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Evaluating the relationship between clinician experience and accuracy in robotic-assisted dental implant placement: a retrospective study

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Abstract

Objectives This study aims to evaluate the accuracy of Level of Autonomy 2 (LOA2) robotic-assisted implant placement by dentists with varying experience, analyze learning curves, and identify accuracy-related risk factors.

Materials and methods This retrospective study included 362 patients (585 implants) who underwent LOA2 robotic-assisted implant placement (April 2022–April 2024). Six novice clinicians (no robotic experience) and two expert clinicians (> 50 robotic surgeries) were included. Seven deviation parameters were assessed by comparing planned and actual implant positions. Thirteen potential risk factors were evaluated using statistical analyses in R.

Results After extraoral robotic training, novice clinicians achieved accuracy comparable to experts, with minor exceptions: vertical platform deviation (0.373 ± 0.566 mm vs. 0.255 ± 0.438 mm, $p = 0.007$) and vertical apex deviation (0.348 ± 0.488 mm vs. 0.249 ± 0.437 mm, $p = 0.009$). Learning curves for both groups remained flat (coefficient < 0.001), with no significant accuracy improvement over cases increase. Key risk factors for increased deviations included: immediate/early implantation; implant length > 10 mm; poor bone quality; maxillary placement ($p < 0.05$), and machined-related factors.

Conclusions The LOA 2 robotic-assisted implant system minimizes the dependence of implant placement accuracy on clinician experience, with only minor differences in vertical deviations between novices and experts. Even though accuracy remains at a high level, high deviations are associated not only with traditional risk factors but also with machine-related risks.

Keywords Level of autonomy (LOA), Robotic computer-assisted implant surgery (r-CAIS), Dental implants, Implant placement accuracy, Learning curve, Risk factors, Surgical deviation, Clinician experience

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Clinical significance

The clinical significance of this study lies in its demonstration that LOA2 robotic-assisted dental implant systems can standardize surgical accuracy across clinicians with varying experience, optimizing outcomes and safety to facilitate clinical adoption.

Introduction

Dental implantology is continuously evolving, with the overarching aim of achieving greater surgical accuracy and improved patient outcomes. Traditionally, the freehand dental implant surgical technique was considered the standard approach [1]. However, this method has limitations, as it is heavily dependent on the surgeon's manual dexterity and visual acuity—factors that can be influenced by fatigue and the complexity of oral anatomical structures. These limitations often result in inconsistent implant placement, potentially compromising the long-term success of dental implants.

To address these challenges, robotic computer-assisted implant surgery (r-CAIS) has emerged as a transformative advancement. Multiple clinical studies have demonstrated its superior accuracy versus traditional freehand techniques, yielding reduced marginal bone loss and improved prosthetic fit [2–5]. Robotic platforms exhibit an average deviation of ~0.5–0.7 mm—a notable improvement over freehand methods [2, 5, 6]. Autonomous surgical robots are classified by their Level of Autonomy (LOA), which spans five tiers: LOA1 (robot assistance) to LOA5 (full autonomy). Currently, commercially available systems include LOA1 platforms and LOA2 (task-level autonomy) systems. LOA2 system, with representative examples like Remebot (semi-active) and Yakebot (full-active), is a system where the robot completes specific sub-tasks autonomously under clinician supervision during critical steps [7, 8].

LOA2 task-level autonomous r-CAIS supports both the preparation and insertion phases of implant surgery, and it still requires continuous interpretation of computer-generated guidance [3, 9]. Notably, clinicians currently possess extensive freehand surgery experience, and such expertise may implicitly influence their adaptation to robotic systems and interpretation of digital guidance. This underscores the need to elucidate how surgeon experience, learning curves, and other factors impact LOA2 systems' accuracy. In freehand implant placement, clinicians typically face a steep learning curve, where surgical accuracy improves incrementally with the accumulation of a large volume of clinical cases. By contrast, LOA2 robotic systems may substantially reduce dependence on prior clinical experience, potentially enabling a flatter learning curve that could help to standardize training protocols and reshape dental implant education, yet the specific features of this learning curve for training design remain understudied. Given these knowledge gaps, the present study aimed to assess robotic implant placement accuracy among clinicians with varying experience, evaluate learning curves, and identify factors affecting accuracy.

Materials and methods

Study design and ethical approval

This retrospective study, conducted at Xi'an Jiaotong University between April 2022 and April 2024, utilized a semi-active robotic surgical system (Remebot, Beijing Baihui Weikang Technology Co., Ltd., Beijing, China). The study adhered rigorously to the Declaration of Helsinki principles, with ethical approval secured from the Ethics Committee of Xi'an Jiaotong University (Approval No: xjkqll[2021]NO.43). The study adhered to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines. All consecutive patients who underwent the Remobot robotic-assisted implant surgery in our department during the study period were included. The inclusion criteria are as follows: (1) age ≥ 18 years old with single/multiple missing teeth requiring dental implant treatment using Rembot during April 2022 and April 2024; (2) Systemically healthy or with mild/well-controlled conditions (e.g., hypertension, diabetes, leukemia); (3) non-smokers or less than < 10 cigarettes/day; (4) Sufficient bone volume (no need for augmentation). The exclusion criteria were: (1) Presence of severe systemic disease, pregnancy and lactation; (2) Registration error > 0.5 mm or intraoperative plan changes interrupting robot use; (3) Cone beam computed tomography (CBCT) artifacts or unclear postoperative images; (4) Refusal to undergo r-CAIS before the procedure.

Definition and recruitment of surgeons

Surgeons were categorized as either expert or novice based on their experience with robotic implant systems. The expert group consisted of 2 clinicians with more than 50 robotic implant surgeries [10–12], while the novice group included 6 clinicians with no prior robotic experience and completed comprehensive robotic training based on the manufacturer's guidelines (Remebot, Beijing Baihui Weikang Technology Co., Ltd., Beijing, China). They had 1–20 years of experience in freehand implant placement, as detailed in Supplementary Table 1.

Surgical procedure

Preoperative preparation

Preoperative imaging and digital planning were performed as follows: all patients fixed with a position maker (Remebot, Beijing) underwent the preoperative CBCT images (KAVA 3D eXam, 110 kV/5 mA 0.3 mm voxel size, 12 s scanning time) in DICOM format; and intraoral scans (3Shape Trios) were obtained for anatomical details and saved in STL format. Both files were imported into the Remebot planning software for integrated analysis. The targeted implant positions and restoration design adhered to the prosthetic-driven principle, and appropriate size of implant was chosen. Post-planning, digital restoration models were generated, with optional 3D-printed models for verification [5]. Suitable drill bits and drill sequence were virtually designed.

Intraoperative phase

Standard preoperative steps, including oral rinsing, sterile draping, and local anesthesia (2% lidocaine with 1:80,000 epinephrine, Dentsply Pharmaceuticals, USA), were followed. Prior to initiating surgery, the Remebot robotic arm underwent alignment and registration to ensure positional accuracy. The positioning marker (equipped with reflective spheres, Remebot, Beijing) tracked real-time patient movement during the procedure, with the robotic system automatically compensating for minor positional shifts to maintain alignment with the preoperative plan. Subsequently, osteotomy drilling was performed by the robotic arm in strict accordance with the pre-designed drilling sequences and surgical protocols. Throughout the drilling process, real-time feedback data—including drilling depth, applied force, and orientation—were displayed on the system screen, alongside the real-time drilling position visualized in the transverse, coronal, and sagittal planes. After the drilling procedure, the implant was placed immediately using the robotic system. Primary implant stability was evaluated by measuring the insertion torque value (ITV) with a dynamometric wrench. A representative surgical procedure is summarized in Supplementary Fig. 1.

Data acquisition and accuracy evaluation

Postoperative CBCT scans (KAVA 3D eXam) were reconstructed and aligned with preoperative ones using the accuracy verification software (default setting) of the robotic system (Remebot, Beijing) (Fig. 1). The software automatically extracted implant insertion points and apical coordinates based on known implant dimensions. Deviations in seven parameters were evaluated (Fig. 1C): (1) Global platform deviation: distance between the centers of the planned and placed implant platforms. (2) Lateral platform deviation: distance between the center of the placed implant platform and the axis of the planned implant. (3) Vertical platform deviation: distance between the projection points of the centers of the planned and placed implant platforms. (4) Global apical deviation: distance between the planned and placed implant apices. (5) Lateral apical deviation: distance between the placed apex and the axis of the planned implant. (6) Vertical apical deviation: distance between the projected apex of the placed implant and the planned apex along the implant axis. (7) Angular deviation: angle between the axes of the planned and placed implants. Deviations were defined as positive when the actual implant position was apical to the planned implant position and negative when it was coronal. For comparison with free-hand techniques, deviation data were extracted from published literature [2–5], which used consistent measurement parameters (coronal/apical deviation, angular deviation) to ensure comparability.

Demographic and procedural data were also collected, including: participant age, sex, socioeconomic data, implant brand, implant location, and operating surgeon details (implant education and years of postgraduate experience in implant dentistry). Implants were categorized as single or multiple, maxillary or mandibular, and anterior (esthetic zone) or posterior.

Statistical analysis

All statistical analyses were performed using R software, with visualizations generated using the ggplot2 package [13]. Categorical data were compared between the expert and novice groups using the chi-squared test. Correlations between factors and implant deviation were assessed using Pearson correlation coefficients and principal component analysis (PCA). Box plots and Wilcoxon rank-sum tests were used to compare deviations. Loess-smoothed line charts were used to illustrate trends over time. A linear mixed-effects model was built, considering random and fixed effects. Model assumptions were tested; variables were selected using a backward elimination approach, and the best model was chosen based on the Akaike Information Criterion (AIC).

Results

Patient and implant data characteristics

Three hundred sixty-two patients (193 females, 169 males) with 585 implants were placed were included in this retrospective analysis. Manual implant placement was required in 25 cases due to registration errors or excessive torque; these 25 cases were thus excluded from the study.

The various implant brands were included, with Straumann BLT being the most common, accounting for 443 (75.7%) of all placements (Table 1). Conical implants were predominant, representing 88.5% of all implants. Additional factors such as implant diameter, implant length, timing of implant placement, implant site, insertion torque, number of adjacent implants, bone quality, and whether a flap was used were analyzed in detail. The expert group placed 366 implants, whereas the novice group placed 219 implants. Upon comparing the expert and novice groups, no statistically significant differences were observed in implant shape, implant diameter,

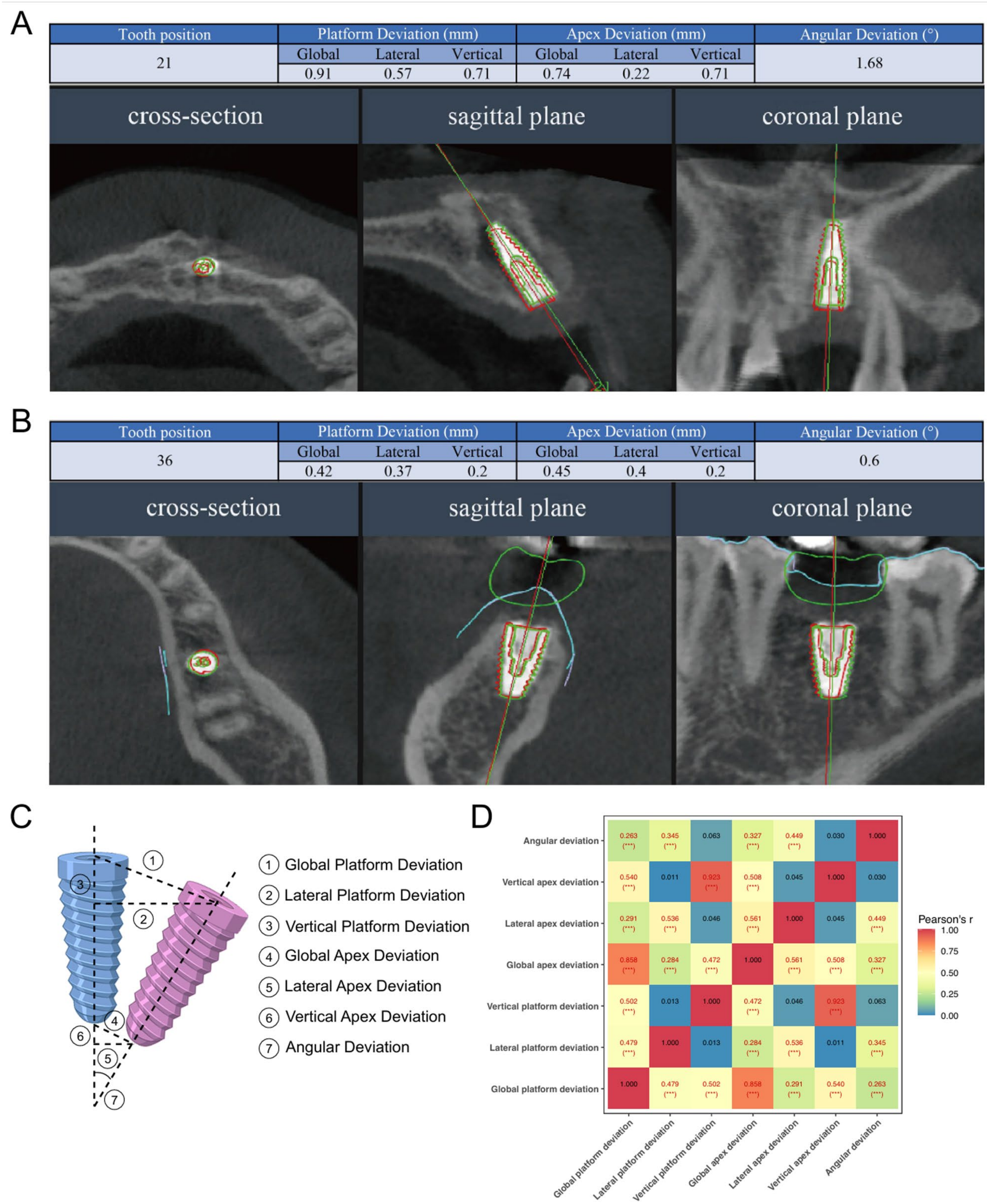

Fig. 1 Deviation Analysis and Correlation of Planned and Inserted Dental Implants. **A**-**B**. Calculation of deviations in the planned and actual implant positions measured on cone beam computed tomography. **A** anterior tooth region and (**B**) posterior tooth region. **C** Parameters used to analyze the deviations between the planned (blue) and inserted (purple) implants. **D** Pearson correlation coefficient matrix plot, which illustrates the correlations between different variables. Each cell in the plot represents the Pearson correlation coefficient between two variables, and the color intensity indicates the strength of the correlation. The color bar shows the range of correlation coefficients from 0.25 to 1.00

Table 1 Clinical characteristics of the included implants

	Expert ($N=317$)	Novice ($N=268$)	p	Overall ($N=585$)
Implant brand				
Straumann	228 (71.9%)	215 (80.2%)	0.001	443 (75.7%)
Astra	36 (11.4%)	25 (9.3%)		61 (10.4%)
NOBEL	27 (8.5%)	7 (2.6%)		34 (5.8%)
BEGO	19 (6.0%)	10 (3.7%)		29 (5.0%)
ZIMMER	4 (1.3%)	0 (0%)		4 (0.7%)
COR	3 (0.9%)	4 (1.5%)		7 (1.2%)
Osstem	0 (0%)	5 (1.9%)		5 (0.9%)
HIOSSEN	0 (0%)	2 (0.7%)		2 (0.3%)
Implant type				
Conical	278 (87.7%)	240 (89.6%)	0.568	518 (88.5%)
Cylindrical	39 (12.3%)	28 (10.4%)		67 (11.5%)
Implant diameter				
< 4 mm	131 (41.3%)	122 (45.5%)	0.349	253 (43.2%)
≥ 4 mm	186 (58.7%)	146 (54.5%)		332 (56.8%)
Implant length				
< 10 mm	97 (30.6%)	28 (10.4%)	< 0.001	125 (21.4%)
= 10 mm	106 (33.4%)	141 (52.6%)		247 (42.2%)
> 10 mm	114 (36.0%)	99 (36.9%)		213 (36.4%)
Implant placed timing				
1 + 2	15 (4.7%)	23 (8.6%)	0.169	38 (6.5%)
3	43 (13.6%)	34 (12.7%)		77 (13.2%)
4	259 (81.7%)	211 (78.7%)		470 (80.3%)
Site position 1				
Maxillary	107 (33.8%)	106 (39.6%)	0.172	213 (36.4%)
Mandibular	210 (66.2%)	162 (60.4%)		372 (63.6%)
Site position 2				
Anterior	115 (36.3%)	120 (44.8%)	0.045	235 (40.2%)
Posterior	202 (63.7%)	148 (55.2%)		350 (59.8%)
Torque				
(0,10)	8 (2.5%)	5 (1.9%)	0.0267	13 (2.2%)
(10,20)	38 (12.0%)	51 (19.0%)		89 (15.2%)
(20,30)	56 (17.7%)	59 (22.0%)		115 (19.7%)
(30,40)	185 (58.4%)	139 (51.9%)		324 (55.4%)
(40,50)	30 (9.5%)	14 (5.2%)		44 (7.5%)
Bone quality				
1	44 (13.9%)	25 (9.3%)	0.0053	69 (11.8%)
2	169 (53.3%)	148 (55.2%)		317 (54.2%)
3	99 (31.2%)	77 (28.7%)		176 (30.1%)
4	5 (1.6%)	18 (6.7%)		23 (3.9%)
Flapped				
No	58 (18.3%)	25 (9.3%)	0.0029	83 (14.2%)
Yes	259 (81.7%)	243 (90.7%)		502 (85.8%)
Number of implants placed				
Single	110 (34.7%)	100 (37.3%)	0.569	210 (35.9%)
Multiple	207 (65.3%)	168 (62.7%)		375 (64.1%)

p: chi-square test. Expert: conducted over 50 robotic surgeries; Novice: no robotic implant surgery experience

The timing of implant placement after extraction was categorized as follows: Type 1/2: Immediate/early (4–8 weeks post-extraction, with/without soft tissue healing). Type 3: Early with partial bone healing (12–16 weeks post-extraction). Type 4: Delayed implantation (≥6 months post-extraction). Bone quality was classified according to the Lekholm and Zarb classification [14]: (1) Thick cortical bone, narrow medullary canal (low trabecular density); (2) Thick cortical bone, moderate trabecular bone; (3) Thin cortical bone, large trabecular volume; (4) Thin cortical bone, dense trabecular bone

Table 2 Seven types of deviations in robotic-implant placement comparing novice and expert groups

Deviations	Expert	Novice	p	Overall
Global platform deviation	0.572 ± 0.293 [0.100, 2.390]	0.642 ± 0.352 [0.130, 2.220]	0.046	0.604 ± 0.323 [0.100, 2.390]
Lateral platform deviation	0.349 ± 0.183 [0.030, 1.220]	0.356 ± 0.215 [0.030, 1.780]	0.921	0.352 ± 0.198 [0.030, 1.780]
Vertical platform deviation	0.255 ± 0.438 [−1.120, 2.380]	0.373 ± 0.566 [−1.920, 5.110]	0.007	0.309 ± 0.504 [−1.920, 5.110]
Global apex deviation	0.613 ± 0.332 [0.100, 2.490]	0.660 ± 0.336 [0.080, 2.200]	0.032	0.635 ± 0.334 [0.080, 2.490]
Lateral apex deviation	0.412 ± 0.260 [0.030, 2.280]	0.390 ± 0.194 [0.040, 1.340]	0.870	0.402 ± 0.232 [0.030, 2.280]
Vertical apex deviation	0.249 ± 0.437 [−1.120, 2.290]	0.348 ± 0.488 [−1.920, 2.130]	0.009	0.295 ± 0.463 [−1.920, 2.290]
Angular deviation	1.312 ± 1.345 [0.060, 12.590]	1.201 ± 0.879 [0.050, 6.970]	0.939	1.261 ± 1.156 [0.050, 12.590]

Platform deviation/Apex deviation: mean ± standard [min, max] deviation (when reported) in mm. Angle deviation: mean ± standard [min, max] deviation (when reported) in degrees. The vertical deviation > 0 indicates that the actual implantation position is more apical, and < 0 indicates that it is more coronal. *p*: Rank sum test

implant placement timing, site (maxillary or mandibular), or number of implants placed each time ($p > 0.05$, Table 1).

Novice and expert groups show consistency in implant deviation patterns and platform positioning exhibits a higher risk of deviation

Implant deviation is described using seven widely recognized parameters (Fig. 1A-C) [4, 15]. The Pearson correlation coefficient matrix (Fig. 1D) revealed a strong positive correlation between platform and apical depth deviations ($r = 0.923$), indicating that vertical deviation in the platform could be accompanied by vertical deviation in the apex. Conversely, lateral platform deviation showed a weaker correlation with lateral apex deviation ($r = 0.536$), while angular deviation exhibited weak associations with lateral deviations and no correlation with vertical parameters.

In the novice group, 6 clinicians with varying freehand experience showed no difference in all deviations after extraoral robotic training ($p > 0.05$). When comparing novice and expert groups (Table 2), novices showed greater vertical deviations: vertical platform deviation was 0.373 ± 0.566 mm (novices) vs. 0.255 ± 0.438 mm (experts; $p = 0.007$), and vertical apical deviation was 0.348 ± 0.488 mm vs. 0.249 ± 0.437 mm ($p = 0.009$), these differences were small in clinical terms. Notably, lateral platform/apex deviations ($p = 0.921$; $p = 0.870$) and angular deviation ($p = 0.939$) did not differ significantly between groups.

Data from 585 implants were classified into low/medium/high deviation as previously reported [16]. PCA showed consistent deviation distribution patterns between novice and expert groups (Fig. 2A), with most implants exhibiting low-level deviations. Platform deviations posed the highest risk irrespective of experience: only 69.91% (409/585) of platform measurements met high-accuracy criteria, with 3.59% (21/585) showing high deviations. In contrast, angular deviations demonstrated 92.31% (540/585) high accuracy and only 1.88% (11/585) high deviations (Fig. 2B).

Robotic-assisted implant placement accuracy shows minimal association with clinician experience and a flat learning curve

Learning curves for both groups were flat across all deviation types (Fig. 3). Controlling surgical difficulty factors (bone density, tooth location, implant length) did not

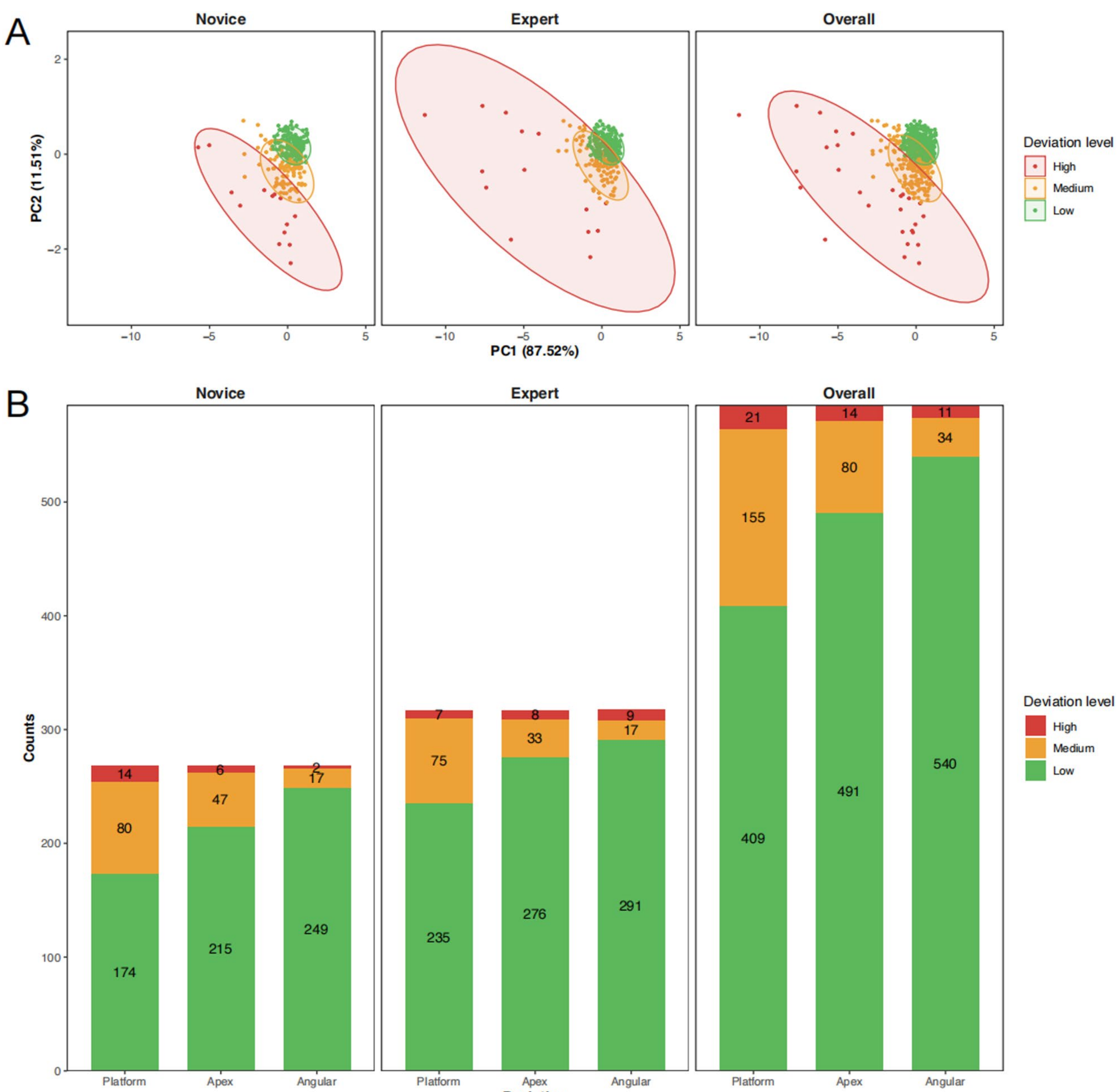

Fig. 2 Deviation Level Analysis of 585 Robotic-Assisted Implants. **A** The principal component analysis graph clustered 585 implants into three deviation levels: high, medium, and low. **B** The bar graph displays the deviation levels of robotic-assisted implant surgery at three positions: platform, apical, and angular. The colors in the bar graph represent different deviation levels as follows: Red: High deviation, Yellow: Moderate deviation, and Green: Low deviation. The y-axis shows the number and proportion of cases at each deviation level. high > 1 mm, medium = 0.5–1 mm, low < 0.5 mm [16]

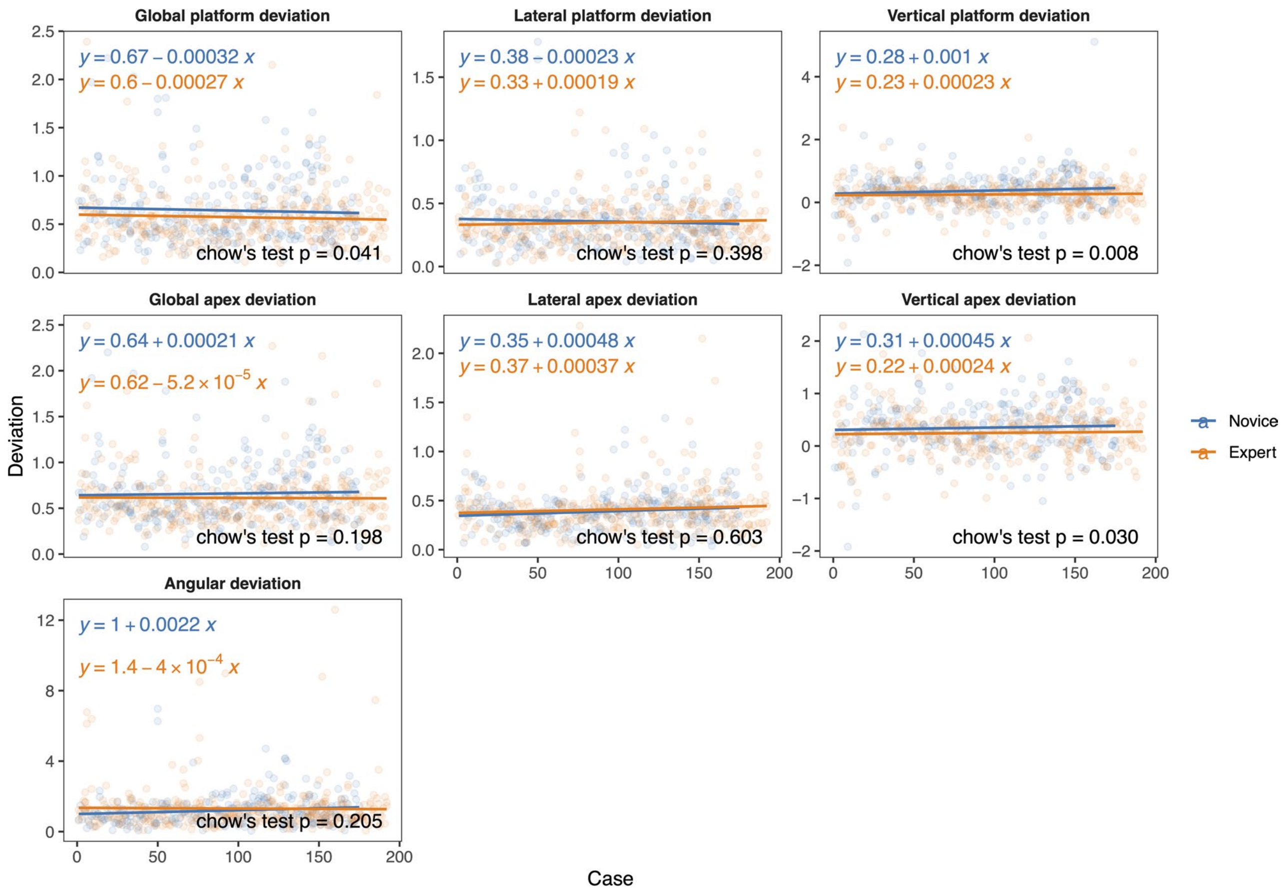

Fig. 3 Learning Curve Over Time Between Novice and Expert Groups. Learning curve comparison between novice (blue) and expert (orange) in robotic implant surgery as the number of implant cases increased. The x-axis represents the case number, and the y-axis lists the different types of deviation. The equation of the linear fit for each group is presented. Chow's test was used to compare the groups' curves

alter this flat trend, with no significant accuracy improvement in novice group as case volume rose; linear trend coefficients were negligible (<0.001, Fig. 3), indicating surgical accuracy is largely independent of accumulated clinician experience.

A detailed temporal analysis of deviation was conducted (Fig. 4). Both the novice and expert groups exhibited the low-level deviation with minimal fluctuations. However, an overall upward trend was observed in August 2023, particularly in global platform and apex deviations. Further investigation attributed this anomaly to machine-related factors.

Impact of multiple factors on the accuracy of robotic-assisted implant placement

Thirteen factors were considered to explore the sources of deviations and eight were identified as significant using the Wilcoxon rank-sum test (Fig. 5; Table 1). The expert group had significantly less vertical platform deviation than novices. Implant parameters: diameter ≥ 4 mm was associated with less global platform, apex, and vertical apex deviation ($p < 0.05$); implants > 10 mm had greater vertical platform deviation ($p < 0.05$); immediate/early implantation (types 1/2) showed higher global and lateral platform deviation than delayed (type 4, $p < 0.05$).

Patient- and site-specific conditions such as site (maxillary vs. mandibular, posterior vs. anterior) and bone quality (classified as 1 to 4 [14]) also exert a significant influence on implant placement accuracy. Specifically, our data revealed that implants placed in the maxilla exhibited significantly greater global platform deviations, apical deviations, and vertical apical deviations compared to those placed in the mandible. Bone quality and insertion torque were also correlated with deviation parameters. With respect to bone quality, a trend was observed wherein more dense bone (Types 1–2) was associated with greater coronal vertical deviations. Regarding insertion torque, higher insertion torque values were correlated with increased coronal vertical deviations.

Multifactorial model for identifying key influencing factors on implant deviations

To accurately predict implant deviation levels, a linear mixed-effects regression model was developed to identify

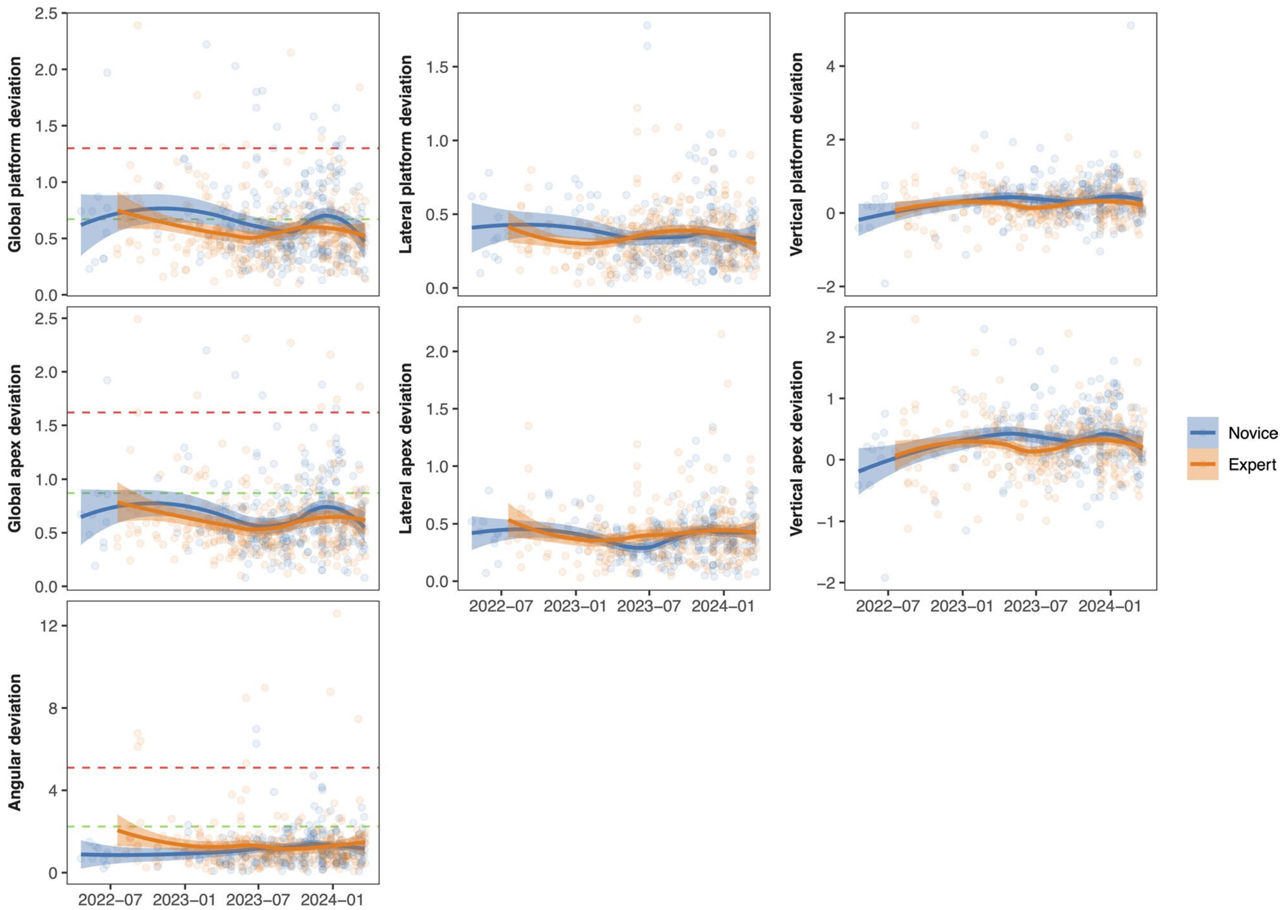

Fig. 4 Deviation Trend Over Time Between Novice and Expert Groups. The graph displays the deviations of implants at different deviations over time (from April 2022 to April 2024) by expert and novice groups at low and high deviation levels, using two colored lines to represent the deviation levels (red: high-level deviation; green: low-level deviation) [13]

key factors influencing deviations. The model included both fixed and random effects (Table 3) and considers 13 key factors. Following model selection, the influential factors identified included implant length, time of placement after extraction, implantation site, bone quality, and number of implants.

Platform deviation was influenced by short implant, time of placement after extraction, bone quality and implantation site. Immediate and early placements (types 1 and 2) led to a 0.158 mm increase in global platform deviation compared with delayed implantation (implant placed timing type 4). Similarly, lateral platform deviation was also influenced by implantation timing. Short implants (< 10 mm) had greater coronal displacement (vertical platform: −0.147 mm; vertical apex: −0.127 mm, $p < 0.01$). Bone quality 4 had greater apex vertical deviation compared to other bone types ($p < 0.01$); anterior sites had increased apical vertical deviation by 0.169 mm ($p < 0.001$). Angular deviation was influenced by implant length and site: short implants (< 10 mm) increased deviation by 0.503° compared to 10 mm implants ($p < 0.001$); maxillary sites had higher deviation by 0.244° compared to mandibular sites ($p < 0.1$).

Discussion

Digital assistance in achieving precise three-dimensional implant positioning has significant clinical implications. The dental implant robots integrate the advantages of surgical guides and dynamic navigation systems while addressing many of their limitations. The robotic system autonomously positions the implant in the site at the desired axis, continuously monitors the procedure, and adjusts to the drill position and direction. This approach effectively mitigates human errors stemming from operator fatigue, visual blind spots, and suboptimal positioning, thereby enhancing surgical accuracy, reducing procedural complexity and trauma, and enabling minimally invasive treatment [9]. However, currently dental implant robots have not achieved full autonomy (LOA5); instead, they remain at task-level autonomy (LOA2), which underscores the crucial role of clinicians in critical steps.

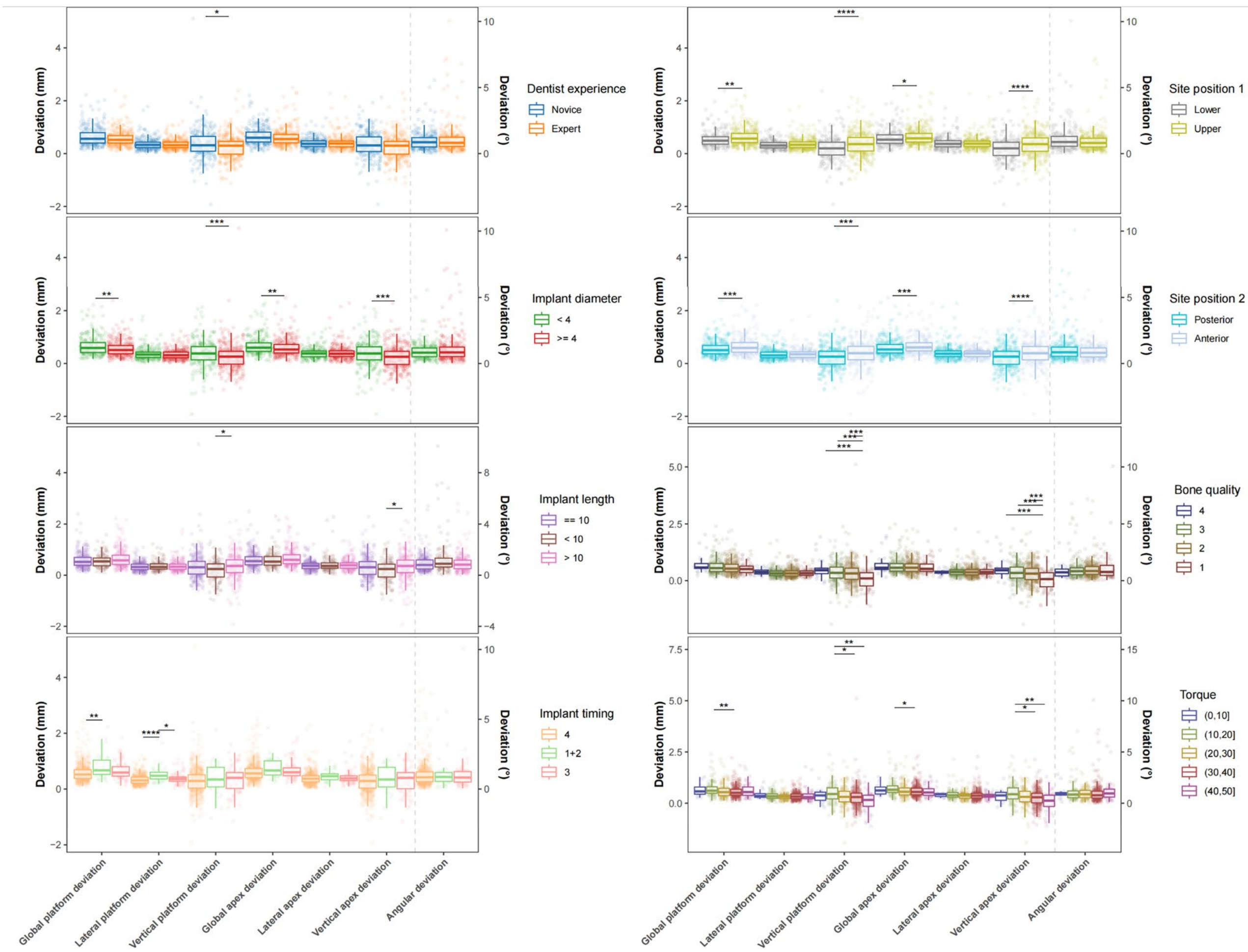

Fig. 5 Factors Influencing Implant Deviations in Robotic-Assisted Implant Placement. Impact of various factors on implant deviations in robotic implant surgery, with each subplot representing a factor, such as dentist experience, implant diameter, implant location, timing of implantation, and torque, on different deviation indicators. Wilcoxon rank test was used, * 0.1; ** 0.05, *** 0.01, **** 0.0001

A key novelty of this study lies in its in vivo investigation with a large sample size (585 implants) to systematically comparing the accuracy and learning curve characteristics between novice and experienced clinicians in LOA2 robotic-assisted dental implant surgery. Previous relevant studies were mostly in vitro experiments or small-sample explorations, and few focused on the role of LOA2 systems [10–12]. This study showed that after extraoral training, novice clinicians achieved implant accuracy comparable to that of experienced clinicians across angular, lateral, and vertical metrics (Fig. 3), with only minor differences in vertical platform deviation (0.373 mm vs. 0.255 mm, $p = 0.007$) and vertical apex deviation (0.348 mm vs. 0.249 mm, $p = 0.009$). The statistically significant but small vertical deviations between novices and experts are unlikely to affect clinical outcomes, as deviations < 0.5 mm are generally considered clinically acceptable [16]. This indicates that LOA2 systems minimize experience-related variability, even if they do not eliminate it. This discrepancy in vertical deviation may be attributed to novices' tendency to adopt a more conservative approach during surgery, leading to deeper implant placement. This consistency stems from LOA2 systems' ability to autonomously execute predefined surgical sub-tasks (e.g., drilling along preplanned trajectories) while requiring clinician supervision during critical steps [7, 16]. Unlike conventional freehand surgery, where accuracy improves with experience, robotic platforms enforce standardized accuracy through real-time motion tracking and dynamic error correction, resulting in a flat learning curve.

Risk factors identified in r-CAIS—including bone density, implant location, and surgical timing are consistent with those of traditional freehand techniques. For example, dense palatal bone in the anterior region caused labial platform shifts during osteotomy, mirroring freehand surgery's anatomical challenges [17, 18]. Similarly, immediate implantation in the maxillary anterior region posed higher risks due to extraction socket irregularities, a factor well-documented in conventional approaches

Table 3 Linear mix effects model

Platform deviation

	Global				Lateral				Vertical			
Random effects	σ^2		*SD*		σ^2		*SD*		σ^2		*SD*	
Case (intercept)	0.029		0.170		0.011		0.104		0.120		0.347	
Residual	0.070		0.264		0.026		0.161		0.128		0.357	
Fixed effects	***b***	***SE***	***t value***	***p***	***b***	***SE***	***t value***	***p***	***b***	***SE***	***t value***	***p***
(Intercept)	0.544	0.019	28.738	***	0.328	0.010	33.322	***	0.660	0.119	5.54	***
Implant length < 10 mm									−0.147	0.054	−2.749	**
Implant length > 10 mm									−0.117	0.060	−1.940	NS
Implant timing 1 + 2	0.158	0.058	2.756	**	0.171	0.034	5.090	***				
Implant timing 3	0.061	0.040	1.502	NS	0.056	0.024	2.322	*				
Site Anterior	0.080	0.029	2.738	**					0.144	0.060	2.369	*
Site Maxillary												
Bone quality 3									−0.322	0.120	−2.678	**
Bone quality 2									−0.329	0.120	−2.751	**
Bone quality 1									−0.570	0.132	−4.306	***
Implant n Multiple												

Apex deviation

	Global				Lateral				Vertical			
Random effects	*σ2*		*SD*		*σ2*		*SD*		*σ2*		*SD*	
Case (intercept)	0.026		0.160		0.008		0.088		0.081		0.285	
Residual	0.083		0.287		0.045		0.213		0.117		0.342	
Fixed effects	***b***	***SE***	***t value***	***p***	***b***	***SE***	***t value***	***p***	***b***	***SE***	***t value***	***p***
(Intercept)	0.589	0.019	30.807	***	0.369	0.016	23.257	***	0.631	0.107	5.893	***
Implant length < 10 mm									−0.127	0.049	−2.557	*
Implant length >10 mm									−0.107	0.055	−1.943	NS
Implant timing 1+2												
Implant timing 3												
Site Anterior	0.090	0.029	3.111	**					0.169	0.055	3.047	**
Site Maxillary												
Bone quality 3									−0.318	0.109	−2.931	**
Bone quality 2									−0.341	0.107	−3.171	**
Bone quality 1									−0.568	0.119	−4.769	***
Implant n Multiple					0.044	0.021	2.143	*				

Angular deviation

Random effects	*σ2*	*SD*
Case (intercept)	0.140	0.374
Residual	1.145	1.070

Fixed effects	***b***	***SE***	***t value***	***p***
(Intercept)	1.271	0.091	13.906	***

Table 3 (continued)

Fixed effects	*b*	*SE*	*t value*	*p*
Implant length < 10 mm	0.503	0.127	3.959	***
Implant length >10 mm	0.071	0.112	0.635	NS
Implant timing 1+2				
Implant timing 3				
Site Anterior				
Site Maxillary	−0.244	0.104	−2.346	*
Bone quality 3				
Bone quality 2				
Bone quality 1				
Implant n Multiple				

The best model for each measure was selected according to the Akaike information criterion using the backward model selection method, where the vertical deviation >0 indicates that the actual implantation position is more apical, and < 0 indicates that it is more coronal. Reference categories were selected for clinical relevance/data representativeness: implant length=10 mm, implant timing=4, site=posterior/mandibular, bon equality=4, single-implant placement. indicates factors excluded via backward elimination ($p>0.05$)

* 0.1

** 0.05

*** 0.01

[17, 18]. Multifactorial analysis showed no novel risk factors unique to robotic systems, confirming that the technology mitigates human error while preserving known clinical constraints.

A critical finding was the impact of equipment-related anomalies on deviation trends. An unexplained upward shift in global platform and apex deviations was traced to optical locator malfunctions rather than operator error (Fig. 4). This highlights a frequently overlooked aspect of robotic surgery: despite LOA2 autonomy, system accuracy relies on calibrated hardware (e.g., CBCT scanners, robotic arms). Clinicians must prioritize routine maintenance of positioning plates and real-time verification of navigation systems, as machine-induced errors can surpass human variability in magnitude [11].

The key limitation is the findings may not generalize to other LOA2 systems (e.g., Yakebot) with different registration algorithms that could alter experience-accuracy relationships. Future multi-center studies with larger expert groups and diverse LOA2 systems are needed to validate findings on clinician experience and risk factors. Long-term follow-ups should assess how short-term deviations affect implant stability and patient outcomes. Additionally, integrating machine-learning to predict equipment errors could enhance robotic reliability.

In conclusion, r-CAIS at LOA2 autonomy redefines implant accuracy by decoupling outcomes from clinician experience, addressing a key limitation of traditional techniques. LOA2 r-CAIS inherits traditional freehand risk factors, but introduces machine-related variables, requiring routine hardware registration and real-time checks. Thus, LOA2 r-CAIS shifts implantology to technology-driven excellence—relying on standardization, risk mitigation, and maintenance over manual skill—establishing robotics as a modern implant practice cornerstone.

Abbreviations

LOA	Level of Autonomy
CBCT	Cone beam computed tomography
r-CAIS	Robotic computer-assisted implant surgery

Supplementary Information

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Supplementary Material 1.

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Authors' contributions

Miao Wang: Conceptualization, Methodology, Software, Data Curation, Investigation, Validation, Formal Analysis, Visualization, Writing–Original Draft, Writing–Review & Editing. Hui Xia Zhou: Conceptualization, Data Curation, Investigation, Writing–original draft. Cheng Peng Lv: Conceptualization, Investigation, Funding Acquisition. Wai Keung Leung: Conceptualization, Methodology, Investigation, Formal Analysis, Writing–Original Draft, Writing–Review & Editing. Wai Man Tong: Methodology, Software, Validation, Formal Analysis, Visualization. Xiao Xuan Cui: Investigation, Formal Analysis, Writing–original draft. Xin Xuan Wang: Investigation, Validation, Formal Analysis, Writing and Original Draft. Intad Sriprasert: Investigation, Validation, Formal Analysis, Writing the Original Draft. Qin Zhou: Conceptualization, Supervision, Funding acquisition, Project administration, Resources, Writing–Review & Editing. Long He: Conceptualization, Investigation, Supervision, Funding Acquisition, Project Administration, Resources, Writing–Original Draft, Writing–Review & Editing. All the authors have read and agreed to the final version of the manuscript.

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Data availability
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study complied with the Declaration of Helsinki and was approved by the Ethics Committee of the Xi'an Jiaotong University (Approval No xjkqll[2021] No.43). Informed consent to participate was obtained from all the participants in the study.

Consent for publication
For the present retrospective study, all participants/patients whose personal or clinical details are included in the manuscript provided written informed consent for the publication of such information, in compliance with ethical guidelines and the study's ethical approval.
With specific reference to Supplementary Figure 1: While the images contained therein are primarily explanatory in nature and not derived from the study's core participants, any individuals depicted in these figures have also provided written informed consent for their images to be published as part of this supplementary material. These figures are included to illustrate key concepts, methodologies, or contextual information relevant to the study, and all identifying elements therein are published with explicit permission from the individuals involved.

Competing interests
The authors declare no competing interests.

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