have enhanced the accuracy of appliances, biomechanical performance, and overall clinical performance. Such developments will be complementary to digital treatment planning since they allow more personalized and predictable treatment delivery.

Brackets and appliances produced through CAD/CAM have increased the sales of customized orthodontic treatment. The nature of digital design and manufacturing enables the possibility of more standardization, a better fit, and better control of the forces, over the traditionally fabricated parts. Secondly, the reliability of the materials has also emerged as a significant factor in the digitally-controlled orthodontic systems since the accuracy and stability of the treatment, as well as the functionality of the bonded attachments and appliance components, directly depends on the quality of the materials.[57]

Another technological application that is significant in the field of fixed appliance therapy is digital indirect bonding trays. The trays enable proper application of the position of brackets in the virtual environment to the clinical environment thus minimizing the variance of the manual control and enhancing uniformity. Their performance is not based on accuracy of digital planning alone but also the stability of the dimensional and characteristics of the tray material. Subsequently, the choice of materials has been a crucial consideration when it comes to the high accuracy of bracket placement and minimization of transfer distortion.

The role of technology in orthodontics has also been added on with the advancements made in the biomaterials. More modern studies have sought to enhance surface characteristics of orthodontic substances to minimize friction, increase corrosion toughness and offer antibacterial qualities, all of which could lead to enhanced clinical efficiency and exterior wear durability of appliances.[58] Simultaneously, improved knowledge about biologic mediators in bone remodeling has offered insight into the behavior of material performance in combination with tissue response during orthodontic tooth movement.[59] These changes embrace an increased biological perspective in the designing and treatment planning of appliances.

The application of 3D printing in orthodontics has become one of the most promising technological advances in the past few years. Through additive manufacturing, models, templates, transfer trays and tailored orthodontic parts can be manufactured within a very short period with high levels of precision. It is also useful to facilitate a leaner digital workflow, including less laboratory work and near-chairside or chairside fabrication in the select cases. New indications indicate that future opportunities of customizing and manufacturing appliances and orthodontic practice can be expanded through integrated 3D-printing strategies.[60]

In general, the application of dental materials and technology in digital orthodontics is not limited to fabrication. It affects appliance accuracy, mechanical efficiency, biologic response and clinical reproducibility. With the further development of digital systems, the material innovation will be a necessary part of the process of converting virtual treatment schemes into effective fixed orthodontic results.

8. Limitations and Challenges

Even though digital orthodontic treatment planning has its benefits, there are a number of limitations that should be taken into account. The cost and access are also a major issue, with the initial cost of acquiring intraoral scanners, CBCT, software, and 3D printing technologies potentially being high, thereby limiting their usage in smaller or resource-limited practices. Moreover, the learning curve of the transformation to digital workflows imposes a burden on clinicians to acquire new technical skills in scanning, their navigation in the software and the interpretation of their data, which can slow down efficiency at first. The variability of the software also

makes the implementation more complicated because the difference in the algorithm and interoperability between platforms may be unequal and cause discrepancy in the treatment planning. The issues of data accuracy are also present, as scanning methods and patient motion or CBCT artifacts can also lead to errors and can influence the diagnostic accuracy and clinical outcomes. Moreover, the problem of ethicality and data privacy is becoming more critical, with the digital systems being associated with the storage and sharing of sensitive patient data, and the need to comply with data protection and cybersecurity regulations. In general, although digital orthodontics has significant clinical advantages, these issues need to be resolved to make sure that it becomes a useful and efficient part of the daily practice.

9. Evidence from Prospective Clinical Studies

Potential clinical investigations offer some of the most pertinent data in order to assess the impact of digital treatment planning on the impact of fixed orthodontic treatment. The existing research shows that digitally guided processes enhance treatment accuracy, especially accuracy in virtual setup, appliance placement, and clinical execution in controlled settings and conditions.[27] This is particularly essential, as, when planned digital moves are directly observed, it would be possible to compare future design with the actual treatment outcomes.

The clinical benefits of digital workflows in the chosen procedures have been supported, in general, by the comparative evidence available on the topic of digital versus conventional methods. The research on digital indirect bonding and personalized bracket placement has demonstrated higher transfer accuracy and better bracket placement than traditional ones and can potentially lead to higher efficacy of treatment and reduced procedural errors.[28] Review evidence on direct and indirect bonding also indicates that digitally assisted bonding techniques enhance consistency in placements and clinical control of them.[30] In associated digitally guided processes, the emerging data have also demonstrated better patient experience and procedural accuracy, indicating that the advantages of digital planning can be not just limited to the placement of appliances.[32]

Prosthodontic and restorative research also support the strength of digital evidence in terms of an interdisciplinary approach. Comparative studies of standard and digital fabrication techniques have shown high proportion of accuracy and reproducibility in digitally fabricated prosthetic frameworks and impressions of implants which support the reliability of digital processes in challenging oral rehabilitation.[55] Even though these studies are not confined to orthodontics, they reinforce the larger clinical argument of digital precision and transferability in specialties.

All in all, the existing body of evidence could be estimated as moderate and encouraging. The current body of prospective and comparative research on the topic is in support of digital planning due to its greater accuracy, predictability, and possibility of controlling of the workflow, although the evidence base remains small with limited sample sizes, diverse study designs, and outcome measures.[27] Additional large-scale prospective clinical trials are required to draw more firm conclusions about the long-term superiority of digital treatment planning in comparison to conventional methods in fixed orthodontic therapy. Table 2 contains a summary of the main clinical outcomes related to the use of digital treatment planning in fixed orthodontics treatment.

Table 2. Impact of digital treatment planning on clinical outcomes in fixed orthodontic therapy

Digital Intervention	Comparator	Outcome Assessed	Key Findings	Clinical Significance
Digital setup	—	Accuracy of tooth movement	High agreement between planned and achieved outcomes	Supports predictability of digital planning[27]
Digital indirect bonding	Conventional bonding	Bracket positioning accuracy	Greater precision with digital approach	Improves treatment accuracy[28]
Indirect bonding techniques	Direct bonding	Bonding accuracy	Improved consistency with indirect techniques	Reduces operator-dependent errors[30]
3D digital bonding systems	Conventional bonding	Bonding efficiency	Enhanced workflow and reduced chairside time	Improves clinical efficiency[31]
Digitally guided TAD placement	Conventional placement	Patient discomfort and placement accuracy	Reduced pain and improved procedural precision	Enhances patient-centered outcomes[32]
Digital impressions	Conventional impressions	Trueness and precision	Comparable or superior accuracy	Reliable for interdisciplinary workflows[51]
Digital fabrication methods	Conventional methods	Prosthetic accuracy	High precision with digital techniques	Supports interdisciplinary integration[55]
Digital impressions	Conventional impressions	Patient satisfaction	Higher patient acceptance and comfort	Improves patient-centered outcomes[29]

10. Future Directions

The prospect of orthodontics is being influenced by the rapid technological progress in digital technologies, especially the growing role of artificial intelligence (AI). The AI will supposedly improve the performance of diagnosis, provide an automatic treatment planning, and

predict the treatment outcome more accurately, which will result in a higher degree of consistency and lower variability based on an operator. Simultaneously, the evolution of self-contained digital workflows is changing the field of clinical practice, enabling the smooth integration of the diagnosis, planning, appliance manufacturing, and treatment monitoring. This integration enhances efficiency as well as facilitates enhanced interdisciplinary collaboration on complex cases.

The other tendency is the movement towards individualized treatment planning, with digital tools allowing it to be tailored to specific anatomical and biological characteristics of a patient, resulting in more predictable and specific results. More innovations in smart materials and automation, such as improved manufacturing processes as 3D printing, are likely to keep orthodontic processes even more streamlined and allow the manufacture of highly customized appliances. All these changes point to the shift towards more exact, efficient, and patient-centered orthodontic treatment.

11. Clinical Implications

There is an evident practical use of digital treatment planning in relation to clinicians who are engaged in fixed orthodontic therapy. It enhances the visualization of a diagnosis and assists in better sequencing of the treatment, which would aid in making more informed decisions by the clinician when planning the case.[2] Digital technologies are particularly effective in everyday practice when it is necessary to be able to position brackets accurately and simulate a treatment virtually since these two procedures directly affect the control and predictability of treatment and are linked to one another.[30]

Digital planning is most useful when it is a complicated case that requires more accuracy, interdisciplinary coordination, or restorative considerations. It is also quite beneficial in those cases when orthodontic therapy should be correlated with restorative or prosthodontic goals since the digital workflow enables a better exchange of information between specialities.[47] The cost benefit aspect of it is that the initial cost of it might be high, but increased efficiency, fewer errors in the process, and workflow can be a worthwhile adoption in the long term. To implement digital systems successfully, clinicians are advised to move step-by-step to digital, choose quality software and hardware and receive proper training to guarantee proper data recording and good clinical utilization.[12]

12. Conclusion

Digital planning of treatment has become a revolutionary practice in fixed orthodontic treatment, which essentially changes the manner of how diagnosis is made, planning is made, and the way treatment is carried out. Replacement of traditional processes with the new digital workflows has enhanced the accuracy of diagnosis, visualization of treatment, and clinical efficiency enabling clinicians to provide a more predictable and patient centered care. The intraoral scanning, CBCT imaging and virtual setups, as well as CAD/CAM systems have all served to enhance the accuracy of treatment planning and enhance the co-ordination in various stages of the treatment. Clinical and prospective studies show that digital orthodontic planning can positively impact the efficiency of the treatment process through error reduction, minimization of refinements, and optimization of clinical processes. Better positioning of braces, simulation of treatments and anchorage planning has further enhanced predictability of orthodontic results. Moreover, digital tools have impacted the experience of the patients positively, enhancing communication, visualization, as well as, satisfaction. One of the strengths of digital orthodontics is that it is connected to the sphere of prosthodontics and restorative dentistry. The idea of the restorative-based orthodontics, which is facilitated by the digital processes, allows the clinician to track tooth motion towards the end-objective of the final prostheses, as well as to enhance the functional and esthetic outcomes. This interdisciplinary strategy underlines the increased role of digital technologies in the overall care of the dentists. Nonetheless, issues like cost, learning curve, variation of software and accuracy of data should be resolved in order to be implemented successfully. Although these constraints exist, the continued progress in artificial intelligence, material science, and computer-aided manufacturing will continue to perfect the orthodontic practice. Conclusively, digital treatment planning is an important innovation in fixed orthodontic treatment that provides better clinical results, increased efficiency, and multidisciplinarity.

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