

Occlusion Chatterbox: an origami-inspired robotic device for enhancing dental occlusion training

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Occlusion Chatterbox: An Origami-Inspired Robotic Device for Enhancing Dental Occlusion Training

Short Title: Occlusion Chatterbox Device

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Abstract

Background: Occlusal morphology is a fundamental component of dental education and is essential for restorative, prosthodontic, and orthodontic procedures. However, traditional teaching methods—such as wax carving, plastic tooth models, and two-dimensional illustrations—often fail to provide learners with an interactive and spatially accurate understanding of occlusal features.

Innovation: We introduce the Occlusion Chatterbox, a novel origami-inspired robotic educational device designed to support the teaching and learning of dental occlusion. The device transforms the geometry of a traditional paper fortune teller (chatterbox) into a foldable structure representing occlusal surfaces. Each modular flap corresponds to a cusp or ridge and is actuated by stepper motors controlled via an ESP32-WROOM microcontroller. A programmable LED system provides real-time color-coded guidance of the occlusal elements, synchronized with a companion Arduino-based software platform.

Preliminary Evaluation: A pilot study involving 23 third-year dental students compared the Occlusion Chatterbox with conventional instruction. Students trained with the device achieved significantly higher scientific assessment scores (7.45 ± 0.93 vs. 5.17 ± 1.99 ; $p = 0.002$) and reported greater satisfaction (43.18 ± 4.42 vs. 33.08 ± 6.02 ; $p = 0.001$), suggesting improved learning outcomes and student engagement.

Significance: By combining tactile interaction, robotic articulation, and LED feedback, the Occlusion Chatterbox bridges the gap between the abstract concepts of occlusal morphology and concrete learner comprehension. It represents a low-cost, portable, and interactive alternative to static models and expensive virtual reality simulators, with the potential for broad adoption in preclinical dental curricula.

To the best of our knowledge, this is the first reported origami-inspired robotic simulator specifically designed for teaching dental occlusion.

Introduction

Occlusion is the cornerstone of functional dentistry. The spatial arrangement of cusps, ridges, grooves, and fossae defines not only tooth morphology but also the efficiency, comfort, and long-term success of restorative procedures (1, 2). A precise understanding of occlusal morphology is thus indispensable in dentistry, from cavity preparation to complex prosthodontic reconstructions.

Despite its central importance, occlusion remains one of the most challenging subjects for dental students to master. Traditional teaching approaches rely heavily on static models, wax carving exercises, and lecture-based delivery. Although these methods provide foundational exposure, they often lack the interactive, dynamic, and spatially accurate representation required for deep learning. For example, in wax carving, the process resembles sculpture rather than genuine anatomical study. As a result, students tend to reproduce shapes from a model without necessarily grasping the true anatomical form and details, which limits their deeper understanding (3). Plastic models, while reusable and convenient, are static and fail to capture the functional interplay of occlusal elements during mandibular movement (4). Lecture-

based approaches, meanwhile, tend to promote passive learning and are constrained by subjective assessment criteria (5).

These pedagogical shortcomings translate into practical consequences. Graduates frequently report difficulties in transferring theoretical knowledge of occlusion into clinical practice (6). Misjudgments in occlusal contact points or interferences can result in discomfort, functional inefficiency, or long-term complications. This gap between preclinical learning and clinical competence underscores the urgent need for more responsive and interactive educational approaches (7, 8).

Recent advances in educational technology have partially addressed this challenge. Virtual reality (VR), augmented reality (AR), and haptic simulators provide immersive environments for exploring dental anatomy. Such systems improve spatial cognition and learner engagement by offering dynamic and multisensory experiences (9-13). However, their widespread adoption is limited by high costs, steep learning curves, and infrastructure requirements. Moreover, the absence of tangible interaction in many digital platforms restricts the embodied learning that physical manipulation affords (14, 15).

Origami-inspired engineering has emerged as a promising solution in various fields, offering a means to create complex, reconfigurable structures from simple folding mechanisms (16). In education, origami-based designs facilitate intuitive interaction, bridging abstract concepts with hands-on learning. The inherent simplicity, portability, and adaptability of the origami-inspired systems make them particularly suitable as potentially low-cost educational devices.

Against this backdrop, the Occlusion Chatterbox was conceptualized as a tangible, interactive, and affordable solution to the pedagogical challenges of teaching occlusal morphology. The device adapts the geometry of a traditional paper chatterbox into a modular robotic framework capable of representing functional occlusal features. By integrating stepper-driven articulation, LED visual feedback, and a companion software interface, the Chatterbox engages learners in tactile and visual exploration of the occlusal anatomy.

This paper introduces the Occlusion Chatterbox as an innovation report, focusing on its design principles, structural components, and educational potential. Although the primary purpose of this report is to describe the design and educational rationale of the device, a preliminary pilot evaluation was also conducted to explore its potential educational effectiveness. Innovation

Occlusion Chatterbox (OCS) is an origami-inspired robotic device developed to enhance preclinical and clinical understanding of dental occlusion through tactile and dynamic interaction. Traditional occlusion teaching tools often rely on static dental models and articulators, which, while helpful, cannot fully represent the continuous and complex movement patterns of the mandible during functional tasks (3, 4). Digital simulators and virtual tools attempt to address these limitations but frequently do so at the expense of direct hands-on engagement, and their implementation may be constrained by cost and infrastructure (9-13). OCS addresses these gaps by combining the reconfigurability of origami-based mechanisms with the programmability of robotic actuation, resulting in a relatively low-cost, physically interactive platform for exploring occlusal relationships (16-21). The device consists of a foldable structural framework that supports dental arch models, a motorized actuation system that drives mandibular motion patterns, an electronic control unit, and a user interface for defining and visualizing movement scenarios. Unlike conventional articulators, OCS can be programmed to simulate a range of mandibular trajectories and occlusal schemes, including normal occlusion, malocclusions, and iatrogenic interferences, thereby providing learners with a richer, more nuanced understanding of occlusal dynamics (1-3). The origami-inspired design enables compact storage and easy deployment, making the device practical for classroom

and laboratory use. Furthermore, by externalizing occlusal concepts into observable and manipulable physical motion, OCS supports embodied learning experiences that can complement and reinforce digital simulations and theoretical instruction (14, 15, 22).

Device Description

The OCS device integrates structural, mechanical, electronic, and software components into a cohesive platform designed for educational use. Its architecture is organized into four main subsystems: (1) an origami-inspired structural framework that defines the kinematic behavior of the mandibular segment, (2) a robotic actuation system responsible for generating motion patterns, (3) an electronic control and feedback module, and (4) a user interface for scenario selection and real-time interaction (16-21). The origami-inspired structural framework is derived from principles of folded mechanical design, utilizing crease patterns that enable controlled rotation and translation of a mandibular platform relative to a fixed maxillary reference (16). By carefully selecting hinge locations and fold geometries, the mechanism can approximate the curved trajectories of mandibular movement in three dimensions, including 4 opening, closing, protrusive, retrusive, and lateral excursions. The framework is fabricated from layered sheet materials, such as laser-cut cardboard or polymer laminates, assembled into a rigid-foldable structure. This approach allows the device to remain lightweight and inexpensive while providing sufficient stiffness and repeatability for repeated educational use (17-20).

Steps for Building a Dental Simulator Robot

Phase 1 – Ideation and Research

The Occlusion Chatterbox was developed through a structured, iterative methodology comprising six sequential phases: ideation, design, fabrication, electronics and programming, testing, and optimization. The process originated from a problem-definition exercise in which the lack of dynamic, visually interactive tools for teaching mandibular movement and occlusal interaction was identified as the central pedagogical gap (3, 7). A review of the literature was subsequently undertaken to survey relevant robotic configurations, motion transmission mechanisms, and visual display technologies. This review informed the selection of an RPP (Revolute–Prismatic–Prismatic) robotic configuration as the most suitable architecture for faithfully replicating the three principal axes of mandibular motion (16). From this foundation, the primary operational objectives were established: the device must simulate opening/closing, lateral excursion, and anteroposterior sliding movements, while supporting real-time visualization of occlusal contact patterns.

Phase 2 – Design

The design phase proceeded along three parallel streams. The first involved drafting a conceptual schematic of the overall mechanical architecture, followed by detailed three-dimensional modeling of all structural and kinematic components in SOLIDWORKS CAD software — encompassing tooth-holding assemblies, origami-inspired flap mechanisms, the robot chassis, and the device housing (16, 17). The second stream addressed the electronic subsystem, including selection of an ESP32-WROOM microcontroller (23), DRV8825 stepper motor drivers, DC–DC power converters (12 V to 5 V and 5 V to 3.3 V), schematic design of the motor driver and LED control circuitry, and layout of a custom printed circuit board (PCB). The third stream formalized the control architecture: an embedded firmware structure was defined for the microcontroller, alongside a companion web application planned to handle command transmission, scenario selection, and real-time feedback display (18, 20, 23).

Phase 3 – Manufacturing and Fabrication

Parts procurement included FDM-compatible filaments (ABS and PLA), photopolymer resin for high-precision dental contact surfaces, aluminum T-slot profiles, stepper motors, motor drivers, limit switches, RGB LED modules, and precision ball bearings; PCB fabrication was commissioned through an external manufacturer. Structural components were produced via FDM 3D printing, with ABS selected for all mechanically loaded parts given its superior tensile strength and thermal resistance relative to standard PLA (24-26). The dental contact elements — specifically the origami flaps representing occlusal surfaces — were produced using resin-based stereolithography to achieve the surface resolution required for educational fidelity (26). Metal components with tighter dimensional tolerances were machined separately. Final assembly brought together all mechanical elements: stepper motors and the belt–pulley transmission system were mounted, LED modules were installed within the tooth analogs (32 addressable RGB LEDs per arch, enabling region-specific illumination of cusps, ridges, and fossae), and the housing was surface-finished before completion of the global mechanical assembly (17, 19).

Phase 4 – Electronics and Programming

Following PCB population, all surface-mount and through-hole components were soldered. Firmware for the ESP32 was developed within the Arduino IDE and implemented closed-loop stepper motor control algorithms, addressable LED management for real-time occlusal contact visualization, limit switch–based positional referencing for repeatable homing, and WiFi-based command reception from the web application [28]. The companion web application was built on a responsive GUI framework, affording instructors and students the ability to transmit movement commands, define simulation parameters, and monitor device status and error states in real time (18, 20, 21).

Phase 5 – Testing and Evaluation

Unit testing was conducted on each subsystem independently — motors, LEDs, and limit switches were each verified in isolation — before the device underwent integrated system testing across a range of motion profiles and simulated occlusal scenarios (27). Motion parameters and sensor thresholds were calibrated iteratively to achieve the target levels of positional accuracy and repeatability. The assembled prototype was then presented to a cohort of preclinical dental students to evaluate its educational effectiveness and to gather formative feedback on usability, comprehension, and ergonomic interaction (3, 7, 10).

Phase 6 – Optimization and Development

Drawing on user feedback and systematic observation of device behavior, targeted refinements were made across mechanical, electronic, and software layers — including adjustments to flap actuation geometry, improvements to LED synchronization logic, and revisions to the user interface workflow. This phase also established the development roadmap for subsequent iterations, identifying the potential incorporation of force sensing, haptic resistance modules, and expanded anatomical coverage of anterior teeth and malocclusion scenarios as priority directions for future work (27, 28).

1. Origami-Inspired Structural Framework

Unlike anatomical moulages that reproduce the full complexity of natural tooth morphology, the Occlusion Chatterbox was intentionally developed with a simplified occlusal design. Although highly detailed dental models are widely used in dental education, their anatomical complexity may hinder the

initial understanding of occlusal concepts among novice learners. Therefore, the device represents cusps, ridges, and grooves as simplified geometric elements while preserving their essential spatial relationships.

The simplified design was adopted as an educational strategy rather than a technical limitation. By reducing unnecessary anatomical detail, learners can focus more effectively on key morphological features and their relationships. This approach is consistent with Cognitive Load Theory, which proposes that minimizing extraneous cognitive load enables learners to allocate greater cognitive resources to the processing and integration of core concepts (29, 30). In this context, the simplified representation was intended to facilitate schema construction by highlighting essential occlusal relationships before students encounter the complexity of anatomical tooth morphology.

The design of the device was inspired by the traditional origami “fortune teller,” commonly known as a chatterbox. The folding geometry of this origami structure served as the conceptual basis for representing the occlusal morphology of posterior teeth, leading to the name “Occlusion Chatterbox.” Each triangular flap corresponds to a specific morphological feature, such as a cusp, triangular ridge, or developmental groove. Beyond providing a tangible representation of occlusal anatomy, the origami-based structure offers a lightweight, compact, and interactive format that can be adapted to different tooth morphologies and occlusal patterns (16).

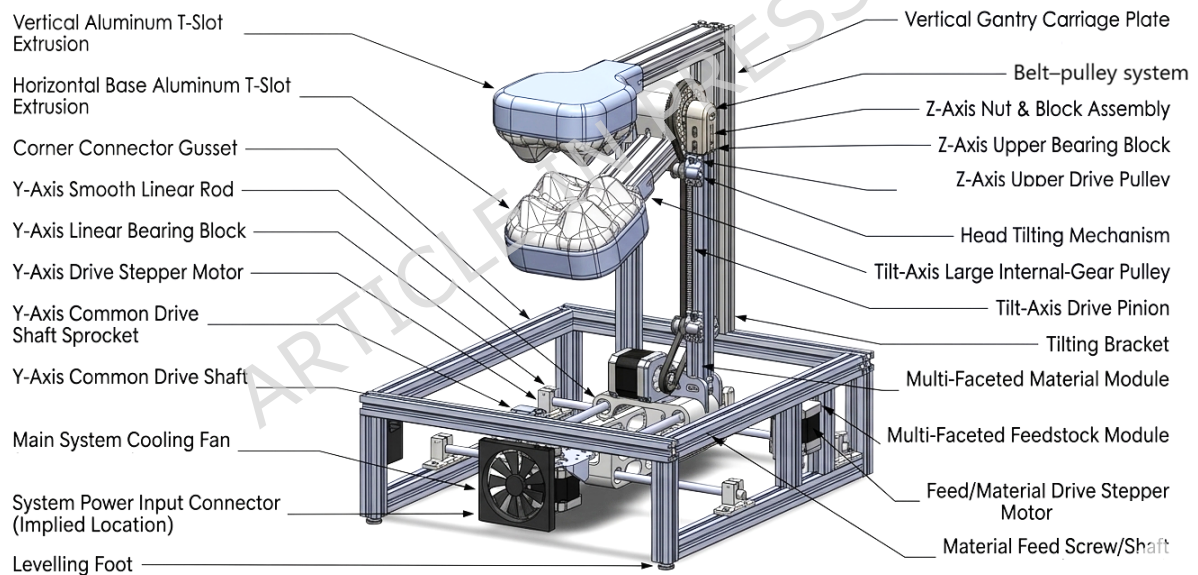


Figure 1



Figure 1

2. Robotic Actuation System

To transform the static origami flaps into functional representations of occlusal movement, the device integrates a robotic actuation system. Each flap is connected to stepper motors mounted on a rigid chassis beneath the origami structure, with linkages transmitting force to the flaps.

Manufacturing Process:

The device functions as a human tooth motion simulator with three degrees of freedom, requiring a specialized robotic mechanism. An RPP configuration (Revolute–Prismatic–Prismatic) was implemented because only the mandibular arch moves. Two linear axes reproduce lateral (left–right) and anteroposterior (forward–backward) displacements, while a rotational axis mounted on the linear stages simulates mandibular opening and closing.

The system was modeled and assembled in the SOLIDWORKS CAD software, and the chassis was constructed from 20×20 mm aluminum extrusions. shafts, ball bearings, and FDM printed custom components provide support for the linear axes. Motion is transmitted from the stepper motors to the axes using a belt–pulley system, ensuring precise and smooth actuation. Mechanical components fabricated with FDM printing employed ABS material for enhanced strength.

The overall device dimensions are $350 \times 350 \times 400$ mm, with a range of motion allowing 250 mm lateral displacement, 150 mm anteroposterior displacement, and 90° rotational opening.

3. LED-based visual guidance and Haptic Feedback Module

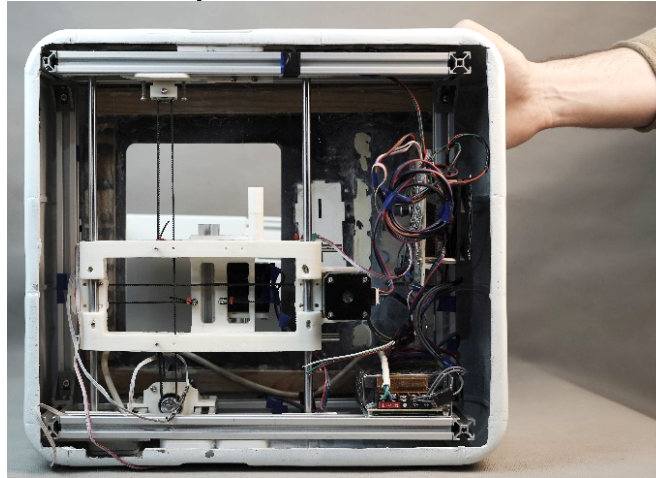


Figure 2

Addressable RGB LEDs are embedded beneath cusp and ridge analogs to illuminate occlusal structures in real time. Color-coded signals guide learners through the identification of anatomical components—for example: red for functional cusps, green for developmental grooves, blue for oblique/transverse ridges, and yellow for marginal ridges. This multimodal approach—combining tactile manipulation with visual cues—reduces the cognitive load and supports deeper encoding of spatial relationships (31).

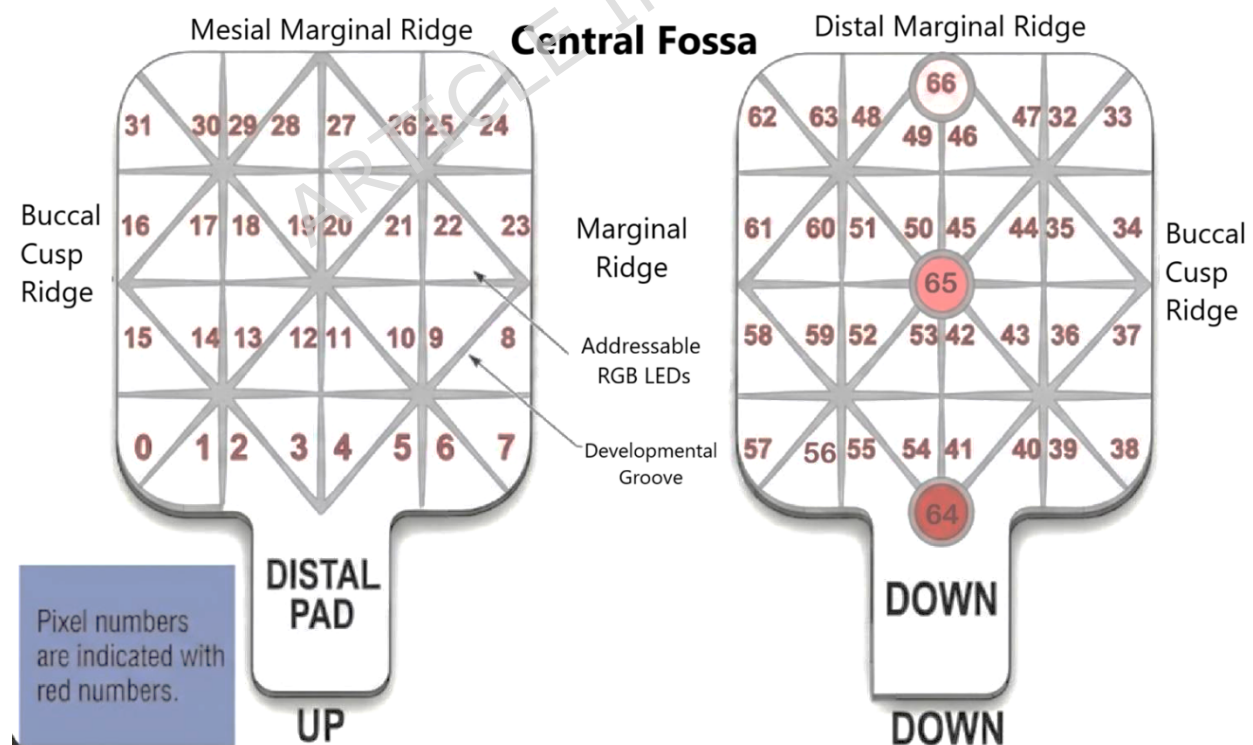


Figure 4

To complement the device's visual and mechanical interaction, a vibration-based haptic feedback system was integrated into the Occlusion Chatterbox. Small eccentric rotating mass (ERM) motors are embedded beneath the structural base to generate localized vibration during defined occlusal interferences in various movements. This tactile cue provides immediate kinesthetic feedback, reinforcing correct motion patterns through sensory association. By translating these interferences into perceivable vibration pulses, the system strengthens motor learning and supports error-aware self-correction during occlusal training.

4. Software Platform and User Interface

A companion software application, developed using the Web-app framework, communicates with the hardware via WiFi to synchronize the motor actuation and LED sequences. The user interface follows human-centered design principles with two main modes: guided learning and free exploration. Guided Learning presents stepwise instruction and demonstrations of interferences; Free Exploration enables manual control for discovery-based learning (20-22, 32).

Control Architecture:

The device utilizes an ESP32-WROOM microcontroller with WiFi capability. Users connect to the device through a Web-app by entering its IP address. Commands are processed on the ESP32 to drive the stepper motors and RGB LEDs. Limit switches provide positioning feedback for accurate calibration. The system was programmed in the Arduino IDE to coordinate the motion and illumination sequences.



Figure 5

Reproducibility, Calibration Accuracy, and Long-Term Durability

Considerations of reproducibility, calibration accuracy, and long-term operational durability were embedded in the design process from the outset, in keeping with the Occlusion Chatterbox's proposed role as a relatively low-cost educational alternative.

In terms of reproducibility, the device was deliberately built around widely accessible components and standardized fabrication methods (28). The structural frame relies on commercially available 20×20 mm aluminum extrusions, and custom mechanical parts were produced by FDM 3D printing in ABS/PLA (25, 26). The actuation and control architecture draws entirely on off-the-shelf hardware, ESP32-WROOM microcontrollers, stepper motors, shafts, bearings, and belt–pulley transmission systems (23). This modular, open architecture means the device can be replicated in other educational laboratories without recourse to specialized industrial manufacturing infrastructure (28). Complete engineering documentation, including computer-aided design (CAD) files, electronic schematics, firmware, and software architecture, has been prepared to facilitate future reproduction, independent implementation, and further engineering development.

Calibration accuracy was addressed through the integration of limit switches and programmable motion control within the ESP32-based system (23). On initialization, the device performs positional referencing to establish repeatable motion boundaries across the rotational and translational axes (33). The belt–pulley transmission and linear guide mechanisms were chosen specifically to minimize backlash and ensure smooth displacement during mandibular simulation (33). While the current prototype has not been validated against clinical-grade biomechanical instruments, repeated internal testing demonstrated stable and visually consistent motion trajectories appropriate for preclinical educational use (27).

Long-term durability was likewise addressed at the mechanical design level. Parts subject to repetitive movement were fabricated in reinforced ABS, which offers greater mechanical resistance than standard PLA (24, 34). Aluminum extrusion framing was selected to improve overall rigidity and limit structural deformation under repeated classroom use. The modular configuration further allows worn components, belts, printed joints, and flap assemblies, to be replaced individually, without necessitating reconstruction of the entire system (28). That said, as a first-generation prototype, extended longitudinal testing under real classroom conditions remains necessary to quantify wear resistance, positional drift, and appropriate maintenance intervals (27).

Taken together, these features support the feasibility of the Chatterbox as a scalable and economically accessible educational platform, while also identifying clear directions for future engineering validation and systematic optimization.

5. Technical Specifications

A summary of the technical details is provided in Table 1. Specifications are adaptable as the device undergoes iterative development.

Table 1. Technical specifications of the Occlusion Chatterbox

Component	Specification (Example)	Notes
Origami mechanism	Chatterbox-inspired, 8 flaps	Modular design
Actuation motors	Stepper motors	Lightweight, precise
Microcontroller	ESP32-WROOM (Wi-Fi)	Web-app control
LED system	Individually addressable RGB	Color-coded guidance (24)
Transmission	Belt–pulley	Smooth actuation
Linear guides	Shafts + ball bearings	Low friction

Power supply	12 V DC, 5 A	Portable use
Dimensions	350 × 350 × 400 mm	Classroom scale
Range of motion	250 mm (L–R); 150 mm (A–P); 90° rotation	Three Degrees of Freedom (DoF)
Materials	ABS/PLA (FDM), F39/M68 (resin)	80% F39 + 20% M68
Software framework	Arduino	Cross-platform
Communication	Wi-Fi	Flexible connection
Compatibility	Windows, macOS, and Android	Broad accessibility

6. Pedagogical Applications

The intended uses include: visualization of occlusal morphology; demonstration of centric and eccentric interferences; exploration of malocclusion classes; and interactive quizzes for formative assessment. In contrast to static plastic models, the Chatterbox offers real-time interaction; compared with VR systems, it preserves physical tangibility while avoiding high infrastructure costs (4, 9-15).

Discussion

The development of the Occlusion Chatterbox (OCS) addresses a persistent gap in occlusion education: the need for accessible, interactive tools that make the dynamic nature of occlusal relationships more tangible and comprehensible to learners. While digital simulations and virtual articulators have advanced considerably, they do not fully replace the pedagogical value of physical interaction with dental models (9-13). OCS leverages origami-inspired robotics to provide a physical platform where students can directly observe and feel mandibular movements, linking theoretical concepts to concrete experiences. This approach aligns with contemporary perspectives on embodied cognition, which argue that cognitive processes are deeply rooted in the body's interactions with the physical world (14, 15, 22). A comparison of these educational methods is summarized in Table 2.

1. Pedagogical Implications

Distorted scale, static geometry and limited functional realism constrain traditional approaches such as wax carving and plastic models (3, 4). By engaging multiple sensory modalities—sight, touch, and movement—the Chatterbox aligns with embodied cognition theories linking physical interaction to improved spatial reasoning and retention (16). LED color coding further supports visual discrimination of complex features, reducing cognitive load and guiding attention to salient structures (31).

2. Comparison with Digital Simulators

VR/AR and haptic platforms offer immersive, dynamic experiences but are hindered by cost and infrastructure requirements (9-15). Similar improvements in student engagement have been reported with VR-based and haptic simulators in dental education. However, unlike these technologies, the Occlusion Chatterbox provides a low-cost and physically tangible learning environment, potentially making interactive occlusion training more accessible in resource-limited educational settings. The Chatterbox complements, rather than replaces, these systems: it targets the foundational understanding of occlusal morphology through a tangible, classroom-ready device with a low technical barrier (4, 9-15).

According to published descriptions of currently available dental simulation systems, including virtual reality platforms such as SimToCare, conventional phantom-head simulators, robotic patient simulators, and laboratory chewing simulators (35), these technologies have primarily been developed to support operative skill training, restorative procedures, patient-management simulation, or laboratory evaluation of restorative materials rather than teaching foundational occlusal morphology and functional occlusal relationships (35, 36). Conventional phantom-head simulators are widely used to develop manual preclinical skills but provide limited support for teaching the three-dimensional spatial and functional relationships of occlusal morphology (36). Similarly, virtual reality systems such as SimToCare mainly focus on operative procedures, including cavity preparation and restorative treatment (36). Robotic patient simulators have been developed to reproduce patient behavior and improve students' clinical communication and procedural skills (37), whereas chewing simulators are primarily intended for evaluating the biomechanical performance, fatigue behavior, and wear characteristics of restorative materials under simulated masticatory loading (38). In contrast, the Occlusion Chatterbox Simulator (OCS) was specifically developed to facilitate students' earliest understanding of occlusal anatomy, simplified occlusal morphology, dynamic occlusal relationships, and Angle classification through an interactive physical model. Rather than replacing established preclinical simulation methods, the OCS is intended to complement existing educational approaches by providing a simplified conceptual foundation before students progress to conventional training methods such as wax carving, tooth anatomy carving, typodont exercises, and phantom-head simulation (36).

Table2. Design characteristics and intended educational applications of representative dental simulation systems compared with the proposed OCS.

Characteristic	Phantom Head Simulator(35)	SimToCare (VR)(36)	Robotic Patient Simulator(35)	Chewing Simulator (39)	Proposed OCS(Current study)
Primary educational purpose	Preclinical manual skill training	Virtual operative/restorative skill training	Simulation of patient behavior during dental treatment	Simulation of masticatory loading for laboratory testing	Designed to support the Teaching of occlusal morphology and occlusal relationships
Typical stage of use	Preclinical	Preclinical	Clinical / advanced preclinical	Research / laboratory	Early preclinical
Primary learning emphasis	Psychomotor or skill acquisition	Operative procedures	Clinical communication and procedural training	Material performance evaluation	Intended to support Conceptual understanding of occlusal anatomy
Operative/restorative procedure training	Yes	Yes	Yes	No	No
Teaching occlusal morphology	Limited	Limited	Not intended	Not intended	Primary intended

					educational application
Demonstration of dynamic occlusal relationships	Limited	Limited	Not intended	Not intended	Designed to demonstrate dynamic occlusal relationship
Simplified morphology for novice learners	No	No	No	No	Yes, by design
Interactive physical model	Yes	No (virtual environment)	Yes	Yes	Yes
Simulation of patient behavior	No	No	Yes	No	No
Material testing capability	No	No	No	Yes	No
Primary curricular role	Manual skill development	Operative skill development	Clinical scenario training	Biomaterial research	Intended for Foundational education in occlusal morphology and occlusal relationships before operative training

The information presented in Table X is based on published descriptions of the referenced simulation systems and on the design specifications and intended educational applications of the proposed OCS; it does not represent direct comparative performance testing.

Unlike most currently available dental simulation systems, the primary objective of the OCS is not to replace conventional preclinical simulators but to establish an intuitive conceptual understanding of occlusal morphology before students progress to manual skill acquisition

3. Comparative Analysis

Table 3. Comparison of educational methods for occlusal morphology

Method	Advantages	Limitations	Accessibility
Wax carving	Develops manual dexterity; low-cost	Distorted proportions; time-consuming (3)	High
Plastic models	Durable; reusable; readily available	Static; limited interactivity (4)	High
Textbook / Diagrams	Theoretical foundation; low-cost	Two-dimensional; limited spatial accuracy (5)	High

VR / AR simulators	Immersive; dynamic; engaging	High cost; requires infrastructure (13-15)	Low–Moderate
Haptic devices	Provides tactile simulation and skill transfer	Expensive; technically complex (9, 12)	Low
Chatterbox device	Tangible, interactive, low-cost, portable, LED-guided learning	Prototype stage; simplified morphology	Moderate–High

4. Technical and Design Considerations

Designing the software interface in accordance with human-centered design improves usability and learnability, echoing established principles in design science and biomedical informatics (20-22, 32). From a cognitive ergonomics perspective, minimizing extraneous load and structuring visual guidance can further enhance performance (40).

5. Estimated manufacturing cost

The total development cost of the first fully functional prototype, including mechanical design, electronic hardware, resin 3D printing, firmware and software development, assembly, and system validation, was approximately USD 2,000. This cost primarily reflects prototype development rather than routine manufacturing. Based on current production estimates, manufacturing approximately ten units would reduce the production cost to around USD 1,000 per device through economies of scale, including lower component procurement and fabrication costs. Although a formal cost-effectiveness analysis was beyond the scope of this pilot study, the use of commercially available electronic components and additive manufacturing provides a practical and scalable approach for producing educational simulators at substantially lower cost than many advanced simulation platforms (35, 36).

6. Limitations

The simplified morphology does not replicate the full anatomical detail of natural crowns; however, this was an intentional educational strategy aimed at enhancing the clarity of the cusps and ridges rather than a design limitation.

Current limitations include the simplified morphology relative to natural crowns, material durability under heavy use, and the absence of force feedback. As a first generation prototype, further refinement of the housings, motion control, and LED integration is warranted.

7. Future Directions

Potential Impact: Beyond preclinical training, the Occlusion Chatterbox may serve as a versatile platform in interdisciplinary education (e.g., dentistry and engineering), as a low-cost alternative in resource-limited countries, and even in Continuing Dental Education programs for practicing dentists. This broader applicability underscores its value as an innovative educational tool with a global reach.

Future iterations may incorporate haptic resistance, advanced composites to mimic dental tissues, touch/pressure sensing for interactive assessments, multilingual software support, and cloud connectivity for analytics. Expanded anatomical modules could cover anterior teeth, interarch relationships, and malocclusion scenarios. To complement the technical development of the Occlusion Chatterbox, a

preliminary pilot educational evaluation was conducted to explore its potential effectiveness in improving student learning outcomes and satisfaction

8. Pilot Educational Evaluation

The present pilot study was conducted to evaluate the effectiveness of the “Occlusion Chatterbox” as an educational tool for teaching dental morphology concepts among third-year dental students with no previous formal instruction in dental morphology or occlusion. The findings demonstrated that students trained using the Occlusion Chatterbox achieved significantly higher scientific scores and reported greater satisfaction compared with those trained through the conventional educational method.

Participants were allocated to either the conventional training group or the Occlusion Chatterbox training group, and outcomes were assessed immediately after the educational intervention.

Scientific knowledge was assessed using a 10-item multiple-choice questionnaire designed to evaluate key concepts of occlusal morphology and related anatomical relationships. The multiple-choice examination was specifically developed according to the predefined educational objectives of the intervention. Before implementation, the questions were independently reviewed by five dentists with teaching experience in dental anatomy and occlusion to evaluate their scientific accuracy, clarity, relevance, and alignment with the intended learning outcomes. Minor revisions were made based on their recommendations before the final version was administered. Each correct response was awarded one point, resulting in a total score range of 0 to 10.

Student satisfaction was assessed using a researcher-developed questionnaire consisting of 10 five-point Likert-scale items (score range: 10–50). In addition, one overall satisfaction question rated on a 0–10 scale was included as a separate global evaluation item. The questionnaire was developed specifically for this study by adapting the general structure and domains of previously published educational satisfaction questionnaires in dental education (41). The wording of the items was modified to reflect the educational objectives and characteristics of the Occlusion Chatterbox intervention. The questionnaire evaluated students’ perceptions of engagement, clarity of instruction, motivation, perceived understanding of dental morphology, and overall learning experience. Both positively and negatively worded items were included, and negative items were reverse-scored during analysis. Content validity was established through independent review by three faculty members with expertise in dental anatomy and dental education. Internal consistency of the final questionnaire was evaluated using Cronbach’s alpha, which demonstrated excellent reliability (Cronbach’s $\alpha = 0.898$).

Statistical Analysis

Data were analyzed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean $\pm$ standard deviation (SD). Comparisons between the two groups were performed using the independent samples t-test for continuous variables and Fisher’s exact test for categorical variables. A p-value of less than 0.05 was considered statistically significant.

Table 4. Distribution of the study groups according to gender and residential status

Variable		Conventional Training Group Frequency (%)	Occlusion Chatterbox Group Frequency (%)	P-value
Gender	Female	6 (50%)	9 (81.2%)	0.11
	Male	6 (50%)	2 (18.8%)	

Residential status	Dormitory	9 (75%)	5 (45.5%)	0.15
	Non-dormitory	3 (25%)	6 (54.5%)	

Fisher's Exact Test

No statistically significant differences were observed between the two groups regarding demographic variables such as gender and residential status, indicating that the groups were relatively comparable at baseline (table 3).

Table 5. Comparison of the mean values of the studied variables between educational groups

Variable	Conventional Training Group Mean (SD)	Occlusion Chatterbox Group Mean (SD)	P-value
Age	20.50 (0.9)	22.27 (3.8)	0.15
GPA	16.33 (1.24)	16.08 (0.66)	0.57
Satisfaction Score	33.08 (6.02)	43.18 (4.42)	0.001
Scientific Score	5.17 (1.99)	7.45 (0.93)	0.002

Independent t-test, Satisfaction score range: 10-50, Scientific score range: 0-10

The satisfaction questionnaire also demonstrated excellent internal consistency (Cronbach's $\alpha = 0.898$), supporting the reliability of the satisfaction outcomes obtained in this pilot study.

The mean scientific score in the Occlusion Chatterbox group was significantly higher than the conventional training group (7.45 vs. 5.17, $p=0.002$). This finding suggests that the use of a tangible and interactive educational device may enhance students' understanding of complex occlusal and morphological concepts. In addition to improved learning outcomes, student satisfaction was significantly higher in the intervention group (43.18 vs. 33.08, $p=0.001$). Higher satisfaction may be attributed to the interactive nature of the device, increased student engagement, and the opportunity for active learning. The findings of the pilot evaluation provide preliminary support for the educational rationale underlying the device design. The observed improvements in scientific scores and student satisfaction are consistent with the embodied learning and cognitive load principles that informed the development of the Occlusion Chatterbox. The simplified geometric representation may also have reduced extraneous cognitive load, allowing students to focus on essential occlusal relationships during learning (table 4).

Table 6. Distribution of the Correct responses to scientific questions in the study groups

Scientific Question	Conventional Training N (%)	Occlusion Chatterbox N (%)	P-value
Which cusps are involved in forming the oblique ridge?	7 (58.3%)	11 (100%)	0.02
What is a triangular ridge?	8 (66.7%)	10 (90.9%)	0.18
Which cusps are taller and which have rounder cusp tips?	5 (41.7%)	9 (81.8%)	0.04
How is a transverse ridge formed?	8 (66.7%)	11 (100%)	0.035

What is the correct adjustment of cusps in protrusive occlusion?	7 (58.3%)	8 (72.7%)	0.38
Adjustments of working and non-working interferences are performed on which tooth slopes?	6 (50%)	8 (72.7%)	0.24
Marginal ridges of posterior teeth are formed by which structures?	5 (41.7%)	4 (36.4%)	0.56
Which cusps are usually considered functional cusps in normal occlusion?	8 (66.7%)	6 (54.5%)	0.43
Which is the largest cusp of the maxillary first molar and the origin of several important ridges?	3 (25%)	6 (54.5%)	0.15
In Class II occlusion classification, which relationship is correct?	5 (41.7%)	9 (81.8%)	0.04

Fisher's Exact Test

Analysis of individual scientific questions demonstrated that students trained with the Occlusion Chatterbox tended to achieve higher proportions of correct responses across most items. Statistically significant differences were observed in questions related to the oblique ridge, cusp morphology, transverse ridge formation, and Class II occlusion relationships (table 5).

Although the observed improvement represents an educational outcome rather than a direct clinical outcome, strengthening students' understanding of occlusal morphology during the early stages of dental education may facilitate subsequent preclinical training, including tooth carving, typodont exercises, and phantom-head simulation. Whether these educational gains translate into improved clinical performance should be investigated in future longitudinal studies.

Despite the promising findings, this study had several limitations. First, the sample size was relatively small. As a pilot study, the present investigation was not statistically powered to detect small between-group differences. Accordingly, the findings should be interpreted as preliminary and used primarily to inform sample size estimation and the design of future adequately powered multicenter studies. Second, only immediate learning outcomes and satisfaction were assessed, while long-term retention of knowledge was not evaluated. Although a pre-intervention knowledge assessment was not performed, all participants were recruited before receiving any formal instruction in dental morphology and occlusion, reducing the likelihood of substantial baseline differences in subject-specific knowledge. Finally, the study was conducted in a single educational center, which may limit the generalizability of the findings.

Although the satisfaction questionnaire demonstrated excellent internal consistency (Cronbach's $\alpha = 0.898$), comprehensive psychometric validation, including construct validity, test-retest reliability, responsiveness, and factor analysis, was beyond the scope of this pilot study and should be performed in future investigations. Future studies with larger sample sizes, multicenter designs, and long-term follow-up are recommended to further evaluate the educational effectiveness of the Occlusion Chatterbox.

Overall, the findings of this pilot study suggest that the Occlusion Chatterbox may serve as an effective and engaging educational tool for improving the learning of dental morphology and occlusion concepts among dental students. The present study represents the initial educational evaluation of a newly

developed simulator that has already been introduced into undergraduate dental morphology teaching at our institution. However, the current findings should be interpreted within the context of preclinical education rather than direct clinical performance. The primary educational role of the OCS is to simplify complex three-dimensional concepts during students' first exposure to dental morphology and occlusion, thereby bridging the gap between theoretical instruction and conventional preclinical simulation. Rather than serving as a replacement for phantom-head training or other established educational methods, the OCS is intended to provide a conceptual foundation that prepares students for subsequent practical training in wax carving, tooth anatomy carving, typodont exercises, and phantom-head simulation. Future studies involving larger cohorts and multicenter educational settings should investigate whether the conceptual advantages observed with the OCS translate into measurable improvements in knowledge retention, preclinical technical performance, and, ultimately, clinical competence.

Conclusion

To the best of our knowledge, this is the first reported origami-inspired robotic simulator specifically designed for teaching dental morphology and occlusion.

The Occlusion Chatterbox integrates origami mechanics, robotic actuation, and LED-guided visualization into a portable device that supports embodied, active learning of occlusal morphology. While it does not replicate the fine anatomical detail of natural teeth or the full immersion of VR systems, it fills a pedagogical gap by offering a tangible, relatively low-cost, classroom-ready alternative. With continued refinement and validation through adequately powered multicenter studies, the Occlusion Chatterbox may complement both digital simulators and static models, contributing to modern, scalable preclinical dental education.

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Conflict of Interest

The authors declare no conflict of interest.

Figure Legends

Figure 1. Schematic representation of the Occlusion Chatterbox.

Figure 2. Occlusion Chatterbox prototype in the closed position, showing the origami-inspired geometry.

Figure 3. Internal view of the Chatterbox showing the stepper motors and mechanical linkages.

Figure 4. LED pixel layout.

Figure 5. LED feedback system highlighting occlusal features during guided learning.

Declarations

Funding

No specific funding was received for the development of the Occlusion Chatterbox device or the preparation of this manuscript.

Conflicts of interest

The authors declare no conflicts of interest related to this work.

Ethics approval

The development and construction of the Occlusion Chatterbox device were conducted under an institutional approval for a technological development project granted by the Ethics Committee of North Khorasan University of Medical Sciences (IR.NKUMS.REC.1404.064).

The pilot educational evaluation reported in this study was conducted as part of a larger educational research project approved by the same Ethics Committee (IR.NKUMS.REC.1404.189). All participants provided informed consent prior to participation.

Consent to participate

Not applicable.

Consent for publication

All authors consent to the publication of this work.

Availability of data and materials

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Code availability

Custom control code for the Occlusion Chatterbox is available from the corresponding author upon reasonable request.

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