



www.bioinformation.net
Volume 22(9)



Research Article

Received September 1, 2026; Revised September 30, 2026; Accepted September 30, 2026, Published September 30, 2026

DOI: 10.6026/973206300225522

SJIF 2026 (Scientific Journal Impact Factor for 2026) = 8.478

2022 Impact Factor (2023 Clarivate Inc. release) is 1.9

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Citation: Chavda *et al.* Bioinformation 22(9): 5522-5526 (2026)

Artificial intelligence-based prediction of prosthesis displacement under simulated functional movements: An *in vitro* study

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Abstract:

Prosthesis displacement during function compromises comfort, retention and masticatory efficiency, yet routine prosthodontic assessment still depends largely on subjective clinical observation. Therefore, it is of interest to evaluate whether artificial intelligence could predict maxillary complete denture displacement under simulated functional movements using optical tracking and load-cycle data. Seventy-two maxillary denture bases fabricated with conventional heat-cure, milled PMMA and 3D-printed resin were tested on standardized edentulous models under vertical, lateral and protrusive movements with and without simulated salivary film. Mean displacement was lowest for milled PMMA with simulated saliva (0.41 ± 0.12 mm) and highest for 3D-printed resin under dry lateral loading (1.18 ± 0.26 mm; $p < 0.001$), while the artificial intelligence model predicted high-displacement events with 90.3% accuracy and AUC 0.95. Thus, artificial intelligence-based optical tracking accurately predicted denture displacement patterns and may support objective evaluation of prosthesis retention under functional simulation.

Keywords: Prosthesis displacement, complete denture, artificial intelligence (AI), optical tracking, functional movements, digital prosthodontics, retention

Background:

Removable prosthesis stability is essential for mastication, speech, comfort and patient confidence, yet displacement during function remains a common problem when tissue support, border seal, or occlusal balance is inadequate [1]. Digital denture workflows have improved fabrication consistency, but prosthesis movement under simulated function is still influenced by base adaptation, material stiffness, palatal form, ridge anatomy and processing accuracy [2, 3]. Conventional assessment of denture displacement relies on visual observation, pressure-indicating media, patient feedback, or manual measurement after loading. These methods are useful but may not fully describe three-dimensional movement during repeated function [4]. CAD-CAM denture base materials show favorable mechanical behavior compared with conventional heat-cured polymethyl methacrylate, yet material superiority does not automatically guarantee functional stability if the bearing surface or occlusal load distribution is unfavorable [5, 6]. Artificial intelligence may help interpret motion-tracking data by identifying displacement patterns associated with specific movements, base designs, or supporting anatomy [7]. This could provide a quantitative framework for prosthesis design refinement. Removable prosthodontics has begun to incorporate digital design and algorithmic planning, but experimental validation of artificial intelligence for predicting prosthesis displacement remains limited [8]. The present *in vitro* study aimed to evaluate artificial intelligence-based prediction of maxillary prosthesis displacement under simulated functional movements and to compare predicted values with three-dimensional motion tracking measurements. Denture movement is not a single-direction event. During chewing, the base may

rotate, lift, slide and rebound depending on mucosal resilience and occlusal contact. A method that captures only vertical lift may therefore underestimate functional instability. Optical tracking can record movement continuously, but the resulting data are complex. Artificial intelligence offers a way to convert these multiple movement vectors into a clinically understandable prediction of whether prosthesis is likely to remain stable under a selected load. Patient dissatisfaction with complete dentures is often attributed to soreness or poor retention, but the underlying mechanical problem may be excessive movement during function. Objective displacement data can help identify whether instability is due to base adaptation, occlusion, or tissue support. As digital dentures become more common, laboratories need methods to test whether a design is mechanically stable before delivery. Prediction of displacement may eventually allow virtual adjustment of flange extension, relief areas and occlusal scheme before a prosthesis is fabricated. The use of simulated movements also recognizes that dentures fail functionally during repeated activity, not during passive seating alone. Prosthesis may appear stable at rest yet become unstable when lateral and protrusive forces are applied rhythmically. Recent prosthetics-focused literature also describes AI as a promising predictive and decision-support tool, while emphasizing the need for validation before routine clinical use [15, 17]. Therefore, it is of interest to report the AI-based prediction of maxillary complete denture displacement under simulated functional movements and to compare predicted values with three-dimensional optical-tracking measurements.

Materials and Methods:

Study design and setting:

This experimental *in vitro* study used edentulous maxillary models with standardized ridge forms and digitally fabricated complete denture bases. Testing was performed on a functional movement simulation platform.

Sample size and groups:

Seventy-two prosthesis specimens were fabricated and distributed into three groups: conventional heat-cured denture bases, milled CAD-CAM denture bases, and three-dimensionally printed denture bases. Each group contained 24 specimens.

Model preparation:

Edentulous casts were duplicated using a master model. Border extensions, posterior palatal seal area and occlusal plane orientation were standardized digitally. Denture bases were fabricated using the respective processing protocols and finished without altering the tissue surface.

Functional movement simulation:

Each prosthesis was seated on a resilient mucosal analog and subjected to standardized vertical loading, lateral excursion, protrusive movement and combined chewing-cycle simulation. Three-dimensional displacement was recorded using optical markers and motion-tracking cameras.

Artificial intelligence workflow:

Input features included base material, ridge form, tissue-surface gap, load magnitude, movement type, palatal form and early displacement vectors. A gradient boosting regression model and a neural network model were trained to predict maximum displacement during functional cycles.

Outcome variables:

The primary outcome was maximum prosthesis displacement in millimeters. Secondary outcomes included anteroposterior movement, mediolateral movement, vertical lift, model prediction error and classification of displacement above 1.5 mm as clinically unfavorable.

Statistical analysis:

Group comparisons were performed using one-way ANOVA with Tukey post-hoc tests. Model performance was calculated using R2, mean absolute error, root mean square error and receiver operating characteristic analysis for unfavorable displacement classification. Significance was set at $p<0.05$. The mucosal analog was replaced after a predefined number of cycles to prevent permanent deformation from influencing later tests. Dentures were resealed using a standardized load before each movement simulation to reproduce a consistent starting position. Optical markers were attached at the midline incisal region, right molar region and left molar region of each prosthesis. This arrangement allowed the analysis to distinguish

true vertical displacement from rotational movement around a posterior or anterior fulcrum. Before loading, each denture base was inspected for processing defects and seated on the master model with light finger pressure. A thin layer of indicating silicone was used on selected pilot specimens to confirm broad contact before the actual displacement test. The motion-tracking cameras were calibrated using a reference frame before every session. Marker coordinates were exported as three-dimensional displacement files and synchronized with the load-cycle record so that peak movement could be linked to a specific functional movement. The sequence of vertical, lateral, protrusive and combined movements was randomized for each specimen to reduce order effects. Between tests, the mucosal analog surface was cleaned and allowed to recover before the next loading sequence. A high-displacement event was defined before analysis as movement exceeding the predetermined clinical threshold. This binary outcome allowed the regression prediction to be supplemented by a clinically interpretable classification task.

Results:

Material type and salivary film significantly influenced prosthesis displacement. Milled PMMA showed the lowest displacement across all movements, while 3D-printed resin showed greater lateral and protrusive movement under dry conditions. Simulated saliva reduced mean displacement in all groups, with the largest reduction observed in conventional PMMA dentures. Lateral movements produced greater displacement than vertical seating loads. The gradient boosting model performed best for high-displacement classification and identified lateral movement, dry condition, denture base material and early-cycle instability as the most important predictors. Simulated saliva reduced displacement in all groups, but the magnitude of improvement was greatest in conventional heat-cured specimens. Dry lateral loading generated the highest instability across materials, confirming that horizontal forces are more disruptive than purely vertical seating loads. The artificial intelligence model identified lateral displacement during the first 50 cycles as a major predictor of later high-displacement events. Ridge form and tissue-surface gap were more influential than base thickness after early movement vectors were included. Dry conditions exaggerated base movement, especially during lateral excursion. When simulated saliva was introduced, vertical lift decreased more than horizontal slide, suggesting that salivary film improves retention but does not fully control lateral instability. The classification model showed highest sensitivity for identifying high-displacement events during dry lateral loading, which was the condition most likely to destabilize the denture base. Specimen distribution and testing conditions are summarized in **Table 1**; detailed displacement values are presented in **Table 2**; and AI model performance is summarized in **Table 3**.

Table 1: Specimen distribution and testing conditions

Fabrication method	Dry condition n	Saliva condition n	Total n	Mean base thickness (mm)
Heat-cure PMMA	12	12	24	2.54 ± 0.08

Milled PMMA	12	12	24	2.51 ± 0.07
3D-printed resin	12	12	24	2.56 ± 0.09

Table 2: Mean prosthesis displacement under simulated movements

Group	Vertical (mm)	Lateral (mm)	Protrusive (mm)	p value
Heat-cure dry	0.62 ± 0.16	0.96 ± 0.21	0.84 ± 0.18	<0.001
Heat-cure saliva	0.48 ± 0.13	0.71 ± 0.17	0.63 ± 0.15	
Milled dry	0.53 ± 0.14	0.78 ± 0.19	0.69 ± 0.16	
Milled saliva	0.33 ± 0.09	0.41 ± 0.12	0.38 ± 0.10	
3D-printed dry	0.74 ± 0.18	1.18 ± 0.26	1.01 ± 0.22	
3D-printed saliva	0.56 ± 0.15	0.86 ± 0.20	0.77 ± 0.18	

Table 3: AI performance for predicting high-displacement events

Model	Accuracy (%)	Sensitivity	Specificity	AUC
Random forest	88.9	0.87	0.90	0.93
Gradient boosting	90.3	0.91	0.89	0.95
Convolutional LSTM	89.7	0.90	0.89	0.94
Logistic regression	80.6	0.78	0.82	0.86

Discussion:

The present study showed that prosthesis displacement varied significantly across material and movement conditions. Milled CAD-CAM denture bases exhibited lower mean displacement, while the artificial intelligence model predicted movement magnitude with good accuracy [9]. The lower displacement of milled bases may be explained by reduced polymerization shrinkage and improved adaptation to the intaglio surface. A more intimate tissue fit can improve retention and resist lift during lateral and protrusive movements [10]. Three-dimensionally printed bases showed intermediate values, which may relate to layer orientation, post-curing variation and resin properties. As printing technologies improve, movement behavior may become more consistent, but current results indicate that processing method still matters [11]. The prediction model was particularly effective when early displacement vectors were included. This suggests that the initial response to load contains information about subsequent prosthesis instability, similar to how a small early lift may forecast larger movement during chewing cycles [12]. The clinical relevance of the work lies in design feedback. A digital workflow that predicts high displacement before denture delivery could prompt modification of base extension, occlusal contact, posterior palatal seal, or material selection. Such prediction would not replace clinical adjustment but could reduce trial-and-error stages. The limitations include use of a laboratory mucosal analog, absence of saliva viscosity changes, lack of neuromuscular control and simplified load paths. Patient-specific anatomy and adaptation cannot be fully represented by a mechanical simulator. Future research should integrate intraoral scan data, patient-specific ridge resiliency, dynamic saliva simulation and clinical validation. A validated digital displacement predictor could become a useful adjunct in removable prosthodontic planning and teaching. The study highlights that prosthesis stability is a functional behavior rather than a static property of the denture base. A denture that seats well on a cast may still show unfavorable movement when challenged by lateral or protrusive forces. The stabilizing effect of simulated saliva supports the role of adhesion and cohesion at the tissue-base interface. However, saliva did not eliminate displacement, showing that base adaptation and load direction

remain essential determinants of movement. Prediction based on early-cycle motion is appealing because it could shorten laboratory testing. Instead of completing long simulations for every design, early instability patterns might identify prostheses that require design correction before definitive processing or delivery. The difference between vertical and lateral movement is clinically relevant. A denture that resists vertical dislodgement may still shift during chewing if occlusal contacts generate lateral tipping forces. This explains why retention and stability should be evaluated separately. The inclusion of ridge form in the prediction model was valuable because the same base material behaved differently under different support conditions. A highly accurate base cannot compensate fully for unfavorable anatomy, thin mucosal support, or excessive lateral load. Future digital denture software could incorporate a displacement-risk score. Such a score would not replace clinical judgment, but it could alert the clinician when a design is likely to need occlusal refinement, border modification, or additional retention strategies. The findings indicate that early functional testing may help detect unstable prosthesis designs before patients experience discomfort or loss of confidence. This is particularly important for patients with severely resorbed ridges. A displacement-risk score could also be useful in dental education. Students often learn denture stability conceptually, but three-dimensional movement data can show how small design differences influence actual base behavior. The model should eventually be tested with mandibular dentures as well, where tongue movement, smaller bearing area and lower border seal may create a different pattern of displacement. The displacement vectors also showed that posterior lift and lateral slide frequently occurred together during combined movement. This finding supports the need for multi-point tracking because a single midline marker would not adequately describe rotational instability. The present findings also suggest that functional testing should be integrated earlier in digital denture workflows. If a denture design can be screened for displacement before final delivery, the clinician may be able to modify the design rather than relying entirely on post-insertion adjustments. Movement during dry conditions was especially informative because it represented a worst-case stability challenge. In patients with reduced salivary flow, similar instability may be more

pronounced, making base adaptation and occlusal balance even more important. The comparison of fabrication methods should not be interpreted only as a material ranking. Fit, processing accuracy, tissue surface reproduction and load distribution all contribute to prosthesis movement and these factors may interact differently in each patient. Artificial intelligence is useful in this context because it can combine displacement vectors that are difficult to interpret manually. A clinician may not easily judge whether posterior lift, lateral slide, or combined rotation is the main problem from raw motion data alone. Future studies should include patient-specific scans and resilient mucosal maps. Such information would make displacement prediction more individualized and could help identify cases requiring implants, adhesives, or alternative prosthetic designs. Established CAD-CAM complete-denture reports and system evaluations provide context for the present material and workflow findings [13, 14]. Recent AI-focused prosthodontic literature similarly supports predictive and decision-support applications but cautions that laboratory performance requires clinical validation [15, 17]. Contemporary complete-denture workflows continue to refine CAD-CAM standardization and clinical-laboratory integration [16].

Conclusion:

AI-assisted optical tracking accurately predicted denture displacement during simulated functional movements. Milled PMMA showed the lowest displacement; 3D-printed resin was least stable during dry lateral loading. Simulated saliva improved stability, supporting objective digital preclinical denture evaluation.

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