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The Open Anatomy Explorer – a journey towards accessible open-source 3D learning environments

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ABSTRACT

Anatomy learning has traditionally relied on drawings, plastic models, and cadaver dissections/prosections to help students understand the three-dimensional (3D) relationships within the human body. However, the landscape of anatomy education has been transformed with the introduction of digital media. In this light, the Open Anatomy Explorer (OPANEX) was developed. It includes two user interfaces (UI): one for students and one for administrators. The administrator UI offers features such as uploading and labelling of 3D models, and customizing 3D settings. Additionally, the OPANEX facilitates content sharing between institutes through its import-export functionality. To evaluate the integration of OPANEX within the existing array of learning resources, a survey was conducted as part of the osteology course at Ghent University, Belgium. The survey aimed to investigate the frequency of use of five learning resources, attitudes towards 3D environments, and the OPANEX user experience. Analysis revealed that the OPANEX was the most frequently used resource. Students' attitudes towards 3D learning environments further supported this preference. Feedback on the OPANEX user experience indicated various reasons for its popularity, including the quality of the models, regional annotations, and customized learning content. In conclusion, the outcomes underscore the educational value of the OPANEX, reflecting students' positive attitudes towards 3D environments in anatomy education.

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Introduction

The landscape of anatomical learning resources is swiftly evolving, with digital 3D learning resources gaining important momentum. Literature attributes this surge to the impact of the COVID-19 pandemic, which forced institutions worldwide to adopt new instructional methods to facilitate distance learning (Attardi et al., 2022; Evans et al., 2020; Harmon et al., 2021). These new resources are giving rise to the design of alternative learning environments, including virtual 3D learning environments. Consistent with the conclusions drawn from a systematic review by Triepels and colleagues, students believe that these environments could help improve their anatomy knowledge (Triepels et al., 2020). The implementation of these virtual environments may help tackling the practical constraints and economic considerations in medical education, such as the exponential increase of students, the limitations in curricular time and available infrastructure, escalating costs, and a shortage of trained faculty (Estai & Bunt, 2016). Despite the widespread availability of 3D learning environments, their integration into anatomy education poses several challenges. One of these challenges is largely related to the commercial nature of available solutions. Foremost is the financial burden placed on universities, stemming from initial procurement costs and the recurring licence renewal costs that strain the already limited educational institution budgets. Furthermore, the commercialisation of educational content within these applications undermines the principles of open access and sharing of educational content, crucial for fostering inter-university cooperation. Recent examples, such as the Visible Human project or MedShapeNet, demonstrate that the value of open access initiatives in sharing educational content and making it accessible to institutions that do not have access these resources (Jastrow & Vollrath, 2003; Li et al., 2023). Additionally, the lack of customisability of commercial applications restricts educators to tailor content to specific

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pedagogical requirements and learning objectives. Lastly, concerns persist regarding the overall quality and accuracy of 3D models featured in commercial applications. Models within commercial applications are typically crafted from scratch using software tools, resulting in a lack of realism. Consequently, there is a gap for students between these idealised representations and actual cadaveric specimens. High-fidelity models offer the potential to bridge this gap. Technological advancements such as Computed Tomography (CT), Magnetic Resonance Imaging (MRI), photogrammetry, and surface scanning techniques have made it possible to create high-fidelity virtual representations (Dixit, 2019; Erolin, 2019; Vandenbossche et al., 2022b).

Considering the aforementioned challenges, it is important for academic institutions to reclaim control and engage in collaboration to cultivate a more inclusive, accessible, and effective approach to anatomy education.

In the literature, a handful of non-commercial, open-source 3D platforms can be found. We discuss a subset of these environments. In 2008, BodyParts3D was launched, offering a database displaying anatomical concepts derived from MRI-segmentations (Mitsuhashi et al., 2009). This database enables online access and downloading of resulting 3D models. In 2012, the University of Maribor, Slovenia, launched Zygote Body. This web-based didactical tool, offering both free and paid subscription versions, allows users to navigate through a 3D anatomical model of the human body (Kelc, 2012). In 2017, Halle and colleagues launched the Open Anatomy Browser, an open-access web-based atlas viewer featuring advanced functionalities such as 3D CT-based models, cross-sections of labelled structures, and radiological images, mainly focusing on the brain (Halle et al., 2017). The platform includes collaborative tools that facilitate knowledge sharing among researchers, educators, and students. Other educators opted rather for 3D asset websites such as Sketchfab (Sketchfab, New York, NY). Sketchfab is a web-based platform and online community for sharing, exploring, and trading 3D, virtual reality (VR), and augmented reality (AR) content. It includes an annotation tool enabling the uploader to mark specific points on the 3D model and attach a label to them. More recently, the University of British Columbia developed the VanVR APP, serving as a virtual anatomy lab equipped with high-fidelity 3D models (Alkhammash et al., 2022). The VanVR APP adopts an educational approach and includes a 3D atlas and various lab sessions. The annotation tool is similar to the one in Sketchfab.

Despite being open-source, the platforms discussed above present limitations. The annotation tools of these platforms commonly use point-based labels. However, anatomical features typically extend beyond mere points, rendering these annotations inadequate for a precise regional annotation. Secondly, the absence of options to hide labels within these annotation tools hinders visibility of underlying structures, particularly given the small size of some anatomical models. Thirdly, some of the aforementioned platforms prioritise sharing and storing of 3D content, rather than allowing to adopt an educationally relevant approach. This lack of educational focus is illustrated by the inability to customise learning content, export and share annotated models, the absence of supporting metadata (info beyond labels), or the possibility to create tests or quizzes. Lastly, an ethical concern arises regarding the display of donated human material on open platforms such as Sketchfab.

Driven by the aforementioned limitations, the Open Anatomy Explorer (OPANEX) was developed by a multidisciplinary team of computer scientists, surgeons, anatomical experts, and educators affiliated with Ghent University, Belgium, and the University of Bergen, Norway. The OPANEX provides a solution to challenges cited above by being open-source, customisable, and education-oriented. This article presents an overview of the technical foundations, functionalities, and its user interfaces. Additionally, a survey was conducted among first-year medical students at Ghent University to investigate the integration of the OPANEX within the current array of learning resources in the osteology course and to assess attitudes towards 3D learning environments.

Methods

Development of OPANEX

The OPANEX consists of multiple interconnected components. Different aspects of computer science and web development were applied to build a secure, scalable, and computationally efficient platform. This section presents the methods and technologies used to build the OPANEX.

Software technology stack

The architecture of the OPANEX system can be divided into four categories, as shown in Figure 1. An appropriate **authentication system** guarantees the security of the complete system, including its models and their associated annotations. The **front-end** allows users to interact with the system, from displaying and annotating models to grading completed quizzes. Modifying actions performed on the front-end are delegated to the **back-end**, that in turn stores changes in a **persistent database**. The back-end additionally allows for server-sided computations and provides the user with a secure access point to the persisted data.

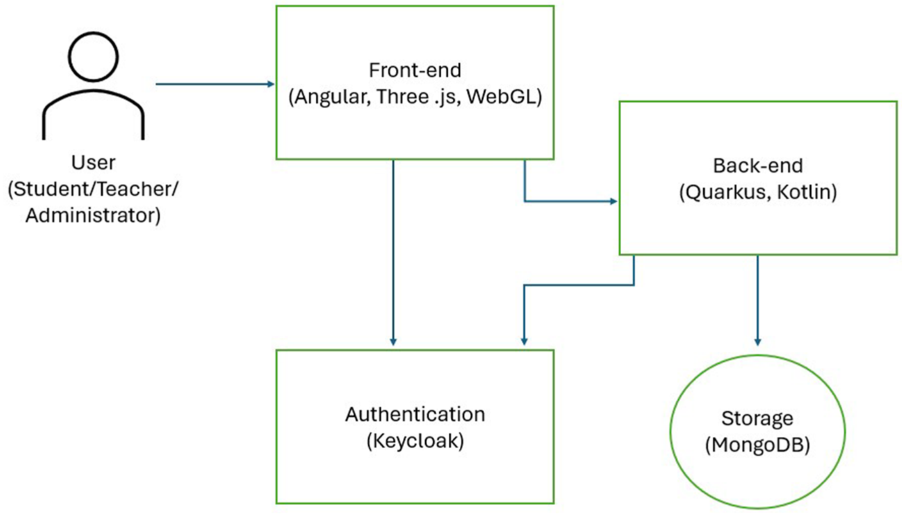

Figure 1. System architecture overview.

Authentication and authorization. Keycloak (https://www.keycloak.org/), an open-source identity and access management system, is employed to provide secure role-based access control (RBAC) to the OPANEX system. Different roles, each with their own respective permissions, are assigned to each user, depending on the access rights required by each of the users. Three roles are available: student, teacher and administrator. The student role is the default role, assigned to each user, and provides the user with the minimum set of permissions. A student can explore available models and learn based on model annotations. Students can also participate in quizzes to test their knowledge. A teacher has all the permissions a student has, and additionally has access to the administration dashboard, where new models can be uploaded and annotated. A teacher can list and view all the stored models in the system but can only modify the models and quizzes under their ownership. Teachers are allowed to create quizzes based on all models, even on models that are not owned by the teacher, effectively allowing the reuse of models and sharing the labour efforts that went into the annotation process of different models. An administrator has the most permissions and is allowed to modify and delete all data, including models, annotations and quizzes. For security reasons, the administrator role should therefore only be assigned to a restricted group of users that maintain the particular OPANEX instance.

Front-end. The front-end of the OPANEX is a visual web platform that allows users to interact with the system, including but not limited to uploading, exploring, and annotating models, creating and participating in quizzes and evaluating quiz submissions. Angular (https://angular.io/), a modern and versatile web development framework, was used to develop the web platform. Angular allows to speed up and facilitate the web development process by dividing the user interface (UI) into smaller abstract components that can be shared between pages and thus promotes the reuse of code. The front-end offers multiple pages, that can be divided into two categories: pages that are only accessible to students and administrative pages that are accessible by instructors. Angular allows for a seamless integration with Keycloak to enable access control to different pages using Angular's built-in route guards.

Displaying 3D models on a screen can be challenging. For this task, a WebGL renderer, implemented by the open-source *three.js* (https://threejs.org/) library was used. Three.js simplifies all the underlying low-level interactions with the WebGL application programming interface (API) and therefore facilitates the rendering of 3D models and the development process. Three.js provides a wide range of features and functionalities to boost the development of 3D based web applications. For instance, it offers built-in functions that simplify the creation of interactive 3D scenes, the 3D environment where all the objects are positioned and models are rendered. Objects such as a virtual camera and orbital controls are available from three.js' library and have been fine-tuned to the specific use-case of the OPANEX.

Back-end. In order to provide the user with access to the data, without compromising the security of the whole database, the need for a back-end arises. The back-end is responsible for storing and accessing data, in a secure and controlled manner, and performing intensive server-sided computations. Quarkus (https://quarkus.io/) in combination with the Kotlin (https://kotlinlang.org/) programming language, is used for the OPANEX back-end development. Quarkus is a cloud-native oriented and reactive Java framework to build performant cloud applications. Quarkus has a reactive architecture that allows the application to scale easily in the future, for example by using asynchronous programming paradigms and guaranteeing responsiveness. When a user performs an action on the front-end, e.g. requesting the object data of a 3D model for exploration purposes, a request is made to the back-end. The back-end verifies that the user is authenticated and has sufficient permissions to access the resource, based on their role, after which a stream to the 3D model object data is returned. The back-end returns an unauthorised error when a user with insufficient permissions tries to perform an action that requires a certain role. Lastly, to export model data, a zip file is created. This is a computationally intensive operation that is performed by the back-end on the server-side.

Storage. To store user data, model data, and annotation data, a persistent storage solution is needed. The OPANEX employs MongoDB (https://www.mongodb.com/), a document-oriented database. This modern and performant database is scalable and can handle a large amount of data (Győrödi et al., 2015). GridFS (https://www.mongodb.com/docs/manual/core/gridfs/) is used to store large 3D model object files in MongoDB.

Data format

The MongoDB document structure is similar to JavaScript Object Notation (JSON) objects. JSON is a lightweight data-interchange format that is widely used in HTTP for front-to-back-end communication. This results in a flexible database schema that facilitates the development process and enables future extensions without the need to migrate the current database.

Models are exported in a standardised zip file, containing the model's object file (i.e. 3D geometry, texture, and labelled anatomical regions) in the standardised OBJ file format and its metadata, annotations and quizzes, as JSON files. Each annotated region is exported in its own JSON file, storing metadata about the region, and a list of 3D vertices that denote the annotation. Exported zip files can be imported in other instances of the OPANEX, e.g. hosted by other universities or educational institutions.

Deployment

The OPANEX consists of multiple interconnected services and will experience a variable load depending on the activity of the users. The system needs to remain available even under sudden high load, for example during a test or an examination. To accommodate these high availability requirements and variable load situations, the OPANEX is deployed in a containerised way using Kubernetes (https://kubernetes.io/), a container orchestration platform. Kubernetes manages the application in a declarative way and will always steer the application to its desired state. To prevent that the OPANEX becomes unavailable at a certain point in time, Kubernetes automatically restarts failed services and facilitates the horizontal scaling of services, allowing that the load is balanced between horizontally scaled instances of each service.

Open-source

The OPANEX system and source code is open-source and available under the Apache Licence 2.0 on GitHub https://github.com/biocat-ugent/Open-Anatomy-Explorer, allowing other educational institutions to install, experiment, and employ the OPANEX system in their courses. We encourage all open-source community members to contribute improvements to the system through GitHub.

Survey

In the second semester of their first year, medical students at Ghent University receive an extensive musculoskeletal anatomy course. In the related curriculum, students participate in a one-week intensive crash course in osteology, preceding the more detailed study of the musculoskeletal system. The osteology course encompasses eight hours of practical sessions supplemented by self-directed study periods. The week concludes with a practical examination focusing on identifying bony landmarks on physical bones. To support the self-directed study of the materials, the course provides various learning resources, including course notes, anatomical atlases, a commercial 3D application (Complete Anatomy (3D4Medical, San Diego, CA)), and the optional purchase of a physical skeleton. Starting from the academic year 2023–2024, the OPANEX was introduced as a supplementary learning tool. In-house surface-scanned human bones with annotations were offered through the platform. The bones were obtained from the anatomy department at Ghent University, Belgium. Ethical approval was received for scanning and uploading human body donor material for educational and research purposes (ONZ-2023-0039). The bones were scanned with the Artec® Space Spider (Artec 3D LUX, Luxembourg City, Luxembourg), a structured light scanner capable of capturing up to 7.5 frames per second with a 3D point accuracy of 0.05 mm and a resolution of 1 mm. The Artec® Space Spider also features a colour camera for capturing the texture of objects. The resulting 3D models were post-processed using the Artec® Studio software (Artec 3D LUX, Luxembourg City, Luxembourg) and Meshlab, version 2020.07 (ISTI-CNR research centre, Pisa-Rome, Italy). To monitor the impact of this implementation, a survey was conducted as part of the osteology course in the five days following the practical examination. All first-year medical students enrolled in this course ($n = 535$) were invited to fill in the survey.

The primary objectives of this survey were to provide insights into (1) the frequency of use of five provided learning resources, (2) student attitudes towards 3D learning environments, and (3) the OPANEX user experience. To assess the first objective, students were instructed to rank the frequency of use of five learning resources on a scale from 1 to 5, with 1 indicating the most frequently used and 5 the least used resource. Additionally, there was a comment section in which students could indicate whether they used other (not listed) learning resources. To assess the second objective, students rated the significance of 3D learning environments through two items on a 5-point Likert scale: '*Digital 3D environments are motivating me to study osteology*' and '*Digital 3D models improve my spatial insight*'. To assess the third objective, students rated two items on a 5-point Likert scale: '*The OPANEX platform is user-friendly*' and '*The quality of the osteology models in the OPANEX platform is good*'. Additionally, there was a comment section where students could provide feedback on the strengths and areas for improvement of the OPANEX.

To visualise the Likert scale results, histograms were plotted. For the qualitative part (= comment section on the OPANEX user experience), a thematic analysis was carried out based on the guidelines of Braun and Clark (Braun & Clarke, 2012). The first phase examined the data to identify overarching themes. Subsequently, in the second phase, subthemes were identified. Finally, during the concluding phase, the subthemes were assessed, and any items that remained were categorised into new or refined subthemes.

The survey was approved by the local Ethical Committee (ONZ-2023-0039) and informed consent was obtained by all participants.

Results

Final product: the OPANEX platform

The OPANEX was created offering two separate user interfaces (UI): one for students and one for administrators. The student UI leads to an exploration window of interactive 3D models, whereas the administrator UI allows instructors to upload and edit 3D models. The user experience (UX) of the exploration window was designed with a focus on intuitive interfaces and control functions to maximise attention on the anatomy content.

Student UI

The student UI features a homepage that provides an overview of the uploaded 3D models. Users can access and explore these models by clicking on the object names in the list. In addition, for models that are not listed, ID codes can be filled in to access them (Figure 2). This functionality allows hiding specific models for e.g. examination purposes.

Upon selecting a 3D model from the list, the user is redirected to the exploration window. Within this

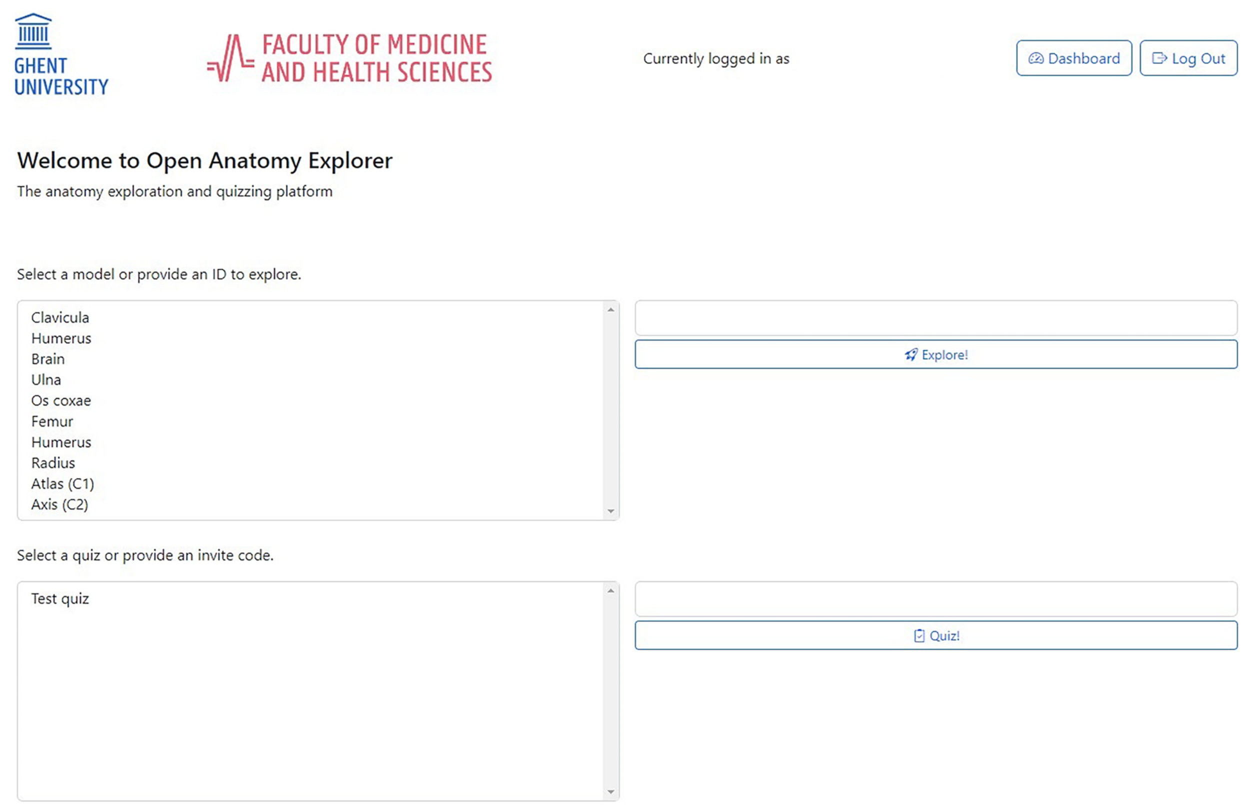

Figure 2. Screenshot of homepage.

window, the model is displayed, enabling users to inspect the model by rotating (left mouse button and rotate), dragging (right mouse button and drag), and zooming in/out (scroll). The 'renderer' panel in the right corner of the exploration window allows users to eliminate the display plane and make adjustments to the ambient light. In the side panel on the right, annotations are displayed. By clicking on the eye icon next to the label name, users can visualise the corresponding region on the model as a coloured area. Multiple labels can be displayed simultaneously (Figure 3).

Besides exploring models, users have the option to exercise and test their knowledge by participating in quizzes. They can either click on the available quizzes in the list or enter an invitation code to participate. Upon selecting a specific quiz, users are redirected to the quiz window (Figure 4). Quiz items are displayed on the right-side panel. There are three question types: localisation questions, identification questions, and free-form questions. Users are provided with controls to either mark specified regions using the label painter, enter the name of an indicated region, or type their answer to a free-form question in a textbox.

Teacher UI

A teacher has all the permissions granted to a student, along with access to the dashboard web page (see § Administrator UI). A teacher can view all the uploaded models but can only modify the models under their ownership. Additionally, teachers are allowed to create quizzes based on all models, including those not owned by them.

Administrator UI

Users with an administrator role have access to a dashboard web page. This web page shows a list of uploaded models. With a slider, the user can choose to display the models that were uploaded personally or to show the uploaded models of all administrators.

The uploading feature enables administrators to 3D models in OBJ format. This format can include models created from scratch using software packages as well as those generated through photogrammetry or structured light surface scanning. Once a model is uploaded, several actions become available. The model can be viewed, copied, deleted, and edited. By choosing the edit option, users are redirected to an edit page on which the model name, category, object file, model rotation, and labels can be adjusted. Labels can be added/removed by using the label painter/remover, respectively (Figure 5). The colour, brush size, and opacity of the painter can be adjusted to suit preferences. A textbox is available to input the label name. Furthermore, the position of the model can be adjusted with the 'edit model rotation'-button.

The administrator can also choose to create a quiz with a respective 3D model. There are three question types available: localisation questions, identification questions, and free-form questions. Moreover, the administrator has access to the quiz submissions of each user and can read the response details.

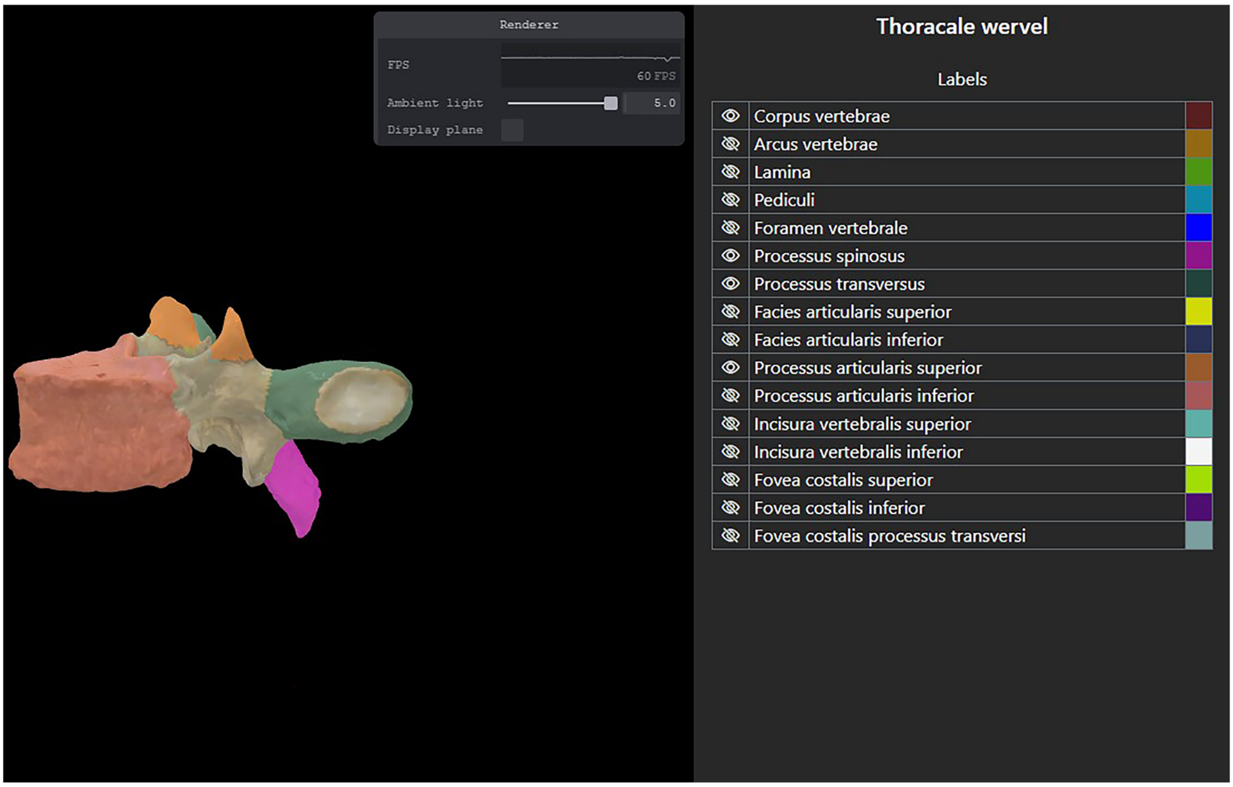

Figure 3. Screenshot of exploration window.

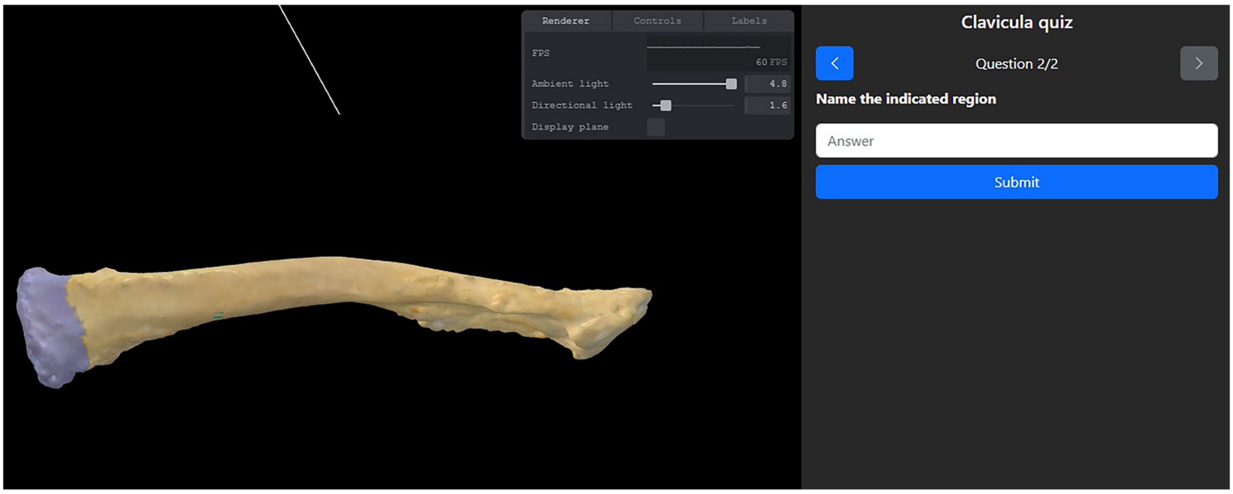

Figure 4. Screenshot of quiz window.

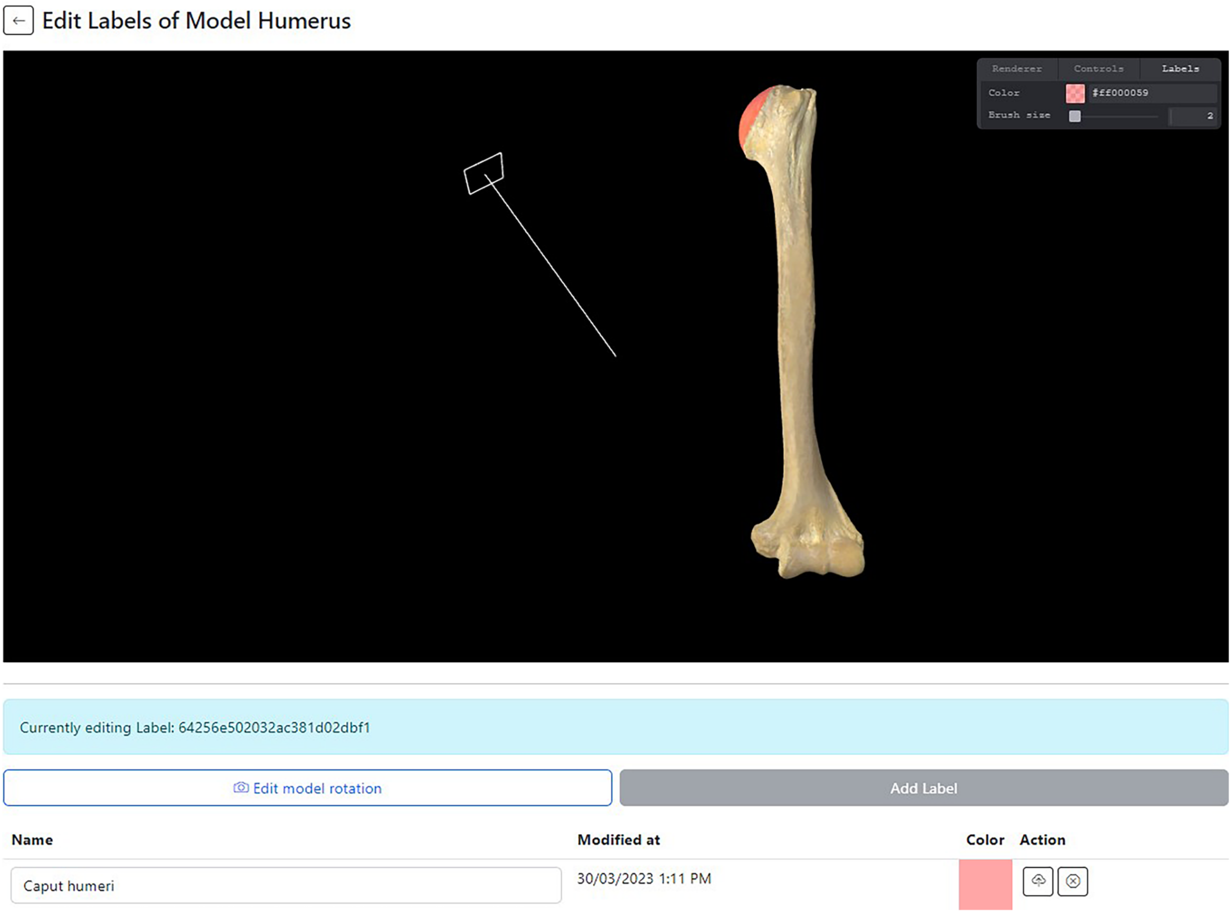

Figure 5. Screenshot of label editor.

Lastly, the administrator can generate a unique ID code for each model. This code can be shared with users, allowing them to access the corresponding model directly in the exploration window. Alternatively, the administrator can use the ID code to create an URL that leads directly to the model.

OPANEX object sharing

The OPANEX includes an option to import and export 3D models along with their metadata. This functionality serves the purpose of establishing an open-source 3D model library and facilitates sharing of dedicated models of interest among various educational faculties or institutions. The exported object is packaged as a zip-file and includes the 3D model in .obj-format, labels with their respective name, coordinates, and colour, and quizzes in JSON-format. The import functionality works in the same way, enabling the upload of zip-files. Imported models are displayed with their annotated regions and allow editing and customising through the dashboard.

Conversely, if institutions prefer not to share their 3D models due to restrictions (cfr. § *Ethical considerations*), they can opt to limit authentication to their university and students only.

Survey

Participants

All first-year medical students enrolled in the osteology course were invited to participate ($n = 535$). A total of 223 students (41.7%) consented to fill in the survey, with 36.3% males and 63.7% females. The average age among participants was 18.8 years.

Frequency of use of five learning resources

Figure 6 illustrates the five distinct learning resources (course notes, anatomical atlas, Complete Anatomy, OPANEX, skeleton) provided during the self-directed study periods within the osteology course, along with their respective rankings according to their frequency of use. A large majority of respondents (59.2%) indicated that the OPANEX was their most used learning material, while the commercial 3D application was ranked as the least used (29.6%). In addition to the five learning resources listed, 57 students (25.5%) also reported using YouTube videos and other websites to access supplementary information.

Attitudes towards 3D learning environments

Figure 7 illustrates the level of agreement with two items regarding student attitudes towards 3D learning environments within the osteology course. The vast majority of respondents (32.7% 'agree', 50.7% 'strongly agree') expressed that digital 3D environments served as a motivating factor to study osteology, while 92.4% (23.8% 'agree', 68.6% 'strongly agree') stated that it enhanced their spatial insight.

OPANEX user experience

To assess students' user experience with the OPANEX, two items were presented. Figure 8 outlines the level of agreement with these items. Respondents indicated that the platform was user-friendly (28.3% 'agree', 61% 'strongly agree') and that the quality of the uploaded models in the OPANEX was good (45.3%, 'agree', 24.2% 'strongly agree').

In the qualitative section of the survey, a total of 164 students (73.5%) provided feedback on the open-ended questions regarding the strengths and areas for improvement of the OPANEX compared to other commercial 3D applications. Through the thematic analysis, the responses were categorised into eight subthemes. Regarding the 3D models within the OPANEX, 27 students (16.5%) appreciated the *realism of the models*. Thirty-four students (20.7%) expressed that they found the *annotations* based on coloured regions clear. Regarding the accessibility, 75 students (45.1%) indicated that they liked the *intuitive user interface* of the platform. Finally, forty-seven students (28.7%) valued the *customised learning content*, citing key benefits such as streamlining their study time by eliminating the need to search for the required learning content, as well as the use of Latin vocabulary instead of English terms. A total of 54 students (32.9%) indicated some areas for improvement: 25 students (15.2%) highlighted the absence of an interface allowing the visualisation of bones within the *full body skeleton* to observe their relative position and orientation; 23 students (14.0%) noted that certain annotations were not clear due to

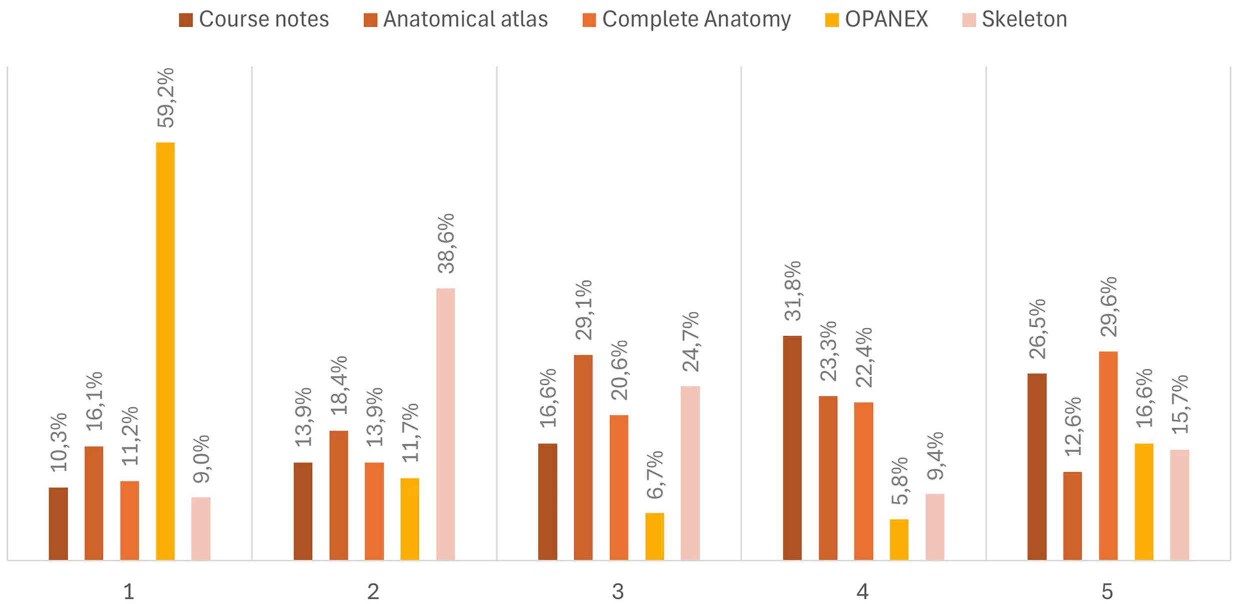

Figure 6. Frequency of use of learning materials. Five learning materials were rated from 1 to 5, with 1 being the most used and 5 being the least used.

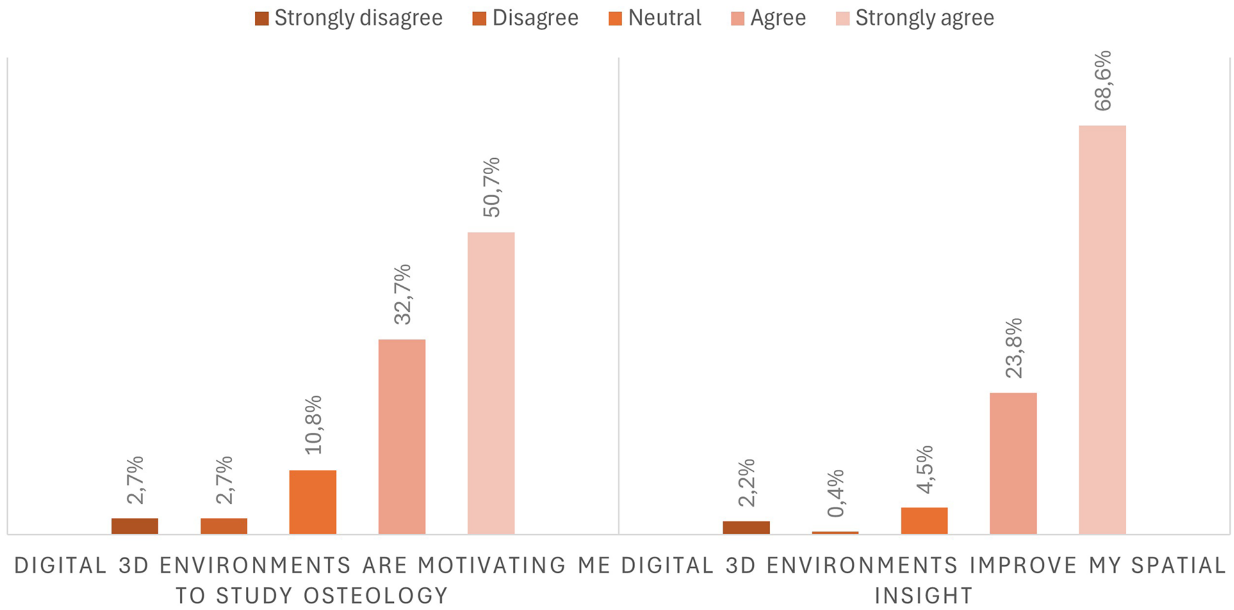

Figure 7. Agreement levels on statements regarding learning in 3D environments. Two statements were rated on a 5-point Likert scale, ranging from 'strongly disagree' to 'strongly agree'.

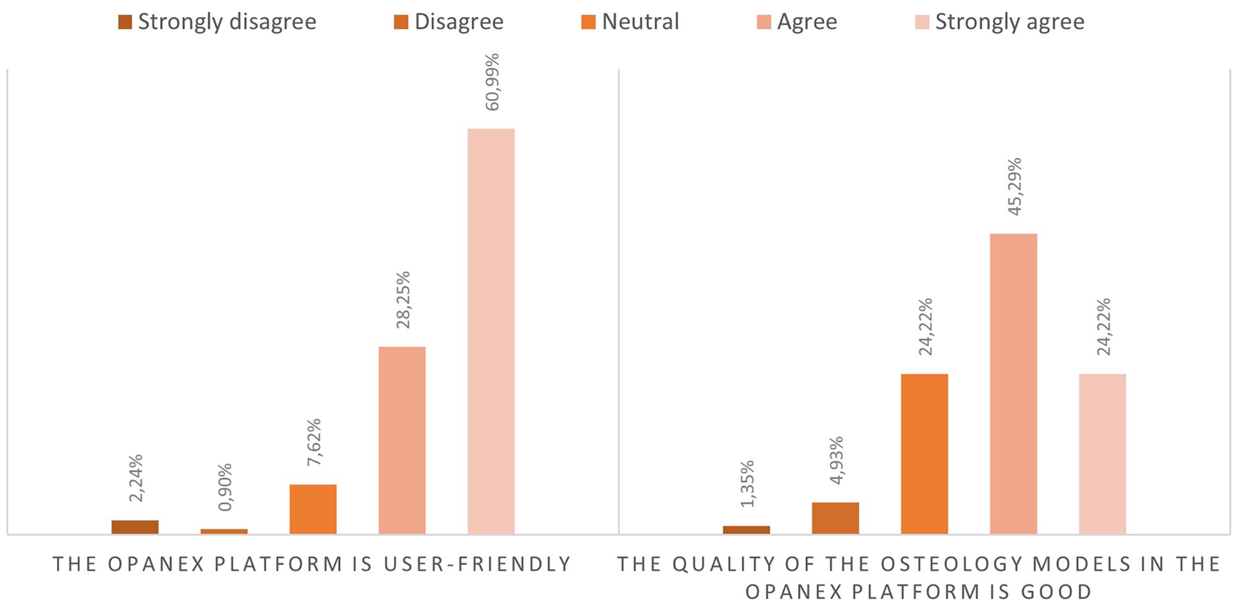

Figure 8. Agreement levels on statements regarding user satisfaction with OPANEX. Two statements were rated on a 5-point Likert scale, ranging from 'strongly disagree' to 'strongly agree'.

missing details on the bone model, and 6 students (3.7%) expressed their desire to have a *search feature* within the platform.

Discussion

Development of OPANEX

Despite the widespread availability of commercial 3D learning environments, several obstacles hinder their adoption. Issues such as exorbitant costs, commercial agendas, and limitations on content customisation undermine the principles of open access and inter-institutional sharing of these resources. Moreover, concerns persist regarding the overall quality and accuracy of 3D models featured in commercial applications. Therefore, it is time for academic institutes to take the lead and collaborate in sharing educational resources to create more inclusive, high-quality, accessible, and effective learning environments for anatomy education.

The OPANEX framework represents a promising stride in this direction by offering an open-source, virtual learning environment that allows creating in-house learning content. The platform facilitates uploading and labelling of 3D models produced locally, along with an import-export feature for exchanging labelled models between institutions, fostering collaborations. Consequently, this re-use and sharing can result in less duplication of effort and can enhance the exchange of scanned specimens. These collaborations can also be beneficial for institutions that have limited or no access to these resources. Furthermore, while the primary purpose of the OPANEX revolves around anatomical needs, its use extends beyond the field of anatomical education and finds applications in various other fields.

Survey

Based on the survey findings, 59.2% of participants selected the OPANEX as their most used learning material among the five available learning resources. This preference can be explained by various factors identified through both qualitative and quantitative data collected during the survey.

Firstly, the responses to the items regarding 3D environments clearly show that students have a positive attitude towards 3D learning environments as part of their educational journey. A large majority (83.4%) of students expressed that virtual environments increase their motivation to study osteology. This finding is consistent with prior research findings (Hu et al., 2016; Triepels et al., 2020). In addition to the increase in motivation, 92.4% of students (strongly) agreed that 3D environments improve their spatial insight. Drawing upon the embodied cognition theory, it is believed that manipulating models in full 360 degrees could increase learning outcomes (Shepard & Metzler, 1971). However, empirical evidence remains unclear regarding the role of digital 3D models in anatomy education and their differential effects on learners with varying levels of spatial ability (Birbara & Pather, 2021; Garg et al., 1999; Khot et al., 2013; Vandenbossche et al., 2022a). To untangle the effects, more research on anatomy learning in 3D virtual environments is needed.

Secondly, based on the quantitative and qualitative data regarding the OPANEX user experience, students expressed that they liked the intuitive interface, the annotations, and the customised learning content. Indeed, the capacity of the OPANEX to create, upload, and modify content through the administrator interface addresses a significant need for customisation. This not only involves aligning the learning content with the unique learning objectives of each student group, but also considers the language preferences and vocabulary. While many commercial applications use English terminology, European institutions frequently prefer Latin nomenclature (Nomina Anatomica) in anatomy.

Lastly, the possibility of uploading realistic, surface scanned models within the platform is especially interesting. This feature bridges the gap between idealised representations in commercial applications and cadaveric specimens, especially given the fact that practical examinations are frequently performed on real cadavers. The preference for realism is also supported by a recent study by Erolin. This study aimed to investigate preferences for varying levels of realism (low, middle, high) in anatomical 3D scans amongst staff and students working with anatomical material at the University of Dundee. In response to the question about which scan would be most beneficial for an anatomy (cadaver) practical, the majority selected the high realism model (Erolin, 2023). Moreover, by including models displaying anatomical variations and pathology, the platform can expand its utility to encompass to postgraduate students and clinicians.

Future directions

Based on the qualitative feedback in the survey, some of the bone models will be reuploaded to enhance the resolution. Additionally, preparations are in progress to incorporate a search functionality and provide an interface for viewing the entire skeleton. In addition, quizzing and scoring functionalities will be expanded to support assessment needs in an examination context. Moreover, with the latest advances in educational and computational technology, efforts will be made to adapt the platform for immersive environments. Finally, given its early stage of implementation in the educational system, the OPANEX requires additional validation and research to further explore its learning performance, transfer to practical sessions in the dissection room, and limitations.

Ethical and legal considerations

When it comes to sharing of 3D anatomical models, ethical guidelines, legal regulations, and institutional policies must be taken into account. Currently, there is a lack of clear and unambiguous guidelines specifically addressing the sharing of digital material derived from cadaveric resources. While general guidelines on the use of human donor material for educational purposes and research exist, they do not provide specific directives regarding the sharing of digital content sourced from these donors. This is especially relevant for soft-tissue donations, where the risk of identifying the donor may be higher. In contrast, bone scans generally pose a lower risk of identification, and are sometimes classified as historical artefacts, permitting more flexibility in sharing images compared to more recent soft-tissue donations (e.g. UK Human Tissue Act, 2004). As the utilisation of digital material becomes more prevalent, there will be an increasing need to address the ethical sourcing and appropriate use of such content. This becomes particularly significant when the distribution extends to the public domain, potentially severing the context and connection with education.

Hence, it is imperative to thoroughly consider the ethical and legal implications of this 'electronic immortalization' (Cornwall, 2017) to prevent anatomists from repeating the same ethical mistakes of the past (Keet & Kramer, 2022).

Conclusion

The aim of this article was to present the OPANEX and its relevance in the educational landscape. The source code is freely available on GitHub: https://github.com/biocat-ugent/Open-Anatomy-Explorer. The goal of this framework is not only to display labelled 3D specimens in an accurate way, but also to create a reference tool for students and institutes. The import and export functionalities enable customisation and sharing of content, surpassing the generic content provided by commercial alternatives. Moreover, while the primary purpose of the OPANEX revolves around anatomical needs, its use extends beyond the field of anatomical education and finds applications in various other fields, including but not limited to chemical engineering, material science, archaeology, industrial product inspection.

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Author contributions

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Disclosure statement

No potential conflict of interest was reported by the authors.

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