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Learning Curve Analysis of Preclinical All-Ceramic Crown Preparation Among Second-Year Undergraduate Dental Students

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ABSTRACT

Mastering complex preclinical skills, such as full-coverage crown preparation, is fundamental in dental education. However, reliable data on the learning progression associated with specific procedures remains limited. This prospective cohort study aimed to evaluate the learning curve for preparing maxillary central incisors for all-ceramic crowns among second-year undergraduate dental students, assess the effectiveness of repeated practice, and estimate the training volume required to achieve clinical competency. Fourteen students performed four weekly crown preparation attempts on tooth #11 of a typodont, following standardized instructions. Preparation time was recorded for each attempt, and three calibrated external examiners assessed the preparations using a validated 15-domain rubric (maximum score: 100). The rubric demonstrated strong internal consistency (Cronbach's $\alpha = 0.86$) and acceptable inter-rater reliability (ICC = 0.66, $p < 0.001$). ANOVA and regression analyses were used to model skill development (score) and efficiency (time) over successive attempts. Results revealed a general upward trend in preparation scores from Attempt 1 (mean = 44.52) to Attempt 4 (mean = 47.10), with a transient decline at the second attempt, characteristic of a non-linear early learning phase. Predictive modeling suggested that students require approximately eight practice attempts to attain the proficiency level expected for clinical performance. By the eighth attempt, preparation time improved significantly, decreasing to an average of roughly 600 to 660 seconds (equivalent to 10 - 11 minutes). These findings offer quantitative insights into the development of preclinical skills in prosthodontics and support the integration of sufficient repetition within preclinical curricula to ensure competency-based training outcomes.

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INTRODUCTION

The foundation of dental education is preparing future practitioners with the critical clinical skills necessary to provide safe and effective patient care [1]. A significant component of this training occurs during the preclinical phase, where students acquire foundational knowledge and develop critical psychomotor skills in a simulated environment before transitioning to direct patient interaction [2]. Within the preclinical curriculum, mastering procedures such as tooth preparation for fixed restorations is crucial. Full coverage crown preparation, particularly for all-ceramic restorations, represents a complex task demanding a sophisticated integration of theoretical understanding, visual-spatial ability, and fine motor skills [3-5].

Achieving proficiency in reducing tooth structure appropriately, establishing precise finish lines, and managing preparation contours is fundamental to the long-term success of the final restoration and the preservation of oral health [6].

Historically, the assessment of skill acquisition in preclinical settings has relied heavily on subjective evaluations by faculty, often using qualitative or basic quantitative measures [7]. While essential, these methods can be influenced by inter-examiner variability and may not fully capture the dynamic process of skill development over time [8, 9]. Ensuring consistency, validity, and reliability in assessment is critical, not only for fair evaluation but also for providing meaningful feedback that guides student learning and improvement [10, 11]. Effective feedback mechanisms, potentially enhanced by tools such as rubrics or digital assessment technologies, are vital for students to understand their performance and identify areas

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needing further development [12, 13].
The process of skill acquisition, characterized by performance improvement with increasing practice or experience, is often conceptualized through the learning curve [14]. First described in an industrial context by Wright in 1936 to model production efficiency [15], the learning curve principle posits that as an individual repeatedly performs a task, their efficiency and proficiency increase, typically rapidly at first, then gradually plateau as mastery is approached [14, 16]. This concept has been widely adopted in various fields, including medicine and surgery, to analyze the trajectory of skill development for new procedures, particularly minimally invasive techniques [17, 18].
In dental education, the learning curve provides a valuable framework for understanding how students' progress in mastering complex procedural skills through repeated practice sessions [1, 19]. Analyzing these curves can offer insights into the effectiveness of different pedagogical approaches, such as instructional videos versus live demonstrations [3], and help determine the optimal amount of practice required to achieve competency [17].
Despite the recognized importance of the learning curve in skill development, research into the specific learning paths for basic preclinical dental procedures remains relatively limited. Preparing a maxillary central incisor for an all-ceramic crown is a common yet challenging task for dental students, requiring adherence to strict dimensional and geometric rules critical for both aesthetic and functional success. Understanding how students, particularly those in the early stages of their preclinical training, such as second-year students, develop skills in this specific task is essential for improving curricula and assessment strategies. Current preclinical training often involves a set number of practice sessions, but the evidence needed to determine the minimum practice required to reach a certain level of skill for this procedure is not well established.
This study aimed to explore the learning curve for second-year dental students as they prepared maxillary central incisors for all-ceramic crowns in a preclinical lab. Our main goals were to predict this learning curve, analyze how effective repeated practice sessions were in improving students' preparation skills over time, and ultimately, to determine the minimum number of training sessions and the time needed for students to reach a competent performance level based on standardized assessment criteria. By addressing these objectives, this study seeks to provide quantitative insights into the skill acquisition process for a core prosthodontic procedure, contributing valuable data to inform evidence-based preclinical dental education and training methodologies.
The present research suggests that a measurable and predictable learning curve is evident for second-year dental students as they acquire the skills to prepare maxillary central incisors for all-ceramic crowns in a preclinical environment. It's further hypothesized that, with time, regular practice sessions will greatly improve these students' tooth preparation techniques. Eventually, a definable minimum number of training sessions and associated time is expected to be required for students to achieve a predefined competent level of performance, as measured by standardized assessment criteria.

METHODS

Study Design and Setting

This investigation employed a prospective cohort study design to assess the development of preclinical skills in fixed prosthodontics among dental students. The research was conducted at the Department of Prosthodontics, Faculty of Dentistry, University of Attahadi, during the academic year 2024-2025.

Participants

Fourteen second-year dental students enrolled in the preclinical fixed prosthodontics course participated in the study. All students provided consent before the commencement of the study.

Procedure and Evaluation

Participants were assigned the task of preparing a maxillary right central incisor (typodont tooth #11, mounted within a standard maxillary arch model) for a full-coverage all-ceramic crown restoration. Each student undertook this preparation task every week over four consecutive weeks, resulting in a total of four preparation attempts per participant. Before engaging in the practical exercises, all participants received standardized theoretical instruction via lectures and visual training through demonstrational videos detailing anterior tooth preparation techniques.
Students performed the tooth preparations independently under the supervision of a faculty member. The duration required for each preparation was carefully recorded in seconds. Following each preparation session, the prepared typodont teeth were evaluated by three independents, standardized prosthodontic faculty members affiliated with an external institution. Each evaluator possessed a minimum of ten years of combined clinical and academic experience. The assessment utilized a modified analytical scoring rubric, adapted from Wu et al. and previously validated for evaluating anterior all-ceramic crown preparations [17]. This rubric included fifteen distinct domains, including aspects such as incisal reduction, labial reduction and contour, proximal reduction and contour, palatal reduction and contour, finish line location and configuration, taper, and the time taken for preparation. Each domain was assigned a predetermined weight, contributing towards a maximum achievable score of 100 points (Table 1). The structured nature of the rubric was intended to bolster objectivity and consistency throughout the

evaluation process.

Table 1. Criteria for evaluation of tooth preparation for an all-ceramic crown of the maxillary central incisor

Feature	Criteria	
Reduction (30 points)		
Incisal reduction (5 points)	1.4-1.6 mm. 1.2-1.4 mm or 1.6-1.8 mm. 1.0-1.2 mm or 1.8-2.0 mm. < 1.0 mm or > 2.0 mm	5 points 3 points 1 point 0 point
Labial reduction (5 points) Mesial reduction (5 points) Distal reduction (5 points) Lingual axial reduction (5 points)	1.0-1.5 mm. 0.8-1.0 mm or 1.5-1.7 mm. 0.5-0.8 mm or 1.7-2.0 mm. < 0.5 mm or > 2.0 mm.	5 points 3 points 1 point 0 point
Lingual fossa reduction (5 points)	0.5-1.0 mm. < 0.5 mm or > 1.0 mm.	5 points 0 point
Contour (15 points)		
Labial contour (5 points)	Labial preparation has two planes, providing adequate material bulk for strength/esthetics without undercut.	
Proximal contour (5 points)	Smooth, connected with labial and lingual surfaces, without undercut	
Lingual contour (5 points)	Coincided with lingual fossa, without undercut	
Taper (20 points)		
Labial-lingual taper (10 points) Mesial-distal taper (10 points)	0°-10°. > 10°-20°. > 20°-30°. < 0° or > 30°.	10 points 8 points 5 points 0 point
Finish line (25 points)		
Thickness of finish line (10 points)	1.0-1.2 mm shoulder. < 1.0 mm or >1.2 mm.	10 points 0 point
Finish line quality (10 points)	Smooth, continuous, well-defined Moderate roughness, moderately noncontinuous, moderate lack of definition. Significant roughness, noncontinuous, lack of definition.	10 points 5 points 0 point
Margin placement (5 points)	At gingivally or not more than 0.5 mm subgingivally. Not more than 1 mm subgingivally or 0.5 mm supragingivally. More than 1 mm subgingivally or 0.5 mm supragingivally.	5 points 3 points 0 point
Preparation time (10 points)		
Preparation time (10 points)	≤ 20 min (≤1200 sec). > 20-25 min (>1200-1500 sec). > 25-30 min (>1500-1800 sec). > 30 min (>1800 sec).	10 points 6 points 3 points 0 point

Measurement of tooth preparation using ImageJ and standardized photography

To ensure consistent and objective evaluation of tooth preparations, a reference index was first fabricated using heavy-body polyvinyl siloxane (PVS) before any cutting was performed. Two sections of the index were prepared: one sectioned labio-palatally and the other mesiodistally, enabling direct visual comparison between the unprepared and prepared tooth surfaces. Upon completing each preparation, standardized photographs were captured, ensuring uniformity through the use of a positioning guide set 18 cm from the tooth. Each tooth was documented from three standard views - labial, distal, and incisal—to comprehensively record all critical aspects of the preparation. The resulting images were then analyzed using ImageJ software (NIH, Bethesda, MD, USA; version 1.54g), where each photo was calibrated using a reference ruler to convert pixel values into millimeters via the "Set Scale" function [20]. Measurements were obtained using the Straight-Line tool according to a predefined scoring rubric. Three independent examiners carried out the measurements, and the average of their results was used to determine the final score for each prepared tooth.

Validity and Reliability of the Assessment Tool

The psychometric properties of the modified scoring rubric, which was used to assess students' performances, were evaluated to ensure its fitness. The internal consistency across its fifteen core criteria was measured using Cronbach's alpha. Inter-rater reliability among the three evaluators was assessed using the Intraclass Correlation Coefficient (ICC).

Data Management and Statistical Analysis

Data concerning preparation timings, rubric scores, and competency outcomes were gathered prospectively employing standardized forms within Microsoft Excel 2019. To maintain confidentiality, participant identities were anonymized through the assignment of unique alphanumeric codes.

The statistical analysis commenced with the calculation of descriptive statistics for all measured variables and an assessment of data normality using the Kolmogorov-Smirnov and Shapiro-Wilk tests. Inter-rater reliability was confirmed using the ICC. Changes observed in preparation time and total scores were analyzed using one-way ANOVA and repeated-measures Analysis of Variance (RMANOVA), respectively. To further investigate the learning progression related to skill acquisition (scores), non-linear polynomial regression analysis was performed to model the relationship between the number of attempts and the scores achieved, specifically examining the progress toward reaching competency, using the formula:

Predicted Score = $51.21 - (8.71 \times \text{Attempt}) + (1.93 \times \text{Attempt}^2)$.

A quantitative learning curve analysis was conducted to evaluate the progression of students' performance based on the time required to complete anterior tooth preparations. This analysis aimed to establish the relationship between the number of preparation attempts (independent variable) and the time spent (dependent variable, in seconds) to complete each task. The objective was to estimate the time required to reach competency, defined as achieving a perfect score or full proficiency. Linear regression was employed to model the learning curve using the following formula: Predicted Time (seconds) = a + b × Attempt.

In this model, (a) represents the initial time taken, and (b) denotes the consistent change (typically a decrease) in time per attempt.

All statistical analyses were performed using SPSS software, version 26 (IBM Corp., Armonk, NY, USA).

RESULTS

Validity and Reliability of the Assessment Tool

The modified analytical scoring tool used to evaluate preclinical tooth preparations demonstrated strong psychometric properties. Scores for all 56 prepared teeth, completed by 14 students, were based on standardized measurements. Cronbach's alpha, calculated from the pooled scores of three examiners, was 0.86, indicating good internal consistency and suggesting that the assessed domains effectively measured the same overall skill related to preparation quality. [21]. Furthermore, the analysis yielded an ICC of 0.66 (95% Confidence Interval [CI]: 0.53 - 0.77), which is generally interpreted as indicating "good" reliability [21]. This finding points to a satisfactory level of agreement among the three external examiners in their independent assessments of the student's preparations. The statistical significance of this agreement was strongly supported [$F(55, 110) = 7.22$, $p < 0.001$], reinforcing confidence in the objectivity inherent in the evaluation methodology.

Descriptive Statistics and Performance Trajectory

The study analyzed data collected from 14 students, each completing four crown preparation attempts. Assessment of normality was conducted using both the Kolmogorov–Smirnov and Shapiro–Wilk tests, which yielded high p-values (0.95 and 0.83, respectively), indicating no significant deviation from a normal distribution. In addition, preliminary graphical inspection (Figure 1) further supported the assumption of normality, showing that the distribution of preparation scores across the four attempts was approximately normal.

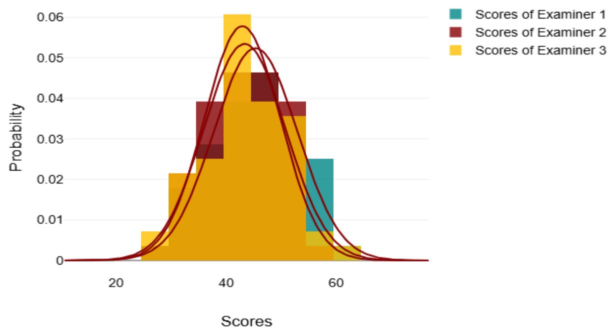

Figure 1. Distribution of scores across the four attempts

The mean performance scores of 14 students across four anterior tooth preparation attempts, as evaluated by three independent examiners, are summarized in Table 2. A general trend of improvement in mean scores was observed over successive attempts, increasing from a combined examiner mean of 44.52 in the first attempt to 47.10 in the fourth. A slight decline occurred in the second attempt (mean = 41.17), followed by incremental improvement in the third and fourth attempts, forming a U-shaped pattern that suggests a typical learning curve (Figure 2).

Examiner-specific means reflected similar trends: Examiner 1 reported an initial drop from 47.21 to 42.21, then an increase to 48.21 by the fourth attempt; Examiner 2 observed a steady rise from 40.29 to 48.29; and Examiner 3 noted an initial decline from 46.07 to 41.14, followed by a modest increase to 44.79. The highest variability in scores, as reflected by standard deviation, occurred in the fourth attempt for Examiner 1 (SD = 9.43), indicating increased performance spread among students. Although mean score levels differed slightly among examiners, the overall trend across all raters consistently demonstrated improvement with repeated practice, highlighting the presence of a performance learning effect over time. The overall mean score calculated across all four attempts was 43.88 (SD = 6.55). Individual scores ranged from a minimum of 29.00 to a maximum of 55.00, with a median score of 44.00. Crucially, every score was below the required passing mark of 60%.

Table 2. Descriptive statistics of mean performance scores with standard deviation across Four Attempts by Examiner

Examiners	Attempts	Number of students	Mean	Std. Deviation	Minimum	Maximum
Examiner 1	1	14	47.21	8.35	30	59
	2	14	42.21	5.45	32	50
	3	14	43.71	5.97	33	53
	4	14	48.21	9.43	25	60
Examiner 2	1	14	40.29	5.64	31	49
	2	14	39.86	6.07	31	52
	3	14	43.36	6.69	28	53
	4	14	48.29	6.57	34	56
Examiner 3	1	14	46.07	8.33	32	62
	2	14	41.43	7.17	30	53
	3	14	41.14	6.63	29	53
	4	14	44.79	7.49	26	53
All examiners	1	14	44.52	6.75	32	53
	2	14	41.17	5.73	31.33	51.67
	3	14	42.74	5.37	31	52
	4	14	47.1	7.31	29	55

As illustrated in Figure 2, the mean performance scores, averaged across the three examiners, demonstrated a clear non-linear progression over the four attempts. After a relatively strong start, a noticeable dip occurred during the second attempt. This temporary decline was followed by steady improvement in the third and fourth attempts, suggesting that with continued practice, students began to refine their skills and achieve greater consistency. The overall pattern forms a U-shaped curve, characteristic of early adaptation followed by progressive learning.

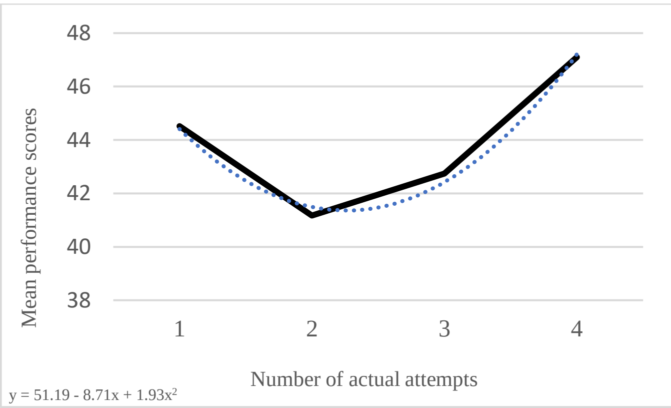

Figure 2. Mean Performance Scores Across Four Attempts Showing a Non-Linear Learning Progression

Inferential Analysis of Learning Effects

To rigorously assess the influence of repeated practice on performance outcomes, a repeated measures analysis of variance (RMANOVA) was conducted. This analysis revealed a statistically significant main effect for the number of attempts (within-subjects factor) on the achieved performance scores [$F (3, 36) = 5.01$, $p = 0.005$]. This result confirms that performance levels underwent significant changes across the four practice sessions. The associated partial eta-squared (partial η^2) value was 0.29, indicating a large effect size. This suggests that the number of attempts accounted for a considerable proportion (approximately 29%) of the variance observed in performance scores, underscoring a significant learning effect attributable to repeated practice. The statistical significance of this finding remained robust even after applying corrections for potential violations of the sphericity assumption using both Greenhouse-Geisser [$F (1.77, 21.19) = 5.01$, $p = 0.020$] and Huynh-Feldt [$F (2.22, 26.64) = 5.01$, $p = 0.012$] adjustments. The statistical power observed for detecting this main effect was high (0.88), indicating the study was adequately powered to identify this learning trend.

A direct comparison between the initial (first) and final (fourth) attempts using an independent t-test showed an average score improvement of 2.57 points, representing a 5.78% increase. Despite this numerical improvement, the difference failed to reach statistical significance ($t = -0.97$, $p = 0.34$). Similarly, a correlation analysis between the attempt number and the mean score yielded only a weak positive correlation ($r = 0.16$), suggesting that while learning occurred (as demonstrated by the RMANOVA), the overall improvement within the initial four attempts was modest and did not follow a strictly linear pattern.

Learning Curve Modeling and Performance Prediction

The observed pattern of mean scores, an initial decrease followed by a subsequent increase, suggested a quadratic trend, often characteristic of the early phases of acquiring complex skills. To formally model this non-linear relationship, polynomial regression analysis was conducted. The analysis confirmed a significant quadratic relationship between the number of attempts and the achieved score. Extrapolating from the derived quadratic model (Predicted Score = 51.21 – (8.71 × attempt) + (1.93 ×attempt²), it was predicted that students would, on average, require approximately 8 attempts to reach a high level of competence in this specific preclinical task (Figure 3). Moreover, the passing scores began around the sixth attempt.

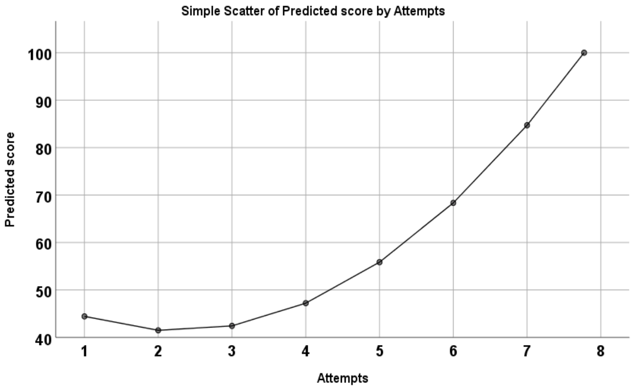

Figure 3. Predicted performance scores across eight attempts based on Polynomial regression

It is important to note that this prediction goes beyond the range of the data collected (four attempts) and depends on the assumption that the observed quadratic learning trend continues, an assumption that may not necessarily hold over longer periods of practice.
Furthermore, simple linear regression analysis was utilized to model the learning curve concerning task completion time, treating the number of attempts as the independent variable (predictor) and the time spent (in seconds) as the dependent variable (outcome) (Figure 4).

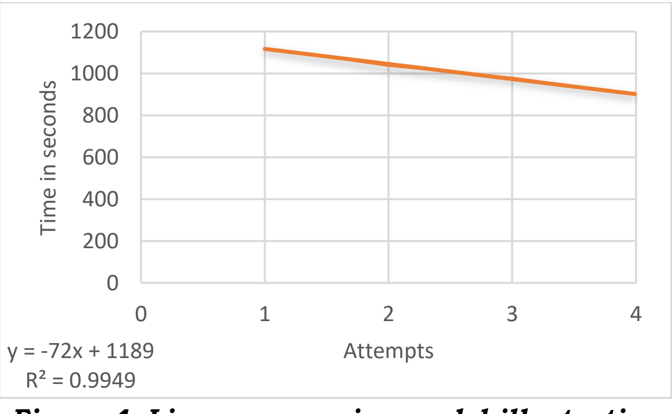

Figure 4. Linear regression model illustrating the reduction in time efficiency across four actual attempts

This analytical approach enabled the prediction of temporal efficiency trends across repeated practice attempts. The derived regression equation was as follows:

Predicted Spending Time (seconds) = (-72×Attempt) +1189

This model demonstrates a consistent decrease of approximately 72 seconds in task completion time with each successive attempt, commencing from an estimated initial duration of 1189 seconds. The negative regression coefficient signifies a progressive improvement in efficiency as practice continues.

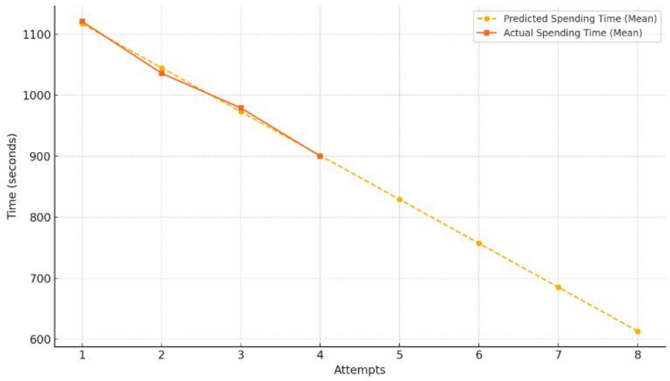

Figure 5. Actual vs. predicted mean tooth preparation time across attempts

According to the linear model in Figure 5, the predicted completion time at the eighth attempt, corresponding to the projected attainment of competency based on performance scores, was approximately 600 to 660 seconds (10 to 11 minutes). Statistical analysis using one-way analysis of variance (ANOVA) confirmed that this effect was statistically significant, $p < 0.001$, R2=1, indicating that the observed reduction in completion time with repeated practice is unlikely to be due to chance. These results also demonstrated a strong and statistically significant improvement in preparation efficiency over repeated attempts.

DISCUSSION

Tooth crown preparation was selected for investigation because it constitutes a basic technique for dental treatment and therefore plays an essential role in preclinical dental education [22 - 24] Moreover, learning the widely differing forms of tooth preparation places high demands on both students and faculty in terms of 3D conceptualization, precision, reproducibility, and evaluation [24, 25]. The shortage of senior faculty in dental schools' places additional pressure on existing staff to maintain consistent student evaluations and minimize potential conflicts.
Many studies used assessment methods [25 – 30] to evaluate preclinical all-ceramic crown preparation among second-year undergraduate dental students. A typodont model is used in dental training to mimic the anatomy of the human jaw and teeth. All participants received theoretical instruction on all-ceramic crown preparation for maxillary central incisors and watched a training video before beginning the practical training. This approach standardized the learning experience and ensured that all participants received the same instructions and practiced under similar conditions.
Understanding and tracking the progression of

individual student performance in preclinical dental training remains a persistent challenge [7, 8]. Learning curve analysis offers a promising method to quantify skill improvement, predict future performance, and establish evidence-based benchmarks for competency [14, 17]. Learning curve models, which have proven useful in analyzing both manual and digital dental tasks [17, 31], could provide a quantitative basis for evaluating preclinical training modules and informing decisions about curriculum design and resource allocation. There's a clear need to investigate the applicability and predictive power of such models for complex manual dental procedures like all-ceramic crown preparation within the context of undergraduate dental education. However, existing studies on the learning curve of full crown tooth preparation often have a limited number of observations, which may not fully reflect the changes in student skill levels throughout the entire preparation process [17, 32].

The successful implementation of a validated rubric (as used by Wu et al. [16]) and the application of ImageJ software [20] for objective, quantitative measurements demonstrate a robust and replicable assessment approach. Integrating objective measurement tools is essential for accurate learning curve analysis and effective, data-driven student monitoring. As noted, subjective evaluations can be inconsistent and lack the precision required to accurately track skill improvements or to identify specific areas of deficiency over time.

Combining a highly reliable rubric with precise digital measurements provides objective, reproducible data. This allows for detailed analysis of performance across specific domains (e.g., incisal reduction, taper, finish line quality, as per Table 1), enabling educators to pinpoint exact areas where students excel or struggle. Objective data facilitates highly specific and actionable feedback. For example, instead of general feedback such as "your preparation needs improvement," educators can provide targeted feedback such as "your incisal reduction is consistently below 1.2mm, and your taper is exceeding 10 degrees." This clarity empowers students to understand their performance and target their practice effectively.

This study examined the learning progression of second-year dental students during anterior all-ceramic crown preparation tasks through four consecutive training attempts on typodont models. The results revealed a non-linear learning trend: an initial dip in performance followed by a gradual improvement, reflecting a typical U-shaped trajectory in skill acquisition. This pattern aligns with common cognitive and psychomotor adaptation processes during the early stages of learning, where performance may initially decline as students adjust their technique and integrate feedback before achieving refinement and consistency [33].

Initially, students performed relatively well in the first attempt, achieving a mean score of 44.52. However, a noticeable decline occurred during the second attempt, with the mean score dropping to 41.17. This temporary setback was subsequently followed by steady improvement in the third (42.74) and fourth attempts (47.10). This initial decrement is common in complex psychomotor skill acquisition, as early performance might stem from a superficial understanding or even novice overconfidence [34]. As learners engage in repeated practice, they develop increased familiarity with the task and a heightened awareness of its detailed demands. This deeper engagement, coupled with conscious efforts to correct errors or include new technical details (possibly from initial feedback or self-reflection), can temporarily increase cognitive load and disrupt performance fluidity. Such a temporary decline aligns with models of skill acquisition, where individuals transition from a cognitive phase (understanding the task) to an associative phase (refining movements and identifying errors). This transition can involve transient performance dips as new neural pathways are established and less efficient ones are discarded. This non-linear progression underscores that learning is rarely a simple, linear ascent; educators must recognize and anticipate these phases to provide targeted support and constructive feedback during periods of apparent regression, as these can be crucial moments for deeper learning and technique refinement [33].

Research on learning curves in dental education reveals varied patterns across different aspects of dental practice. Studies on dental CAD software show that learning times decrease with repeated use, though initial differences between software types diminish over time. While dental technicians initially outperform other dental personnel, all groups eventually achieve similar proficiency levels with practice [31]. However, contradictory findings emerge in clinical skills acquisition, where one study found no correlation between repeated practice and improved performance, challenging the assumption that more practice leads to better outcomes [5]. In contrast, research on cavity preparation among dental students demonstrated significant improvement over time, with performance increasing at two-week intervals. Notably, students exhibited diverse learning curves and rates of proficiency acquisition, suggesting the need for modified teaching approaches to accommodate individual differences in motor learning [35]. On the other hand, Xu et al. in 2020 demonstrated that crown preparation scores significantly increased through training, aligning with our results [36].

Our findings demonstrated statistically significant within-subject improvements across the four sessions [$F(3, 36) = 5.01$, $p = 0.005$], with a large effect size (partial $\eta^2 = 0.29$), indicating that repeated practice had a substantial impact on performance. A polynomial regression model further confirmed a quadratic relationship between attempt number and performance, projecting that students might need approximately eight attempts to reach full competency, assuming the trend continues. This projection was also supported by improvements in task efficiency, with a linear decrease in preparation time per attempt.

When comparing our findings with the study conducted by Wu et al. [17], key similarities and methodological distinctions become evident. Wu et al. also conducted four actual training sessions to evaluate the performance of postgraduate dental students on maxillary central incisor preparations. However, unlike our design, they extended their analysis by applying a modified Wright learning curve model to predict performance over 30 hypothetical attempts. Their model estimated that the competency threshold - defined as a score of 80 - would typically be reached after 14 predicted attempts. Notably, this threshold was not based on observed data but rather on statistical extrapolation using a modified function to estimate future performance trends [17].

The results of the present study, along with those from Wu et al., reveal a consistent pattern: more practice generally leads to improved performance, even though the studies differed in who participated and how the data were analyzed. The observed data in our study indicated a 5.78% increase in mean scores between the first and fourth attempts. While this improvement wasn't statistically significant in direct comparison ($p = 0.34$), this was likely due to sample size limitations and restricted training duration. Interestingly, Wu et al.'s predicted learning curve showed a more consistent, continuous improvement over time, highlighting how predictive models can effectively estimate long-term learning potential [17]. Despite this, their actual observed data, which also covered only four sessions, showed similar early learning patterns, with score improvements after the initial practice session.

The strong psychometric properties of our evaluation rubric (Cronbach's $\alpha = 0.86$; ICC = 0.66) strengthen the reliability of our findings and underscore the importance of rigorous assessment design in early-stage training studies. Although both studies support the effectiveness of repeated preclinical training, our results caution that four sessions may be insufficient to achieve consistent competency across learners. Instead, a longer practice regimen—estimated at 8 to 14 sessions—may be necessary for most students to stabilize and consolidate essential tooth preparation skills.

While Wu et al.'s use of predictive modeling provides a longer view of the learning progress, it assumes that learners will keep improving at a steady rate, which may not be true in real-world situations [17]. Our study complements this approach by capturing actual performance data, including score variability, evaluator reliability, and temporal efficiency - factors that influence learning but may be underrepresented in theoretical models. For example, we observed increased score dispersion (SD = 9.43) in later attempts, suggesting that while the group average improved, individual differences in learning pace became more apparent. However, this difference was not statistically significant in pairwise comparisons ($p = 0.34$), possibly due to limited sample size and the narrow range of observation. Notably, Wu et al.'s use of 30 data points per student, as well as the integration of statistical modeling using the Wilcoxon test and prediction functions, provided greater resolution to identify the session threshold (the 14th attempt) that marked competency achievement [17].

In addition, our study highlighted a time-efficiency gain through linear regression modeling, estimating a 72-second reduction per attempt, paralleling findings in the literature that report improved efficiency with increased practice [37]. Wu et al. did not report task completion time, but their progressive performance scores suggest a similar trend in efficiency.

In summary, this study supports the presence of a measurable learning curve in anterior crown preparation through direct observation, while agreeing with the predicted outcomes of Wu et al.'s model. Taken together, these findings suggest that early-stage improvements are detectable after just a few sessions but that skill mastery likely requires extended, structured repetition. Future studies should incorporate longer observation periods and combine predictive models with empirical validation to guide curriculum development more effectively.

CONCLUSION

Within the scope of this study involving second-year undergraduate dental students, the preclinical preparation of a maxillary central incisor for an all-ceramic crown demonstrated a significant, non-linear learning curve over four practice attempts. Preparation quality scores showed statistically significant improvement across sessions, as analyzed by RMANOVA, with the progression exhibiting an initial decline before improvement, suggesting a complex early adaptation phase. Concurrently, task completion time consistently decreased, indicating enhanced efficiency with practice. Extrapolated modeling suggests that achieving a high level of competency likely requires at least eight practice attempts, with the time required per attempt ranging from an average of approximately 20 minutes in the first attempt to about 11 minutes by the eighth. These findings quantitatively highlight the effectiveness of repeated practice in developing both skill and efficiency in this core prosthodontic procedure, while also underscoring the need for sufficient practice volume in preclinical curricula to meet proficiency benchmarks. Thus, our study supports the initial hypotheses and offers evidence-based recommendations for undergraduate dental education.

Limitations

This study on the learning curve of preclinical all-ceramic crown preparation among second-year undergraduate dental students has several limitations. Its small sample size inherently limits the statistical power, and the observation period was confined to just four consecutive weekly preparation attempts. This short duration means any extrapolation of the findings beyond the observed data range is speculative and risks inaccuracy, as learning curves rarely follow a perfectly continuous function indefinitely. Finally, because the study was conducted at a single institution, the Department of Prosthodontics, Faculty of Dentistry, University of Attahadi, the generalizability of its findings is limited.

Recommendations

Based on this study's findings and limitations, several key recommendations are proposed for advancing dental education. Future research should prioritize larger sample sizes in multi-institutional, longitudinal studies to provide a more comprehensive understanding of learning progression. It's also crucial to investigate different teaching methods and feedback mechanisms, ensuring students receive targeted and timely feedback tailored to their learning curves. Ultimately, these insights should drive the implementation of evidence-based competency benchmarks and inform the refinement of dental curricula to optimize skill acquisition and ensure student proficiency.

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