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Received: 14 August 2023 | Revised: 30 September 2023 | Accepted: 7 November 2023
DOI: 10.1111/clr.14213

CLINICAL ORAL IMPLANTS RESEARCH WILEY

PERSPECTIVE

Computer-assisted and robotic implant surgery: Assessing the outcome measures of accuracy and educational implications

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Abstract

Objective: This scoping review aimed to (1) critically evaluate the outcomes measures used to assess the accuracy of implant placement with Computer Assisted Implant Surgery (CAIS) and (2) review the evidence supporting the efficient implementation of CAIS in training and education of clinicians.

Methods: A scoping literature review was conducted aiming to identify (a) clinical trials assessing accuracy of implant placement with CAIS, and (b) clinical trials or simulation/cadaver studies where CAIS was utilised and assessed for the training/education of clinicians. Studies since 1995 were assessed for suitability and data related to the outcomes measures of accuracy and educational efficacy were extracted and synthesised.

Results: Accuracy of CAIS has been mainly assessed through surrogate measures. Individual clinical trials have not shown any difference between static and dynamic CAIS, but recent meta-analyses suggest an advantage of dynamic CAIS in reducing angular deviation. The combination of static and dynamic CAIS might offer higher accuracy than each of the two used alone. Dynamic CAIS is suitable for novice surgeons and might even have added value as an education tool for implant surgery, although mastering the technique requires longer training than static.

Conclusion: Meta-analyses of large samples, new and diverse outcomes measures, as well as benchmarking of levels of accuracy with specific clinical outcomes will help to better understand the potential and limitations of CAIS. Dynamic CAIS is suitable for novice operators, but educational interventions distributed over longer periods of time will be required for mastery of the process.

KEYWORDS
clinical research, clinical trials, computer assisted implant surgery, guided implant surgery, navigation, surgical techniques

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1 | INTRODUCTION

Contemporary practice of implant dentistry identifies the optimal design of the prosthesis as a key to long term peri-implant tissue health and successful clinical outcomes (Mattheos, Janda, et al., 2021; Rungtanakiat et al., 2023). The surgical and restorative paradigm is also evolving towards comprehensive pre-intervention design of all components (Mattheos, Vergoullis, et al., 2021), minimal invasiveness and immediacy, shorter treatment and chairside time. Thus, precise implant placement in the pre-determined optimal position is a prerequisite step in the digital workflow and Computer Assisted Implant Surgery (CAIS) a key technology to support clinicians to achieve it. CAIS encompasses a wide array of technologies and protocols that have evolved during a period of over two decades, with robotic implant placement being the latest.

Guided surgery with the use of 3D imaging software and custom-made acrylic surgical guides was introduced at the turn of the century (Fortin et al., 1995; Siessegger et al., 2001) offering complete guidance of the drills throughout the whole osteotomy. Not surprisingly, the early applications of CAIS were driven by the need for immediate loading of edentulous patients (Rocci et al., 2003), with static CAIS becoming soon thereafter a standard part of such immediacy protocols (Marchack, 2005). The origins of dynamic CAIS are found in the same period (Ploder et al., 1995; Watzinger et al., 1999).

Two decades later and CAIS has entered the mainstream implant practice, offering well documented clinical advantages, with accuracy of implant positioning being the best studied one (Pimkhaokham et al., 2022). There is no consensus classification of CAIS at present, but a working definition is emerging in the literature with three distinct technologies as static (s-CAIS), dynamic (d-CAIS) and robotic (r-CAIS). The first is the oldest, where the accuracy of the implant placement is facilitated by removable 3D printed custom guides, the second supports the surgeon by means of real time visual feedback and the latter involves the preparation of the osteotomy and the implant placement conducted by an autonomous or operator-controlled robotic arm. Although static and dynamic CAIS technologies are now well-established steps of the digital workflow, there is a lack of consistent assessment of important clinical outcomes other than accuracy of implant placement. Furthermore, although accuracy is assessed in multifold studies and clinical scenaria, the utilised outcomes measures have never been critically evaluated and there is limited understanding of their relevance to clinical results and limitations.

Finally, with the rapidly increasing application of static and dynamic CAIS, the development of appropriate training and education for clinicians has become an imperative. Competent use of CAIS might require profound understanding of the respective technologies, advanced spatial representation ability (Yao et al., 2019) and skillsets different to these of conventional implant surgery (Perera et al., 2023). Learning patterns of static might be different to these of dynamic CAIS, representing educational challenges and opportunities.

This scoping review combined two aims: First to present an overview of the current assessment of accuracy in static, dynamic and robotic CAIS, map past and emerging outcomes measures and discuss their limitations and potential. Second, to review the available evidence in training clinicians in the use of CAIS and map challenges as well as best practices for the development of the related clinical competences.

2 | METHODS

A comprehensive search of the literature was conducted at PubMed with two sets of queries (Appendix A). The first search query aimed to identify clinical trials where implants were installed with/or combinations of static, dynamic, robotic CAIS, where accuracy of implant placement was assessed and reported. The second query aimed to identify clinical, preclinical and simulation/cadaver studies where static, dynamic, robotic CAIS or combinations of them were utilised and assessed for the training/education of dentists, specialists and dental students. Search was limited in English papers, published between 1995 and May 2023. Screening was performed by two reviewers (SA, KS) independently by reading the titles and abstracts. Full texts of the selected records were read by all authors and tabulated, while freeform data was extracted based on the main questions of the review. Inclusion and discussion of relevant data was conducted through consensus. Systematic reviews and meta-analyses were separately identified by means of the electronic and manual search and read in full text by all authors for possible data related to the aims of the review.

3 | RESULTS

After electronic and manual search 405 studies were identified in the first query (clinical trials/clinical outcomes) and 23 in the second (education/training). After removal of duplicates, 244 studies were excluded on the basis of information available in the title and/or abstract, while after assessing in full text 77 studies were deemed to include relevant content to the aims of the review. For the second query, 8 studies were initially excluded and 12 finally deemed as containing relevant information. Study specifics (author, year, type of intervention, technologies assessed, primary outcomes), were extracted and tabulated for all studies by two reviewers (SA, KS). Further relevant information was extracted in free-form by all reviewers and clustered in clinically relevant themes as presented below.

3.1 | Assessing the accuracy of implant placement: Evolution, potential, and limitations of outcomes measures

3.1.1 | How has accuracy of implant placement been assessed in clinical trials?

Accuracy of an experimental procedure is defined as the combination of its trueness and precision (ISO 5725-1, 1994). In the case of implant surgery, trueness would reflect how close a measured value (implant position) is to the "true" value (intended/planned position), while precision is a measure of the repeatability or reproducibility of the outcomes. Although the majority of studies in CAIS are reportedly assessing "accuracy," clinical trials can actually assess trueness, while precision can only be assessed in simulation studies, as it would require multiple repetitions under identical conditions. Consequently, clinical trials have assessed accuracy by means of surrogate outcomes measures, mainly different measures of deviation between the placed and planned implant position. Early outcomes measures included 2-dimensional deviation (longitudinal, lateral and transversal) in mm, as well as angular deviation in degrees (Brief et al., 2005). Recently, however, 3-dimensional measurements of deviation at implant platform and apex in mm combined with deviation in the angle have become the established norm (Bover-Ramos et al., 2018; Tahmaseb et al., 2018; Yu et al., 2023). It has to be noted that these three measurements of deviation are not independent (Yotpibulwong et al., 2023).

The technology by which measurements were conducted has also evolved significantly. Early studies have conducted measurements of deviation by means of photographs analysed in imaging software, or Coordinate Measurement machine (Brief et al., 2005). In recent studies, deviation is measured almost exclusively by means of automatic comparison function of treatment planning software, measuring the distance between selected points in the planned and placed implant position (Kaewsiri et al., 2019). Consequently, any evolution in the accuracy of CAIS systems has to be approached in two dimensions: technological improvements which lead to more accurate implant placement and those which lead to more accurate measurements of deviation.

Almost all clinical trials have statistically analysed the deviation by means of average/standard deviation values (Pimkhaokham et al., 2022; Vercruyssen et al., 2014). Recently, Yotpibulwong et al. (2023) proposed to additionally report the frequency distribution of the extent of deviation for each measurement, which in the specific study resembled this of a normal distribution with some differences, however, between the different technologies. Such a reporting might be clinically relevant, especially if specific cut-off values of deviation are proven to be associated with better clinical outcomes or easier restoration procedures. Yotpibulwong et al. (2023) described a stratification of deviation on 3 levels (Platform deviation: low <0.67 mm, medium 0.67–1.30 mm, high >1.30 mm) based on K-clusters analysis. Cluster analysis is a technique used in data mining and machine learning to group similar objects into clusters. K-means clustering is an iterative process of assigning each data point to the groups (clusters) and gradually data points get clustered based on similar features. The 3 groups identified, however, and the corresponding benchmarks derived rather from a mathematical observation based on the specific sample and not any observation related to clinical outcomes. At present, there is a lack of evidence-based benchmarks, which can help clinicians identify the impact that different levels of accuracy can have on clinical outcomes, prosthesis fit or other clinical procedures. Finally, scatter plots of the deviation in different directions (mesial, distal, buccal, palatal) have been often used as supplementary outcomes measures, with the potential to reveal "systemic" errors (e.g., the tendency of the surgeon to deviate more towards one direction due to ergonomics or field of view) (Figure 1a–c). Scatter plots have suggested that the combined use of static and dynamic CAIS can increase accuracy by reducing habitual deviation in the placement angle (Yotpibulwong et al., 2023).

Contrary to what one might expect, there is no clear evidence of progressive improvement in accuracy of CAIS since its inception. Systematic reviews and meta-analyses (Tables 1 and 2) typically include studies conducted over different time periods, with results from older studies being pooled and collectively analysed with those from more recent ones. On the other hand, individual studies at different time points can differ significantly in the procedures involved, sample size, protocols and methodology, which limits the ability for comparisons. Nevertheless, what appears to be supported by the evidence from systematic reviews and meta-analyses is that CAIS accuracy is highest in the case of single edentulous spaces, followed by multiple implants and then fully edentulous patients. Likewise, accuracy is found higher in bounded edentulous than distal extension spaces (Putra et al., 2022), with tooth-supported than bone and mucosa-supported guides (Raico Gallardo et al., 2017), in fully guided than half guided surgery (Gargallo-Albiol et al., 2020) and in simulation studies than cadaver and clinical trials (Bover-Ramos et al., 2018; Jorba-García et al., 2021).

Individual clinical studies have further identified several factors that can influence accuracy. Such factors in s-CAIS could be related to data acquisition (i.e., registration between surface scans and CBCT data) (Flügge et al., 2017), design and fabrication of the surgical guide (i.e., guide support, sleeve types, and manufacturing methods) (Choi et al., 2017; El Kholy et al., 2019; Kessler et al., 2021). In d-CAIS on the other hand accuracy can be influenced by data acquisition from CBCT and design software, capacity of the optical tracking soft- and hardware, and experience of the operator (Tao et al., 2022).

A recent development with the potential to further increase accuracy was the combination of static and dynamic CAIS, which has been applied to single gaps (Yotpibulwong et al., 2023), as well as fully edentulous patients (Lorwicheanrung et al., 2023; Pomares-Puig et al., 2023). When static and dynamic CAIS were combined, significantly more cases were included in the highest accuracy cluster (K-means cluster analysis, Yotpibulwong et al., 2023) than static or dynamic alone and freehand. Using the same levels to classify results of other studies with implant placement under CAIS in single gaps, the combined static and dynamic appears to be in the highest accuracy cluster, together with some deviation data from recent case series on robotic placement (Table 3).

3.1.2 | Is accuracy any different between static and dynamic CAIS?

Although the increased accuracy of CAIS over freehand placement is extensively documented, any potential difference between

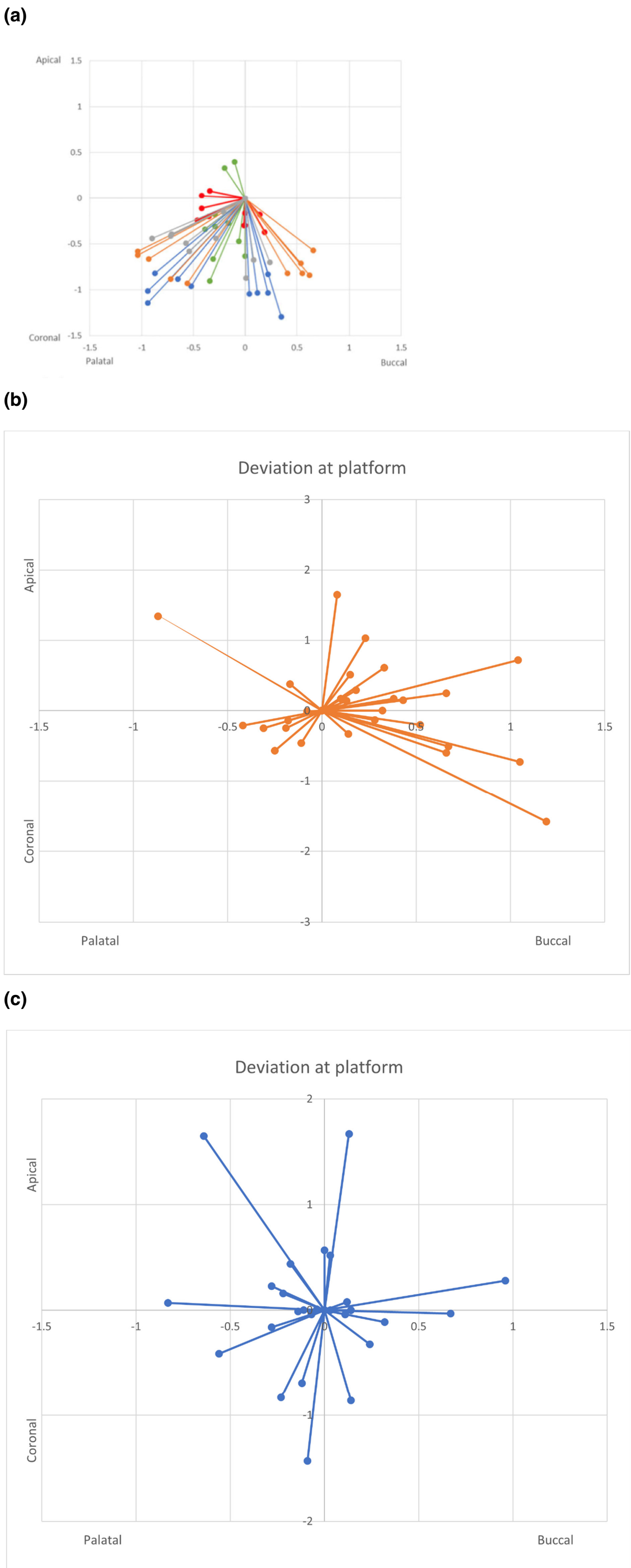

FIGURE 1 Example of 3 scatter plots of deviation between placed and planned position, often colloquially called "firework graphs." Each dot represents the deviation from the planned position (centre) as well as the direction of the deviation (apical, coronal, mesial, distal, buccal, lingual/palatal). (a) Plot of the deviation at platform of implants placed in-vitro in the same position with 5 different static-CAIS systems from Sittikornpaiboon et al. (2021). Observe the "systemic" tendency to deviate towards buccal and buccopalatal, possibly due to ergonomics and operator's position. (b) Plot of the deviation at platform from a randomised clinical trial for single implants placed with s-CAIS from Yotpibulwong et al. (2023). Observe a similar but milder trend for "systemic" deviation towards buccal and apical. (c) Plot from the same study as (b) for single implants placed with a combination of static and dynamic. Observe the more symmetric distribution of the error in all directions, indicating reduction of any systemic error.

dynamic and static remains unclear. Randomised clinical trials comparing s- and d-CAIS in the same clinical setting have not found any significant difference in reported deviations (Jaemsuwan et al., 2023; Kaewsiri et al., 2019; Yimarj et al., 2020; Yotpibulwong et al., 2023) (Table 3), yet it should be noted that only means and standard deviations were analysed. Nevertheless, three recent systematic reviews and meta-analyses provided evidence of difference in the accuracy between static and dynamic CAIS, at least with regards to reducing the angular deviation, where d-CAIS was found superior to static (Jorba-García et al., 2021; Vinnakota et al., 2023; Yu et al., 2023). The possibility of dynamic CAIS improving accuracy at least with regards to angular deviation is also supported by Yotpibulwong et al. (2023), who showed that drilling through a surgical guide can still allow for angular deviation of as much as 8°, something that the operator is unaware, unless prompted to correct by the real time feedback of a dynamic CAIS system. Scatter plots of the direction of deviation in this study showed more common directional deviation with static CAIS, possibly as a result of ergonomics and accessibility, forcing the operator to apply more pressure towards certain directions. The same directional deviation scatter plots appeared more balanced when dynamic CAIS was utilized, suggested some potential advantage at least with regards to the control of the angle. Meta analysis of larger data sets from randomised clinical trials utilizing frequency distribution and scatter plots might help to further comprehend these findings.

3.1.3 | Which technologies and protocols of robotic CAIS have been assessed in implant dentistry?

The robot is a disruptive innovation already extending in several fields of surgery and healthcare. Currently, medical robots can be categorised in six levels based on autonomy of operation: from the lowest levels of (1) "no autonomy" and (2) "assistance," intermediate levels of (3) "task," (4) "conditional" or (5) "high" autonomy to the highest level of (6) "full automation" (Yang et al., 2017). At present the available robotic systems specific for implant surgery are either robot-assisted (level 2: assistance) or autonomous with task autonomy (level 3). The first category, often referred to as operator-controlled or telecontrolled type of surgical robots, is widely applied in orthopaedic surgery. The surgeon has full control of the robotic arms during the whole operation through a

TABLE 1 Summary of systematic reviews/ eta-analyses of the outcomes of dynamic CAIS systems.

Study	Timeframe (year–year)	Patients	Implants	Platform deviation	95% CI	Apex deviation	95% CI	Angle deviation	95% CI
Jung et al. (JOMI 2009)	2001–2007	NA	1041	0.62	0.43–0.81	0.68	0.55–0.80	NA	NA
Wei et al. (COIR 2021)	2015–2020	762	1298	1.02 ± 0.19	0.83–1.21	1.33 ± 0.35	0.98–1.76	3.59 ± 1.5	2.09–5.09
Pellegrino et al. (JOMI 2021)	2002–2019	NA	2756	0.81 ± 0.133	0.677–0.943	0.910 ± 0.14	0.770–1.049	3.807	3.083–4.530
Jorba-Garcia et al. (COI 2021)	2010–2020	NA	NA	0.69 ± NA	0.67–0.72	0.90 ± NA	0.83–0.97	3.68 ± NA	3.61–3.74
Schnutenhaus et al. (JCM 2021)	Up to 2020	298	747	1	0.83–1.16	1.33	0.98–1.68	4.1	3.14–5.10
Aghaloo et al. (JOMI 2023)	2008–2022	NA	NA	0.9	0.8–1.0	1.2	0.8–1.5	3.4	3.0–3.9
Yu et al. (J Dent 2023)	2013–2023	1076	1526	1.07	0.96–1.17	1.27	1.06–1.47	3.43	2.94–3.93
Mai et al. (JMIR 2023)	Up to 2022	NA	346	0.89	0.58–1.21	1.47	0.85–2.10	3.96	3.45–4.48

Note: Platform deviation/Apex deviation: mean ± standard deviation (when reported) in mm. Angle deviation: mean ± standard deviation (when reported) in degrees.
Abbreviations: CI, confidence intervals; NA, not available.

TABLE 2 Summary of systematic reviews/meta-analyses of the outcomes of static CAIS systems.

Study	Timeframe (year–year)	Patients	Implants	Platform deviation (mm)	95% CI	Apex deviation (mm)	95% CI	Angle deviation (°)	95% CI
Schneider et al. (COIR 2019)	2003–2009	46	155	1.16	0.92–1.39	1.96	1.33–2.58	5.73	3.96–7.49
Jung et al. (JOMI 2009)	2001–2007	NA	261	1.12	0.82–1.42	1.2	0.87–1.52	NA	NA
Tahmaseb et al. (JOMI 2014)	2008–2012	414	1941	1.12	0.0–4.5	1.39	0.3–7.1	3.89	0–21.16
Bover-Ramos et al. (JOMI 2018)	2005–2015	476	2244	1.1 ± 0.09	0.912–1.280	1.4 ± 0.12	1.163–1.639	3.98 ± 0.33	3.313–4.642
Tahmaseb et al. (COIR 2018)	2008–2017	461	2194	1.2	1.04–1.44	1.4	1.28–1.58	3.5	3.00–3.96
Gargallo-Albiol et al. (JOMI 2020)	2013–2019	NA	NA	0.51	NA	0.75	NA	3.63	NA
Carosi et al. (Materials 2022)	2010–2017	277	1556	1.23 ± 0.26	0.97–1.49	1.46 ± 0.29	1.17–1.74	3.42 ± 0.6	2.82–4.03
Putra et al. (JPR 2022)	2000–2020	73	146	0.29 ± 0.22	NA	0.33 ± 0.29	NA	NA	NA
Aghaloo et al. (JOMI 2023)	2017–2022	NA	NA	1.2	1.0–1.3	NA	NA	3.8	3.4–4.2
Yu et al. (J Dent 2023)	2013–2023	NA	220	1.13	0.99–1.27	1.37	1.17–1.57	3.81	2.95–4.66

Note: Platform deviation/Apex deviation: mean ± standard deviation (when reported) in mm. Angle deviation: mean ± standard deviation (when reported) in degrees.
Abbreviations: CI, confidence intervals; NA, not available.

TABLE 3 Mean of 3D deviation (platform, apex, angle) as reported in clinical trials (between 2019 and 2023) of implant placement in single gaps with CAIS and robotic surgery, stratified in the 3 levels described by K-means cluster analysis by Yotpibulwong et al. (2023).

Study	Deviation level								
	Low deviation			Medium deviation			High deviation		
	Platform (mm) <0.67	Apex (mm)<0.87	Angle (°) <2.24	Platform (mm) 0.67–1.30	Apex (mm) 0.87–1.62	Angle (°) 2.24–5.10	Platform (mm) >1.30	Apex (mm) >1.62	Angle (°) >5.1
Clinical trials									
Chulalongkorn									
Kaewsiri et al. (2019)									
Static CAIS				0.97	1.28	2.84			
Dynamic CAIS				1.05	1.29	3.06			
Smitkarn et al. (2019)									
Static CAIS				0.9	1.2	2.8			
Freehand				1.3				2.2	7
Yimarj et al. (2020)									
Static CAIS				1.04	1.54	4.08			
Dynamic CAIS				1.24	1.58	3.78			
Yotpibulwong et al. (2023)									
Static + Dynamic CAIS	0.62	0.75	1.24						
Static CAIS				1.06	1.4	3.18			
Dynamic CAIS				1.02	1.28	3.28			
Freehand							1.48	2.18	7.5
Other centres									
Sun et al. (2020)									
Static + Dynamic CAIS	-	-	2.2						
Static CAIS				-	-	4.54			
Dynamic CAIS				-	-	3.24			
Freehand							-	-	6.12
Wu et al. (2019)									
Static CAIS				1.22	1.33	4.34			
Dynamic CAIS					1.48	3.71	1.36		
Aydemir and Arısan (2020)									
Dynamic CAIS				1.01				1.83	5.59
Freehand							1.7	2.51	10.04

TABLE 3 (Continued)

Study	Deviation level								
	Low deviation			Medium deviation			High deviation		
	Platform (mm) < 0.67	Apex (mm)<0.87	Angle (°) <2.24	Platform (mm) 0.67–1.30	Apex (mm) 0.87–1.62	Angle (°) 2.24–5.10	Platform (mm) >1.30	Apex (mm) >1.62	Angle (°) >5.1
Schneider et al. (2019)									
Static CAIS (Stereolithography)				0.97	0.97	4.23			
Static CAIS (3D printer)				0.72	1.08	3.13			
Freehand				1.25				2.32	7.36
Liu et al. (2022)[a]									
Static CAIS				0.92	1.31	3.31			
Dynamic CAIS			2.14	1.07	1.26				
Jorba-Garcia et al. (2023)									
Dynamic CAIS				1.12	1.42	4.02			
Freehand							1.70	2.49	7.97
Fu et al. (2023)[a]									
Static CAIS						2.32	1.56	1.7	
Dynamic CAIS				1.02	1.00	3.87			
Aydemir and Arısan (2020)									
Dynamic CAIS				1.01	1.83	5.59			
Freehand							1.70	2.51	10.04
Varga Jr. et al. (2020)									
Static CAIS					1.59	3.04	1.40		
Freehand							1.82	2.43	7.03
Jia et al. (2023)[a]									
Robotic CAIS	0.43	0.56	1.48						
Static CAIS					1.47	2.42	1.31		
Yang et al. (2023)[b]									
Robotic			1.11	0.74	0.73				
Chen et al. (2023)[b]									
Robotic	0.53	0.53	-			2.81			

Note: Blue: studies conducted at Chulalongkorn University clinic under same protocols and technology. Yellow: studies in other centres.

[a]Retrospective study.

[b]Case series, robotic placement only.

console by means of bimanual wrist manipulation. The autonomous robotic surgery is an extension of the optical tracking technology of the dynamic CAIS coupled with the robotic arm, which can carry a handpiece and conduct the osteotomy and dental implant placement under human supervision but with no active guidance (Figure 2). Thus, autonomous robotic CAIS could combine the benefits of the static and the real-time image-based guidance of the dynamic CAIS. The robotic arm is a steady and precise

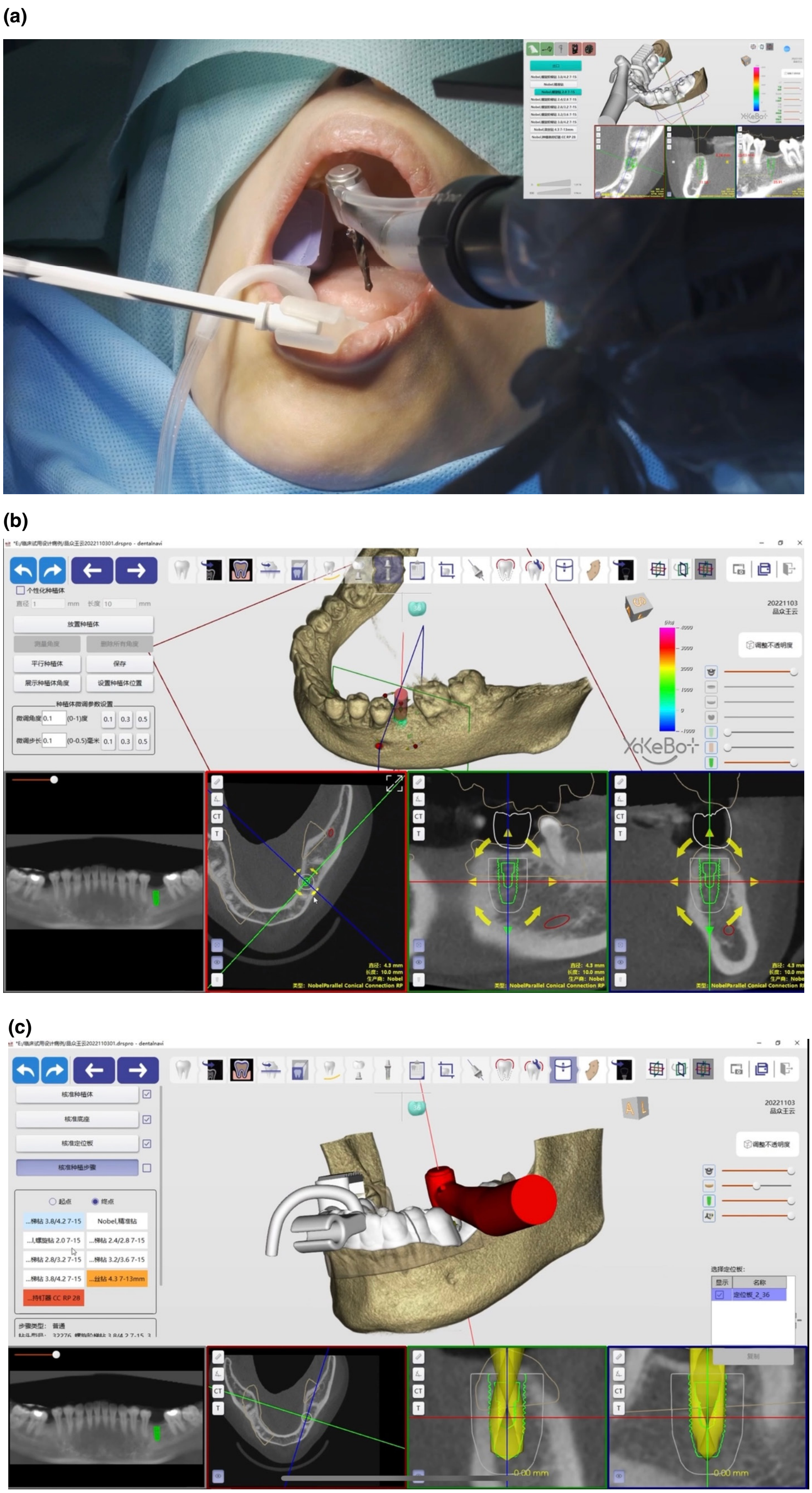

FIGURE 2 (a) The autonomous robotic arm (Yakebot Technology Co Ltd, Beijing) controls the implant drill through an optical tracking system similar to the one used for human operated dynamic CAIS. A tracker with fiducial markers is firmly attached in the operated jaw and can be seen in the left. (b, c) Proprietary navigation software is used to project the planned implant position on the patient's anatomy and guide the osteotomy in a 3-dimensional space.

mechanism that can eliminate any human operator related limitations by ergonomics, reduced field of vision, fatigue or tremor and thus increase precision.

The world's first autonomous dental implant robotic placement, was successfully conducted in 2017 by Peking University (Beijing, China) and the Fourth Military Medical University Hospital (Xi'an, China). Commercial launch of the robotic system followed in 2021 as Yakebot (Yakebot Technology Co Ltd, Beijing). A second robot was registered in China for autonomous placement of dental implants in 2019 under the name Remebot (BeiJing BaiHuiWeiKang Co., Ltd), which has also by now published clinical documentation (Yang, chen, et al., 2023). In Unites States, a dental implant robotic system called YOMI received FDA-approval in US in 2017 and was launched in 2017. YOMI is a autonomy level 2 (robotic assistance) system using haptically guided stereotactic robotic technology (Mozer, 2020).

3.1.4 | What is the evidence of accuracy of implant placement with robotic CAIS?

Autonomous robotic implant surgery is still at an infancy, yet limited evidence in accuracy is at present available in the form of case studies (Yang et al., 2022) or series (Bolding & Reebye, 2022; Chen et al., 2023; Yang, chen, et al., 2023). In the case of robotic implant placement, accuracy has been assessed in the same way as with s- and d-CAIS, by means of comparing implant deviation between planned and placed position at platroms, apex and angle. Yang, chen, et al. (2023) in a case series with autonomous robotic placement of single implants in 10 patients with the system Remebot, reported a mean overall deviation of 0.74 mm at platform, 0.73 mm apical 1.11° in the angle. Similarly, Chen et al. (2023) utilised a robotic arm to place 31 implants in 28 partially edentulous patients, documenting a mean angle deviation of $2.81 \pm 1.13°$, while the 3D deviations at the implant shoulder and apex were 0.53 ± 0.23 mm and 0.53 ± 0.24 mm, respectively.

Such levels of accuracy would be higher than the current benchmarks with human-operated static and dynamic CAIS (Pellegrino et al., 2021) and comparable with the accuracy reported from the few studies combining static and dynamic CAIS in single gaps (Table 3) (Yotpibulwong et al., 2023). The first case of full arch implant rehabilitation with immediate loading has now been reported with autonomous robotic system. Yang et al. (2022) utilised Remebot to place six implants in the edentulous maxilla and to immediately load them with a full arch prosthesis. The process was more complex and required a personalized mucosa-supported template with an optical positioning marker and a tooth-supported guided template, which were fixed together with metallic pins. The template with the positioning marker was secured to the patient jaw using bone screws. The implants were placed in the maxilla with mean coronal and apical deviations of 0.59 ± 0.24 mm and 0.61 ± 0.23 mm, respectively, while the mean angular deviation was 0.89 ± 0.38 degrees.

Case reports have also assessed the accuracy of remotely operated type robots in implant dentistry (Mozer, 2020). Bolding and Reebye (2022), assessed the accuracy of implant placement in five edentulous patients (38 implants – 8 arches) with the YOMi haptic robotic system. They showed an average global angular deviation of 2.56 ± 1.48 degrees, and deviation at the entry and apex of 1.04 ± 0.70 mm and 0.95 ± 0.73 mm, respectively. Such accuracy would be at least as good as results achieved with either static or dynamic CAIS in similar cases (Table 3).

3.2 | Training and education: Developing clinical skills for effective use of CAIS

3.2.1 | Developing competences with CAIS: Is there a "learning curve?"

The term "learning curve" is currently used in education and training to reflect the relationship between the time on task or amount of practice and the level of performance. First proposed by Wright in 1936, it has received many interpretations and modifications, including the frequently cited work of Bills (1934) who expressed it as a graph depicting the rate of competence improvement as a result of practice. The concept of the learning curve is increasingly applied in the training of computer assisted and robotic surgical competences (Perera et al., 2023; Yang, Kim, et al., 2023), as not only it enables deeper insight into the incremental improvements of the surgical skills, but could also aid the educators to identify the stages where more resources and assistance will be required to efficiently improve performance. In particular when new surgical technologies are introduced, studying the learning curves can set the important benchmarks of essential skills for safe practice by a novice, as well as these associated with mastery of the technique (Perera et al., 2023). Commonly applied concepts of the learning curve identify four different types (Figure 3).

Comparative simulation studies with novice operators have suggested that learning the skills of s-CAIS might come with different learning curves to these of d-CAIS. Wang, Zhuang, et al. (2023) studied the learning process of both s-CAIS and d-CAIS in a comparative in-vitro study with 3 undergraduate dental students involving the placement of 150 implants. They documented a learning curve effect for both the operating time and accuracy of placement for the use of d-CAIS, with significant improvement over time, possibly reaching a plateau within the last few attempts. In contrast to that, no learning curve effect was found in the s-CAIS group for accuracy of placement, while the operating time showed only marginal improvements. Thus in this experiment, although the s-CAIS group showed higher accuracy than the d-CAIS at start, when the plateau stage was reached the influence of the two guidance methods disappeared. Similar patterns of improvement for d-CAIS are shown in three other in-vitro studies which included inexperienced operators (Jorba-García et al., 2019; Spille et al., 2022; Zhan et al., 2021), although without direct comparisons to s-CAIS in this case.

Although, clinical studies directly assessing the presence of learning curves are scarce, results could indirectly support the findings of

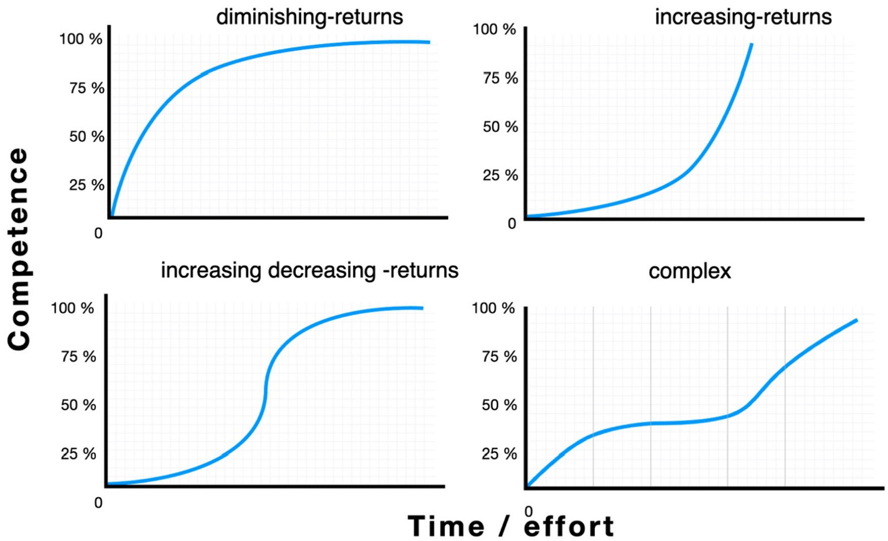

FIGURE 3 Four common patterns depicting the increase of performance and competence in relation to time on task. Upper left: The diminishing-returns curve. Rate of progression is rapid at the beginning but slows down to a plateau soon. This curve describes a task that appears easier to master and progression of learning is initially fast. Upper right: The increasing-returns curve. Rate of progression is slow at the beginning but rises with practice until full proficiency is obtained. This curve corresponds to learning of a more complex task, where the rate of learning is initially slow. Lower left: The increasing-decreasing returns curve, or S-curve, reflecting slow learning at the beginning, followed by a period of fast increase in performance before a plateau is reached, or new challenges encountered. Lower right: The complex curve. A more complex pattern of learning if depicted, with sequential stages of faster and slower growth of proficiency as well as interwinded plateaus.

the simulation studies. Cassetta et al. (2020) did not identify a progress pattern suggestive of a 'learning curve' effect in a prospective cohort study with s-CAIS, where 6 partially and 6 totally edentulous patients were treated by two surgeons experienced in implantology but completely inexperienced in guided surgery. On the other hand, Block et al. (2017), studying the outcomes of consecutive surgeries by 3 implant surgeons with the use of d-CAIS concluded that increase in accuracy of implant placement with d-CAIS was incremental. Their observations showed that a plateau of highest accuracy was only achieved by the surgeon after completing around 20 patient cases, possibly suggestive of a "steep" increasing-returns learning curve.

3.2.2 | Is CAIS suitable for novice surgeons?

The experience level of the operator is shown to influence the clinical outcomes of surgical interventions in maxillofacial region (Sakamoto et al., 2022). Two simulation studies have shown no difference in terms of accuracy when d-CAIS was used by experienced and novice surgeons (Jorba-García et al., 2019; Wang, Shujaat, et al., 2023). The novice surgeons used as control in both studies however where qualified clinicians already experienced with implant surgery, albeit junior and without previous experience with d-CAIS.

Few comparative clinical studies are available directly assessing the influence of the operators' prior level of experience on the outcomes of CAIS and all are limited to s-CAIS. In a comparative study with s-CAIS utilised on 10 fully edentulous patients, Cassetta & Bellardini (2017) concluded that surgeon's experience was not found to improve implant placement accuracy, when the outcomes from 5 novice surgeons were compared to these achieved by 5 experienced ones. van de Wiele et al. (2015) studied the outcomes of flapless s-CAIS surgery conducted by postgraduate students and compared the accuracy achieved with this reported in another study (Vercruyssen et al., 2014) by experienced specialists where similar planning and clinical settings were utilized. The authors did not find any difference in the accuracy of placement between postgraduate students and specialists. Søndergaard et al. (2021) conducted a clinical trial with implant placement by senior dental students, documenting favourable outcomes with both fully and partial guided s-CAIS.

It is important to note that although clinical studies have found no difference in terms of accuracy of implant placement between novice and experienced surgeons, no assessment is present with regards to PROs or other clinical outcomes and complications.

3.2.3 | Does dynamic CAIS have value as an educational tool for teaching implant dentistry?

CAIS requires the operator to spend significant time in planning of the surgical intervention, analysing 3-dimensional imaging. In addition, d-CAIS offers 3-dimensional real time intraoperative feedback of the surgical anatomy. Both tasks could contribute to the development of the Spatial Representation Ability of the surgeon, a competence shown to be critical for surgical performance which relates to the interpretation of 2-dimensional representations (radiographs, images) into 3-dimensional spatial understanding of anatomic structures (Yao et al., 2019). CAIS could have an educational value in the training of novice surgeons with implant surgery, assisting them in the development of essential surgical skills, as suggested by a comparative simulation study (Zhan et al., 2012). Students showed significantly greater improvement in freehand implant placement after being trained with the dynamic navigation system, as opposed to conventional training (Zhan et al., 2012). In another simulation study by Kunakornsawat et al. (2023), novice students improved the accuracy of implant placement with the use of d-CAIS and there was a strong but marginally not significant trend for higher accuracy when CAIS training was distributed in multiple sessions over time. On the other hand, when static CAIS was used for the training of students in implant placement, Søndergaard et al. (2021) noticed that some students felt that the learning outcome was diminished, as they did not have to "think for themselves."

4 | DISCUSSION AND CONCLUSIONS

Static and dynamic CAIS are already well-established technologies, with long documentation in implant dentistry, while robotic implant surgery has gone beyond the "proof of principle" stage and is rapidly expanding. As the CAIS was perceived primarily as a means for increasing precision in implant placement, it is not surprising that accuracy is the most common primary outcome assessed in clinical trials. Secondary outcomes often included implant survival and less frequently intraoperative or post operative complications and some short-term measures of success. Patients Reported Outcomes (PRO) and Experience (PRE), outcomes related to aesthetics and or restorative parameters have not been frequently assessed.

Although the large body of evidence is focused in "accuracy" of implant placement as compared to a pre-planned position, accuracy is not assessed as defined by the ISO standard, but rather using surrogates such as linear and angular deviation. This is understandable, as accuracy defined as combination of both trueness and precision cannot be fully assessed in clinical trials. Nevertheless, expanding the outcomes measures beyond the average deviation could increase our insights in the advantages and limitations of each specific technology and protocols. Such outcomes measures could include reporting of the frequency distribution of the deviations, detailed scatter plots and advanced clustering statistical methods. At present, there is no clear evidence suggesting any difference in the outcomes of accuracy between static and dynamic CAIS, although recent meta analyses (Jorba-García et al., 2021; Vinnakota et al., 2023; Yu et al., 2023) have suggested higher reduction of angular deviation with d-CAIS. In the future, analyses of larger samples possibly and outcomes measures other than average deviation might help to clarify the potential differences. For now, the choice between static or dynamic CAIS should be safer conducted based on local anatomic, patient and operational factors rather than any differences in the anticipated accuracy. Combining static and dynamic CAIS has the potential to further increase implant placement accuracy in both single gaps and edentulous patients, but it comes with significant operational and cost implications which raise questions with regards to cost effectiveness of the outcomes. Finally, there is a strong need for research which can investigate the association of the increased levels of accuracy with clinical and patient reported outcomes, assess the actual patient benefits and document the cost efficiency of all these technologies.

Robotic CAIS will most certainly attract increased attention in the near future, as case series have demonstrated accuracy of placement that appears higher than this achieved by human operated CAIS, even in complex cases such as the edentulous arch. Nevertheless, the high costs and complexity of this technology, as well as the need for human intervention (at best task autonomy only) and direct supervision, would limit its wider application into practice. In the future, expanding the use of robotic arms to other surgical and non-surgical procedures might increase the indications and thus the benefits of such a system. Coupled with advances in machine learning and artificial intelligence, new possibilities could emerge for autonomous robotic surgical applications, including wider implementation in implant dentistry (Revilla-León et al., 2023; Saeed et al., 2023).

Clinical studies suggest that qualified implant surgeons without prior experience in static and dynamic CAIS can safely practice both techniques after basic instruction and/or simulation training. Nevertheless, clinical (Cassetta et al., 2020) and simulation (Wang, Zhuang, et al., 2023) studies demonstrated differences in the pattern of improvement of the operator's performance with regards to accuracy for static and dynamic CAIS. Overall, comparative simulation studies have shown the increase in performance to be incremental in the case of dynamic CAIS, while transition from the novice to the experienced level accuracy with static CAIS appears to be faster.

Available clinical and simulation studies have shown similar implant placement accuracy achieved by novice and experienced implant surgeons, at least when the novice has basic experience with implant surgery. Nevertheless, differences in important clinical outcomes such as frequency and management of complications or Patient Related Outcomes/Experience with the use of CAIS have not been investigated between novice and experienced surgeons. Limited evidence from simulation studies suggests that dynamic CAIS has additional potential as educational tool for novice implant surgeons, something not likely for static CAIS.

AUTHOR CONTRIBUTIONS

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ACKNOWLEDGEMENTS

The study was supported by Ratchadapiseksompotch Fund, Chulalongkorn University, Bangkok, Thailand.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available from authors upon reasonable request.

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How to cite this article: Pimkhaokham, A., Chow, J., Pozzi, A., Arunjaroensuk, S., Subbalekha, K., & Mattheos, N. (2023). Computer-assisted and robotic implant surgery: Assessing the outcome measures of accuracy and educational implications. *Clinical Oral Implants Research*, *00*, 1–15. https://doi.org/10.1111/clr.14213

APPENDIX A

Search method

Two comprehensive searches of the literature were conducted at PubMed:

1. Clinical Outcomes of static, dynamic and robotic CAIS

Clinical trials where implants were installed with static, dynamic, robotic CAIS or combinations of them, either compared with conventional free-hand implant placement or not.

- Search Querry

The electronic databases PubMed was searched in May 2023 for articles in English since 1995 using the search query below:

{"Computer assisted implant surgery" OR "Computer aided implant Surgery" OR "guided implant Surgery" OR "implant navigation" OR "static guided" OR "dynamic guided"} AND Dental.

In addition, manual search was conducted on the reference list of systematic reviews and meta-analyses.

- Inclusion/Exclusion criteria

Studies were *assessed* for potential data extraction if they fulfilled the criteria below:

(i) Human clinical trials, where dental implants were placed in the maxilla or mandible using either static or dynamic or robotic CAIS or combinations (with or without comparison with conventional freehand).
(ii) Studies in English.
(iii) Studies where CBCT was utilised for surgical planning.

The following types of studies were *not assessed*:

(i) Cadaver, preclinical and in-vitro simulation studies, expert opinions, reviews.
(ii) Case reports and case series with less than ten patients.
(iii) Studies with zygomatic, pterygoid, and orthodontic implants.
(iv) Studies reporting implant placement in extra-orally harvested bone (iliac grafts etc) or with unconventional protocols such as socket shield, trephination-based osteotomies.
(v) Studies reporting on patients with systemic disease, irradiated, having received gnathectomy or under serious medical treatment.

- Data extraction

Data extracted from identified studies covered author/year, study design and methodological parameters, treatment planning and surgical and loading protocols, study population, elements of the workflow utilised, clinical outcomes, PROs and PRE, respective instruments/outcomes measures, main conclusions and limitations. The clinical outcomes from the included studies were extracted and systematic organized into tables to determine the most appropriate method for collective analysis for each field.

2. Education and training of clinicians with static, dynamic and robotic CAIS

Clinical and pre-clinical, simulation and cadaver studies, where implants were installed with static, dynamic, robotic CAIS or combinations of them, either compared with conventional free-hand implant placement or not.

- Search Querry

The electronic databases PubMed was searched in May 2023 for articles in English since 1995 using the search query below: {"Computer assisted implant surgery" OR "Computer aided implant Surgery" OR "guided implant Surgery" OR "implant navigation" OR "static guided" OR "dynamic guided"} AND {"Dental" AND "education"}.

In addition, manual search was conducted on the reference list of relevant papers and systematic reviews.

- Data extraction

Data extracted from identified studies covered author/year, study type/design and methodological parameters, study population, elements of the workflow utilised, assessed primary and secondary outcomes, respective instruments/outcomes measures, main conclusions and limitations. The outcomes from the selected studies were organized into tables to determine the most appropriate method for collective analysis for each field.

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