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# Development of 3D training models for the identification and classification of colorectal polyps

Anna Roberts[a], Paul O'Toole[a,b], Mark Roughley[a] and Melissa Rankin[a]

[a]Liverpool John Moores University, Liverpool, UK; [b]Department of Gastroenterology, Royal Liverpool University Hospital, Liverpool, UK

**ABSTRACT**
Colorectal cancers develop from pre-malignant polyps that can be removed during colonoscopy. Detection, assessment, and removal of polyps has a major role in bowel cancer prevention and is an important part of bowel cancer screening programmes. Trainee colonoscopists must acquire skills to recognise and classify colorectal polyps. Accurate classification is based on morphology, surface pit and capillary patterns. It is difficult to teach assessment skills because static polyp images are often of poor quality and cannot show all areas of interest. Based on anonymised, endoscopic reference images, 3D polyp models were created in ZBrush, demonstrating a variety of morphological forms. The models had detailed pit patterns to show the capillary structure, a key predictor of pathology. The models were subsequently uploaded to the online 3D repository and model viewer, Sketchfab, to create an interactive training resource for trainee colonoscopists. The digital models were evaluated by a panel of expert colonoscopists who scored them for realism and potential as aids for training. There was agreement that the digital polyp models would be useful for teaching. Polyp morphology was rated as realistic however representation of pit patterns received a mixed response, highlighting areas for further development.

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Polypectomy; colon; colonoscopy; 3D modelling; colorectal polyp; biomedical visualisation

## Introduction

### *Identifying and removing colorectal polyps*

Colorectal polyps occur when cells in the lining of the colon undergo genetic change, resulting in rapid and unregulated growth. This creates a small bump on the colonic surface which, left unchecked, can continue to enlarge and may progress to cancer (Leslie et al., 2002). Detecting and removing polyps reduces colorectal cancer incidence and mortality (Brenner et al., 2011; Corley et al., 2014; Kaminski et al., 2017; Winawer et al., 1993; Zauber et al., 2012) and this is the basis of bowel screening programmes around the world (Kanth & Inadomi, 2021).

As they grow, polyps take on a variety of different shapes (or morphologies); while most appear as disc- or dome-shaped elevations on the surface (flat or sessile polyps), others may grow up on stalks (pedunculated polyps). Rarely, the abnormal cells grow downwards, creating a depressed lesion. Polyps that become very large and spread laterally may begin to display several different morphological forms across their surface. Polyp morphology can be used to predict the likelihood that the lesion has already progressed to invasive cancer. This is a vitally important factor when planning how best to remove the polyp (Burgess et al., 2017).

Based on their microscopic appearance, the commonly encountered polyps can be classified as serrated or adenomatous (adenomas). Adenomas can be further divided, according to growth pattern, as villous, tubulovillous, or tubular. Serrated polyps can be subclassified as hyperplastic polyps, sessile serrated lesions, or traditional serrated adenomas (Jass, 2007; Øines et al., 2017).

Each of these sub-types has a subtly different endoscopic appearance, largely because of the patterns formed by the pits or grooves on the surface (see Figure 1), and the density and arrangement of capillary blood vessels (Kudo et al., 1996; Sano et al., 2001). As polyps progress towards cancer these surface features change, so recognition of subtle alterations in pit and capillary pattern can be used, alongside assessment of morphology, to estimate cancer risk (Kanao et al., 2008; Sano et al., 2016).

Polyps are identified and removed during colonoscopy. A flexible endoscope is inserted into the rectum and advanced around the colon, providing high-definition views of the colonic lining.

Small benign polyps can be removed relatively easily using an electrically heated wire loop (snare) that is passed through the colonoscope (polypectomy). The polyp is then retrieved for pathological examination. Larger polyps require a modified

**CONTACT** Anna Roberts A.R.Roberts@2024.ljmu.ac.uk Liverpool John Moores University, Liverpool, UK

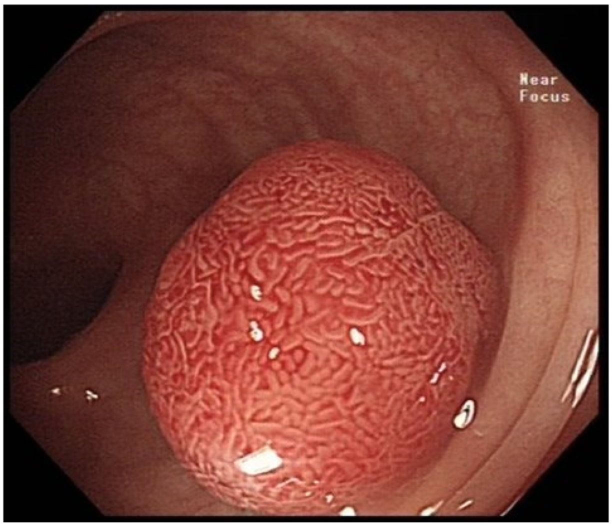


Figure 1. Image of polyp with pit pattern. [Image courtesy of Dr Paul O'Toole].

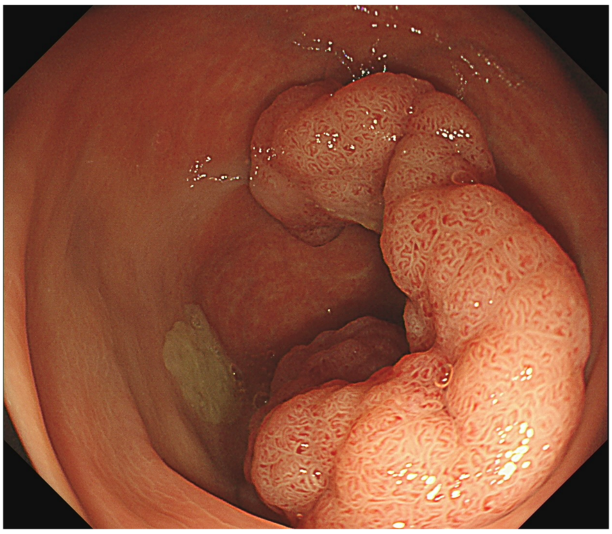

Figure 2. Endoscopic image of a colonic LST. [Image courtesy of Dr Paul O'Toole].

approach, known as piecemeal endoscopic mucosal resection (pEMR), whereby the polyp is lifted on a bed of injected fluid before being removed in pieces using a snare. However, if there is a risk of superficial cancer within the polyp, a more sophisticated technique is preferred, known as endoscopic submucosal dissection (ESD), which allows the polyp to be removed in one piece using an electrosurgical knife (Ferlitsch et al., 2024). This allows proper pathological evaluation of the whole polyp to determine whether the cancer has been completely removed. In contrast, polyps suspected of harbouring deeply invasive cancer are not suitable for colonoscopic removal and should be referred for surgical resection.

Colonoscopic polypectomy is a complex technical procedure that is difficult to learn and requires a combination of advanced motor and cognitive skills. It is not without risk; potential complications include bleeding, perforation, and post-procedure pain (post-polypectomy syndrome). Risk relates to the size, morphology and anatomical position of the polyp, alongside patient factors (e.g. comorbidities, age) and the experience of the endoscopist (Rutter et al., 2015).

## *Training challenges*

When polyps are encountered during colonoscopy, their accurate assessment and classification is essential so that they can be removed completely, using the most appropriate technique and with the minimal risk of complications (Rutter & Jover 2020).

This is particularly important for large lateral-spreading polyps (LSTs) because of the risk that they may harbour superficial cancer within them (Figure 2). It is vital that the endoscopist makes a thorough examination of the pit pattern and morphology across the whole surface of the lesion to identify any suspicious areas.

If malignant transformation is suspected, the polyp should be removed in one piece with a good margin of normal tissue around it. Removing a malignant polyp by piecemeal EMR results in uncertainty about completeness of excision and may condemn the patient to surgical removal of part of their colon (Rutter et al., 2015).

In the UK, standards for training and certification in colonoscopy have recently been updated with emphasis on polypectomy competency (Siau et al., 2023) and a training pathway has been proposed for advanced polypectomy (EMR) (Tate et al., 2023). These both emphasise the importance of training in optical diagnosis of colorectal lesions. However, current training opportunities in polypectomy are limited (Geraghty et al., 2015). Large LSTs account for only 1% of all polyps so are rarely encountered during training (Cronin & Bourke, 2023) and access to training lists is often limited (Biswas et al., 2018; Patel et al., 2017). Some are forced to use their annual leave to gain additional endoscopy training (Anderson & Lockett, 2019). For those who have completed basic training and commenced independent colonoscopy practice, acquiring more advanced polypectomy skills, and improving lesion recognition expertise is difficult because of a lack of formal training opportunities in this area (Barbour et al., 2021).

It is widely accepted that additional training tools and learning resources are required to improve colonoscopy and polypectomy technique (Cappell, 2008; Biswas et al., 2018; Lieberman & Gupta, 2020). Advanced lesion assessment is usually taught using endoscopic image libraries or, in some cases, video clips. The range of polyp photographs available in most libraries is limited and their quality variable. It is often difficult to get a proper impression of the 3-dimensional morphology of a polyp from a still image. Furthermore, for large lesions, photographs and videos will invariably highlight any small regions of interest on the surface, such as demarcated areas of depression, or subtle changes in the pit pattern. Consequently, trainees do not develop the skills required to identify such areas of interest for themselves, as is necessary when assessing such lesions in clinical practice. Accurate 3D reproductions of complex polyps might overcome these restrictions by allowing the trainee to manipulate and interrogate the simulated polyps independently, recreating the experience of real-life colonoscopic lesion assessment.

### *Affordances interactive 3D digital models for medical education*

Surveys have revealed inconsistencies in endoscopy training (Anderloni et al., 2014; Parker et al., 2023; Scaffidi et al., 2021), particularly in relation to polypectomy (Patel et al., 2017). This suggests a requirement for additional and complimentary learning tools that enable training in advanced assessment and diagnosis, through self-directed study or in the classroom.

Digital visualisation has an established use in medical education, producing detailed 2D illustrations, 3D printed models and virtual reality interactions that replicate anatomy and pathologies for learning (Ainsworth et al., 2011; Azer & Azer, 2016; Urlings et al., 2023; Youn et al., 2023).

Although digital 3D resources for polypectomy training are currently limited, specialist software like ZBrush enables the sculpting of organic, high-resolution 3D models with customisable brushes to create bespoke surface textures (Kutz, 2018). These 3D models can then be exported and presented on free, online, and interactive 3D model hosting repositories such as Sketchfab (https://sketchfab.com/). Examples of this approach have been shown to improve anatomical understanding of morphology and pathology (Ardila et al., 2023; Erolin et al., 2019; Pokojna et al., 2022).

Interactive 3D digital models can act as complementary learning resources to support trainee colonoscopists' understanding, assessment, and psychomotor abilities (Ardila et al., 2023; Biasutto et al., 2006; Erolin, 2019; Vernon & Peckham, 2002). Digital learning is often akin to game-based learning, which can help with key translational skills, such as critical thinking, collaboration, and creativity. (Xu et al., 2023). Critical thinking is key to determining a diagnosis and observing 3D digital models from differing perspectives enhances the ability to assess and identify potential malignancies (Ardila et al., 2023; Earley et al., 2017; Mikami et al., 2022).

The nature of endoscopic procedures holds relevance to 3D interactive models on screens, as clinicians observe live video feeds of patients' colons on monitors to assess the patient's condition (Martin et al., 2014). Moreover, this offers trainee colonoscopists a simulated environment for learning, by replicating highly detailed models out of a risk-intense, clinical environment.

Having digital models available online also assists with collaboration, as digital models can be shared over the internet to be interacted with via open-source software (Xu et al., 2023). This allows other institutions to present high-resolution 3D models and share them for educational purposes.

The research project presented in this paper sought to develop a series of 3D digital colorectal polyp models, with varying morphologies, sizes and pit patterns that could be used to train endoscopy trainees on polyp assessment and diagnosis. In the following sections we describe the developmental process in creating the polyp models, using software including ZBrush, Reaction Diffusion Playground and Sketchfab. We discuss and investigate the output using feedback from surveys with expert colonoscopists and consider further development of the 3D models for training.

## Materials and methods

Six 3D digital polyp models were created in the digital sculpting software ZBrush, with a range of morphologies (one pedunculated and five sessile) and distinct surface patterning to mimic the capillary structure. The 3D models were exported and hosted on Sketchfab as a virtual, interactive teaching resource. Of the five sessile polyps, it was important to have small and larger, lateral spreading lesions. This was to train colonoscopists on the differences between these morphologies, to enable accurate diagnosis.

### *Digital 3D modelling of polyps*

ZBrush is a digital sculpting tool that is considered an industry standard for creating high-resolution 3D models (Kutz, 2018). The software allows for various customisable brush settings, fundamental tools for re-topologising, and projection mapping of textures based on reference images (Kutz, 2018).

The six 3D polyp models were sculptured from a base spherical mesh. Using the native 'Move Topological', 'Standard' and 'Form Soft' brushes within ZBrush, polyp shapes were sculpted. To create more definition, the 'DAM Standard' brush was used to chisel the models to create defined contours as shown in Figure 3.

The 'DynaMesh' tool was used frequently to retopologise the meshes to ensure there was limited mesh distortion, and to allow for sculpting finer details. Once the desired shapes were achieved (Figure 4), detailing of pit patterns was undertaken.

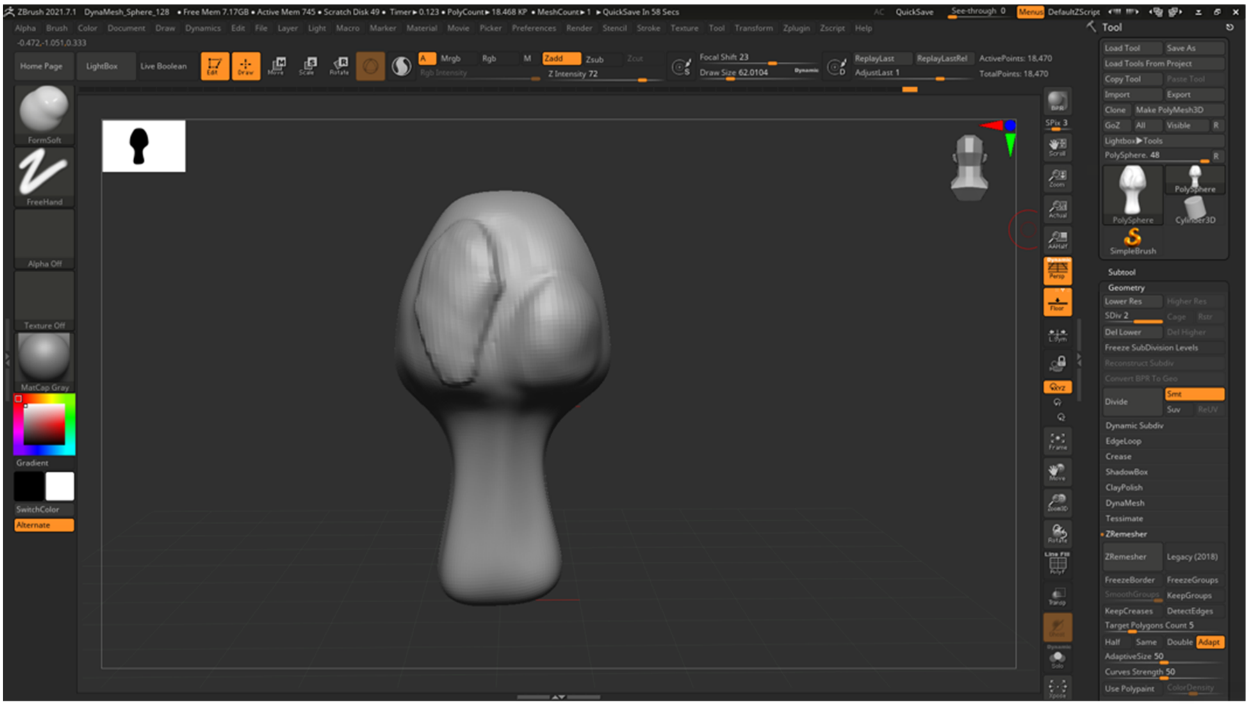

Figure 3. Dynamesh model sculpted using the 'Move Topological', 'Standard', 'Form Soft' and 'Dam Standard' brushes in ZBrush.

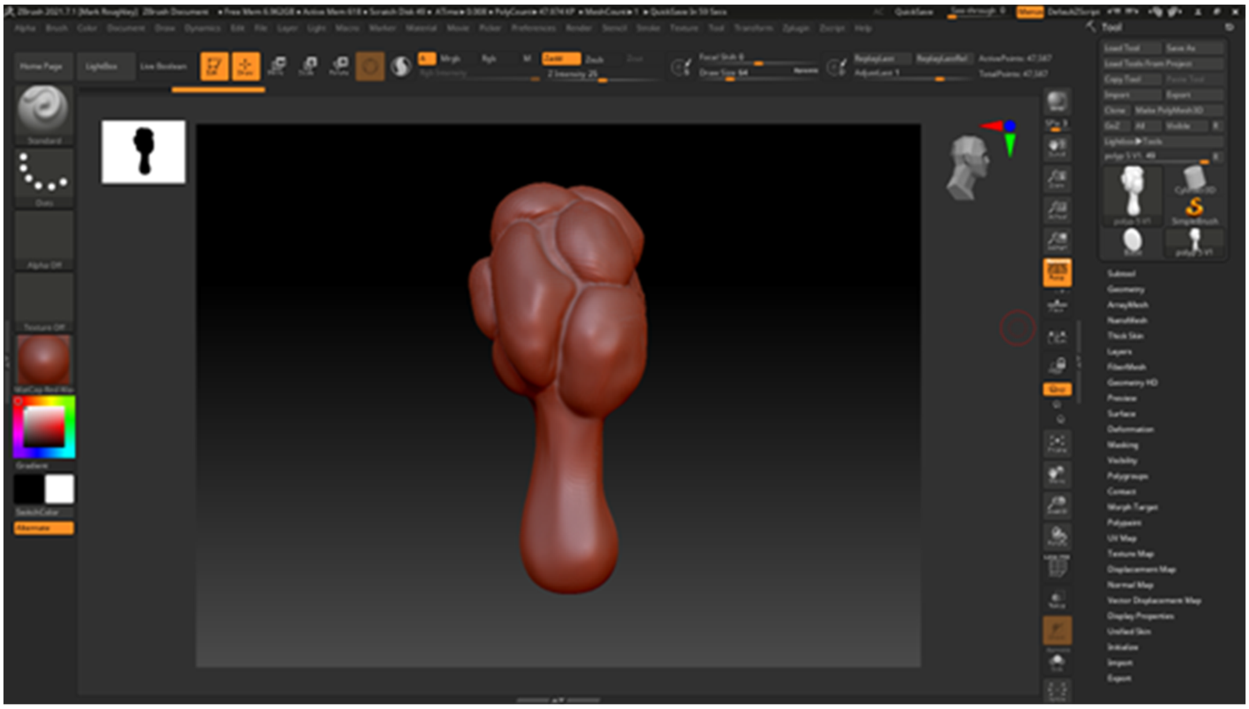

Figure 4. Low resolution mesh of a pedunculated polyp model in ZBrush.

## 'Pit pattern' sculpting and painting

When characterising polyps for diagnosis and treatment, pit pattern classification is an important part of the assessment. Pit patterns can be used to predict the histological sub-type of the polyp and determine whether it is likely benign. Using magnification endoscopes combined with pit pattern assessment can reveal the presence of covert submucosally invasive cancer and increase the accuracy of diagnosis (Maeda et al., 2017).

The surface structure of polyps appears as a series of repeating patterns with a degree of randomness. Alan Turing, in 1952, first described how repeating patterns found in nature could be mimicked by the behaviour of a system in which two diffusible substances interact with each other (Turing, 1952). These have become known as Reaction-Diffusion systems and Turing Patterns (Landge et al., 2020). The commonly encountered polyp pit patterns show similarities to those seen in coral reefs and animal camouflage patterns; these can be well simulated by Turing Patterns. This led us to explore whether polyp pit patterns could be mimicked using Reaction-Diffusion systems. We used the Reaction Diffusion Playground (https://jasonwebb.github.io/reaction-diffusion-playground/), to emulate the controlled chaos of pit pattern structure, altering parameters available within the preset menu (Webb, 2023).

By adjusting the 'seed patterns' and switching between presets as the pattern grew, we were able to recreate pit patterns recognisable as Kudo IIIL, IV and Vn (Kudo et al., 1997) (Figure 5).

After creating the reaction-diffusion generated pit patterns, the images were imported into ZBrush as a projectable texture. By experimenting with various brushes, such as the 'Standard' brush tool, the pit patten was applied as a raised or embedded surface using the 'Spotlight' image projection tool (Figure 6). The goal was to make the pit pattern visible on the polyp but not too defined.

Due to the fine detailing of the pit patterns, high polygon meshes were necessary to retain the detail when sculpting. Once sculpting was complete, to protect the high-level of detail, but also the use of a low-polygon model for better interaction when uploading to a web hosting platform, for each high-polygon model with five subdivisions, the model was duplicated, and the duplicate was retopologised using Dynamesh to create low polygon versions. Each polyp, with both high and low polygon models adjacent to each other in the Subtool panel, the 'Project' tool was used to transfer detail from the high polygon mesh onto the low polygon equivalent. This process did produce somewhat successful results, but there were still elements that retained a pixelated appearance. Using the 'Topology' brush, more polygons were created in specific areas of the models that required high levels of detail, to keep details after further projection.

Once the sculpted textures had been created, poly-painting was undertaken. A key part of the poly-painting process is UV mapping. This process involves flattening out the mesh to assign UV coordinates so that when paint is applied it can be mapped to the correct section of the 3D model when exported (Figure 7). UV mapping was undertaken for all six models.

To add colour, the masking tool was used to highlight the pit pattern on each model by outlining each sculpted mark, and colour was added using the 'Spotlight' tool by painting colour onto the un-masked areas of the models and vice versa (Figure 8). The 'Spotlight' tool was also used to create a custom colour palette using the eyedropper tool, which was used to paint any missing colours not added through the 'Spotlight' projection technique (Figure 9). With painting complete, texture maps were created in the 'Texture Map' menu and selecting 'Create'- 'New from Polypaint', ready for export.

When all six 3D polyp models were complete, the meshes and associated texture maps were exported as OBJ files ready for upload to Sketchfab.

During the modelling process, there were numerous consultations with the expert colonoscopist O'Toole, P. to evaluate the models for clinical accuracy. During these feedback sessions, key features were re-modelled and re-defined, such as the pit pattern and colour to emphasise the surface structure, suggesting potential malignancy in some areas and benign adenomatous appearances elsewhere.

Concerning the sessile polyp in Figure 10, the demarcation line was deepened to delineate the

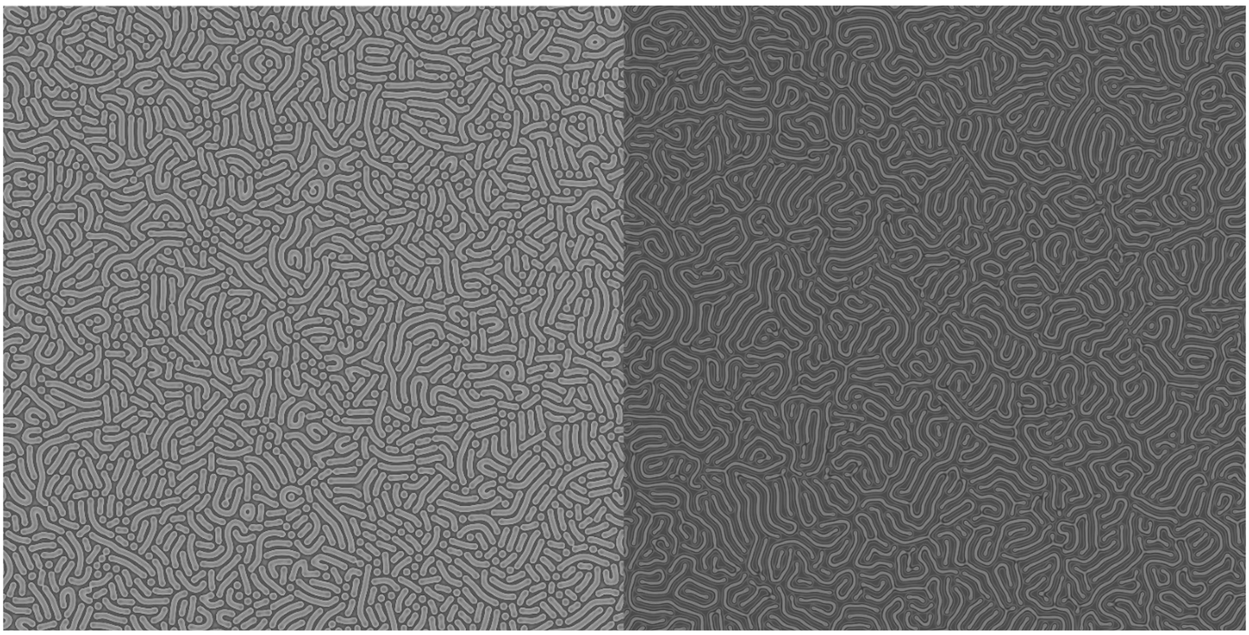

Figure 5. Two pit patterns were created in the Reaction Diffusion Playground. Kudo IIIL pattern (left) and IV (right).

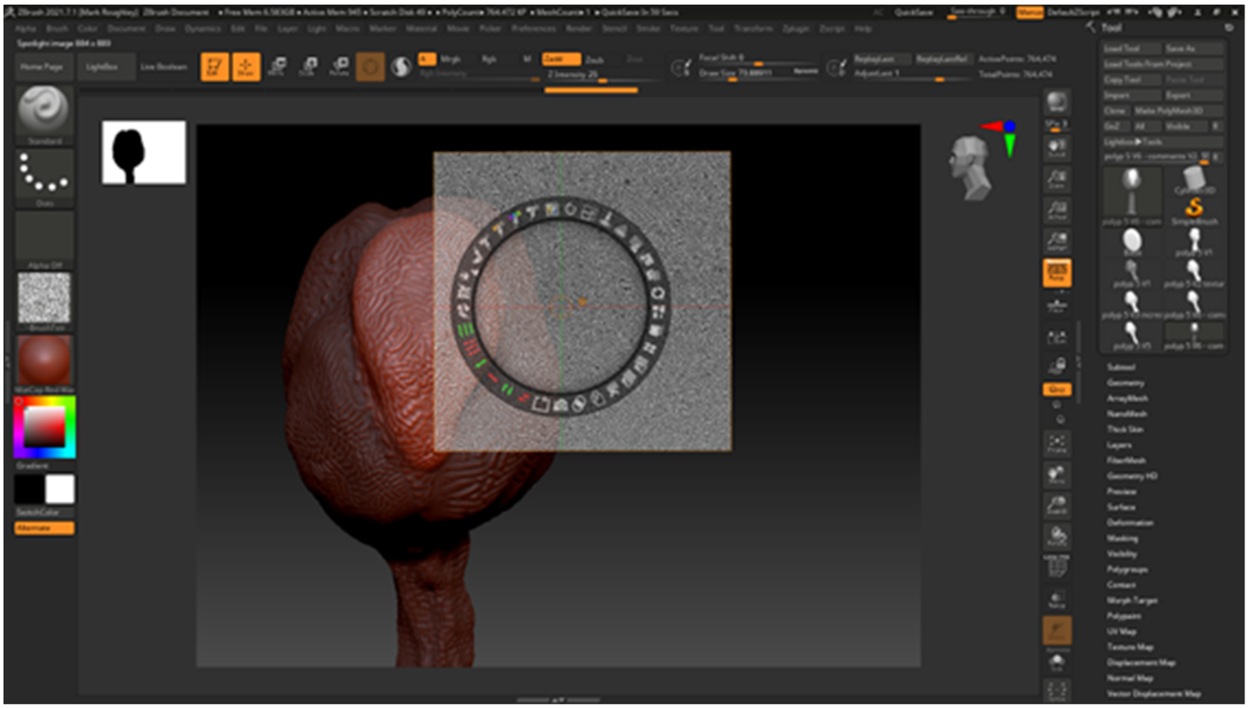

Figure 6. Using the 'Spotlight' tool in ZBrush to apply pit pattern created from the Reaction Diffusion Playground to the surface of a pedunculated polyp model.

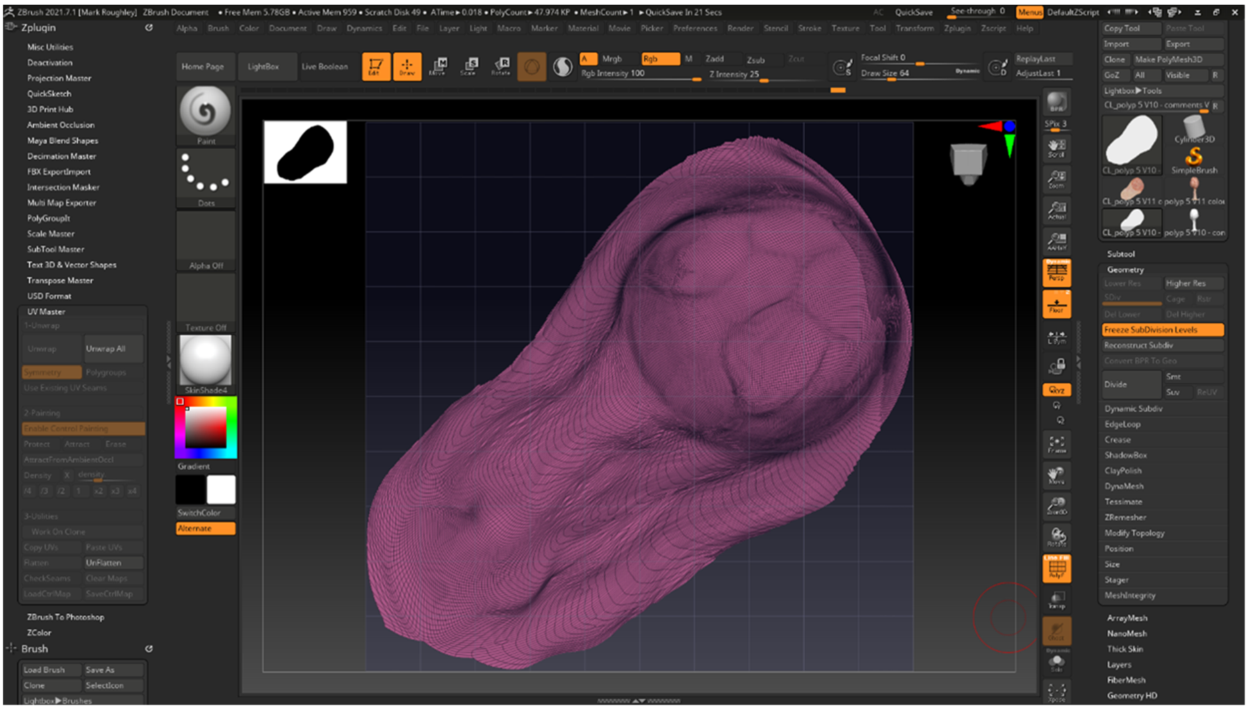

Figure 7. Flattened mesh of polyp model after UV mapping process.

central area of the polyp that had an undefined (Kudo Vn) pit pattern.

For the larger, lateral spreading lesion in Figure 11, a section of bowel mucosa was added to demonstrate how the lesion spreads across normal mucosa and impacts the surrounding bowel tissue. In addition to this, small and amorphous nodules were created around the skirting of the polyp to reproduce the granular appearance found in the flatter areas of such lesions.

Feedback sessions provided crucial guidance in ensuring that important morphological details and realism was retained, especially once the models were exported and uploaded to the online repository, Sketchfab. During this process, the polyp models are compressed which can reduce the resolution and clinical accuracy. For this reason, certain details such as the pit patterns, were emphasised and over-modelled to ensure they were visible in the final build.

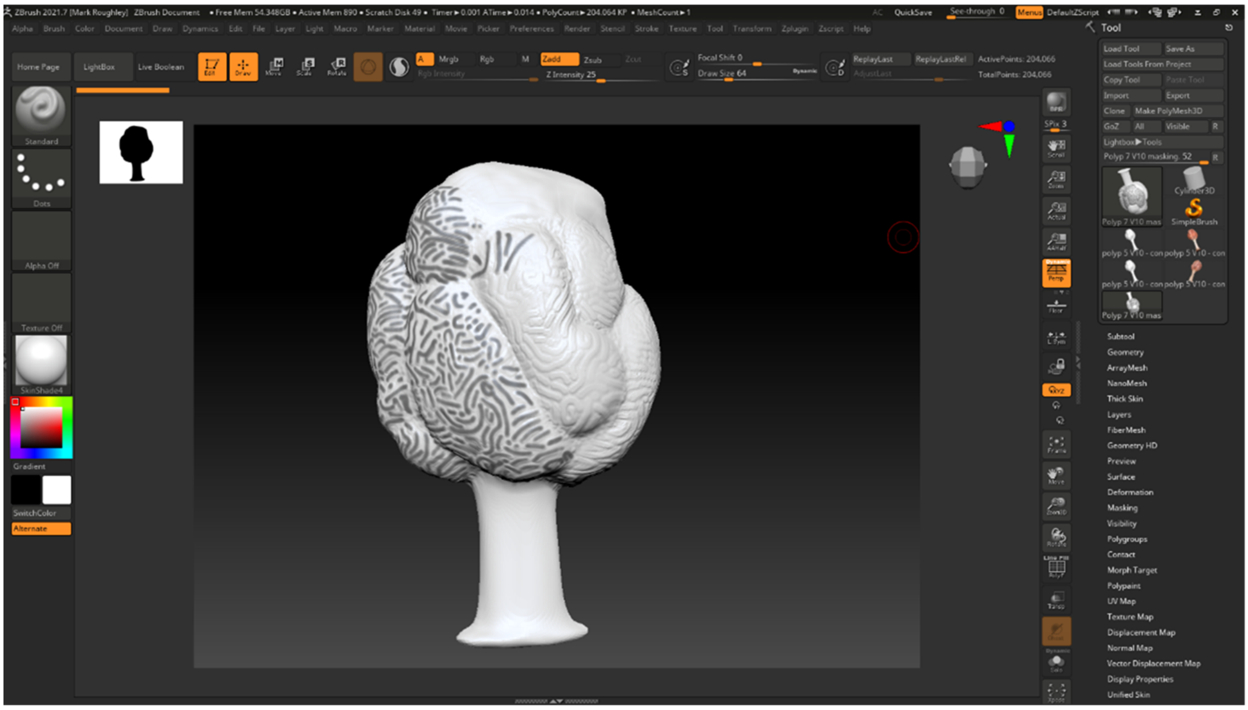

Figure 8. Pedunculated polyp model with masking applied in Zbrush.

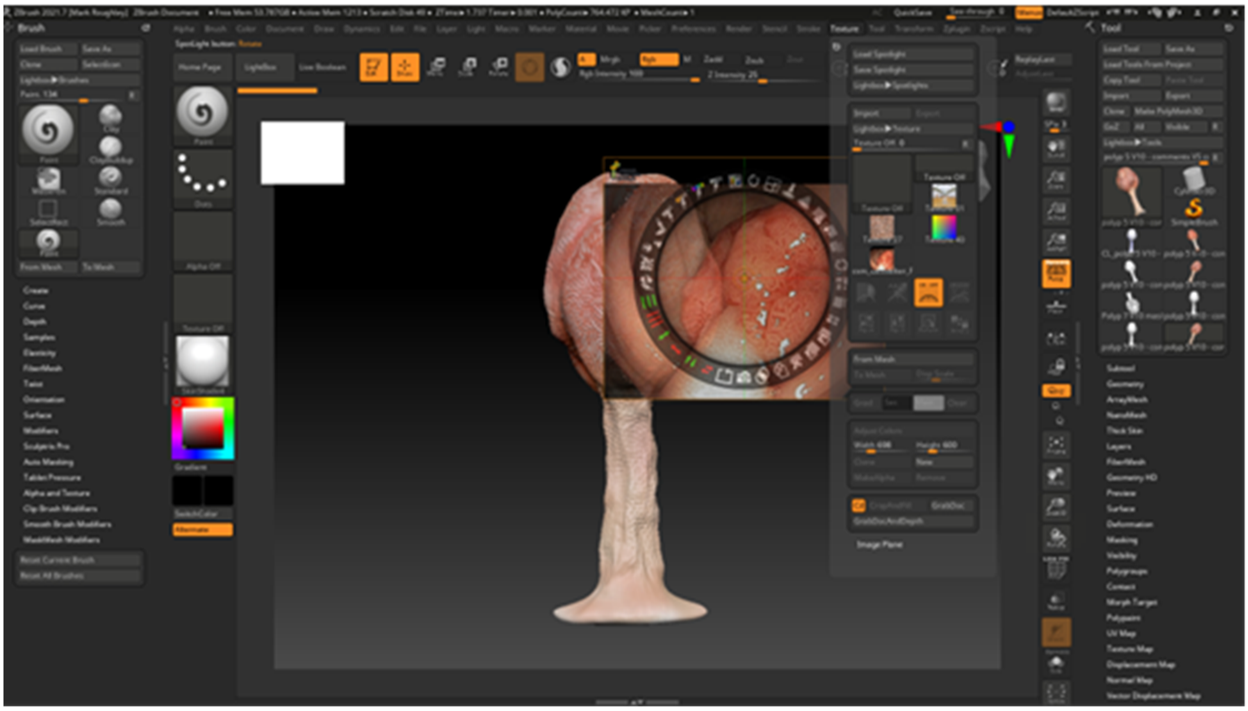

Figure 9. Painted pedunculated polyp using 'Spotlight' texture tool to apply reference photo colour to the 3D model in ZBrush.

## Online interactive presentation of the polyp models on sketchfab

Sketchfab is one of the largest platforms for immersive 3D content. The website allows members to upload 3D models for public access and is fully integrated with different digital modelling software's https://sketchfab.com/. As an open-source, 3D viewing platform, Sketchfab was deemed to be a useful tool to stage the polyp models and to allow for full 360-degree views of the models plus the ability to zoom and assess the models from different angles. Sketchfab also has various post-processing functions such as lighting parameters that when altered can ensure full visibility of the polyps' pit pattern to enable accurate assessment (Figure 12).

Other post-processing functions adjusted the material quality to be reflective and glossy, to portray the

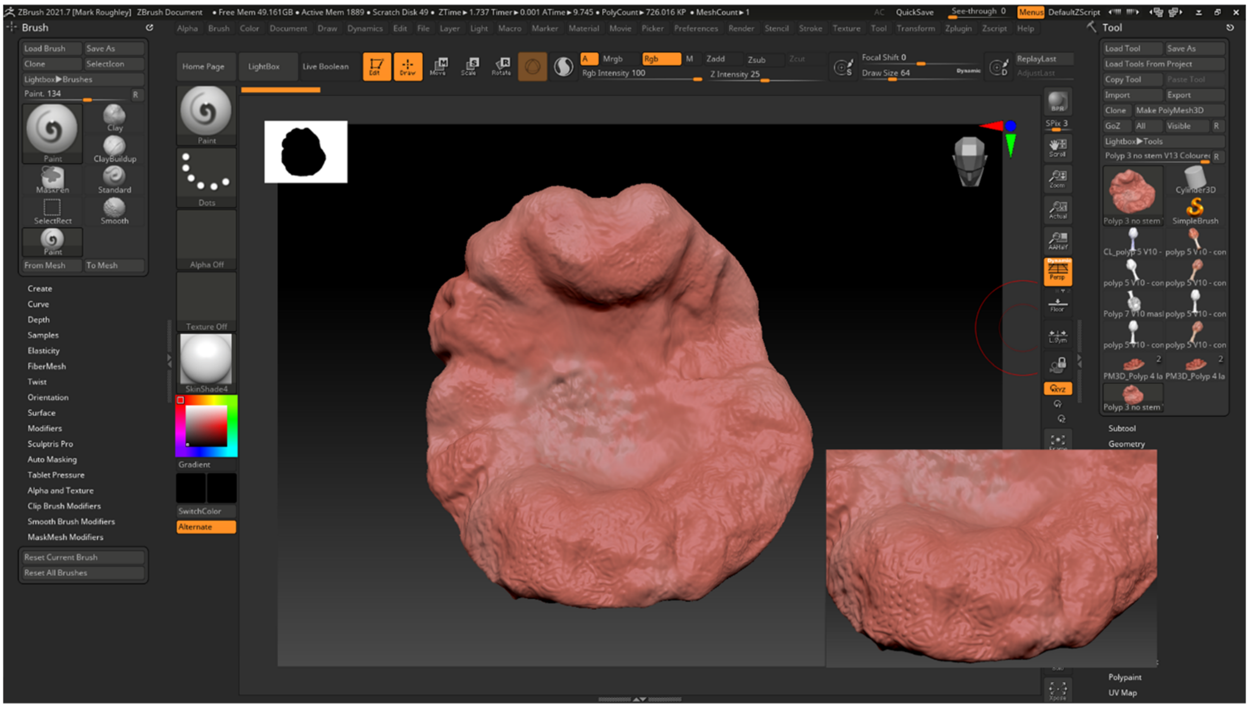

Figure 10. Demarcated depression on an LST-NG (pseudo-depressed-type) polyp model in Zbrush.

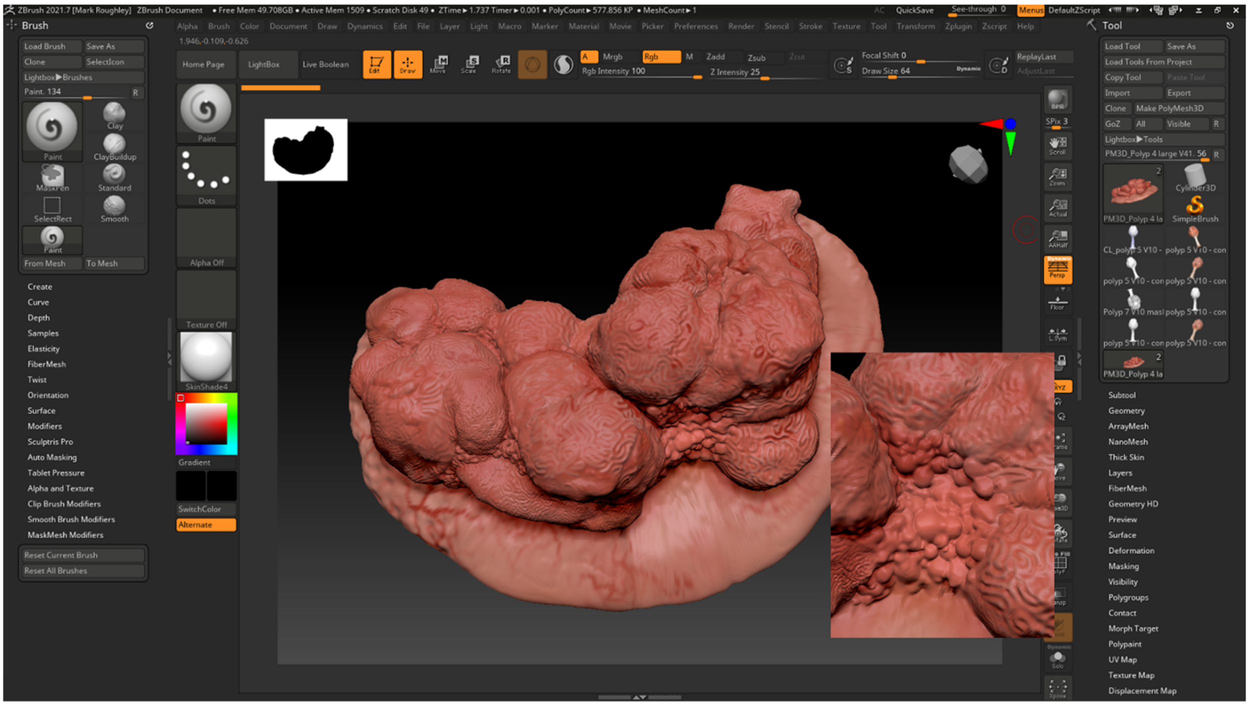

Figure 11. Nodular patterning of an LST-G (mixed nodular-type) polyp model with surrounding bowel mucosa in ZBrush.

wet-like nature of the polyp tissue (Figure 13). By increasing the 'Glossiness' and enabling the 'Clear Coat' setting, a shiny coating was created over the polyp.

When considering the models as teaching aids, the annotations tab was particularly useful. Annotations were used to indicate key diagnostic features of the polyp that would be key for clinical assessments (Figure 14).

There was an average of four annotations per polyp, each identifying the specific Kudo pit pattern, the category of polyp and any key features that may assist in the diagnosis: such as featureless areas or nodular patterning (Figure 15).

In addition to the post-processing filters and annotations, there is a virtual and augmented reality function that creates a first-point perspective for users to have increased interactivity and further understanding of the polyp model (Figure 16).

The final models are accessed freely on Sketchfab (Figure 17) and can be viewed in a collection online

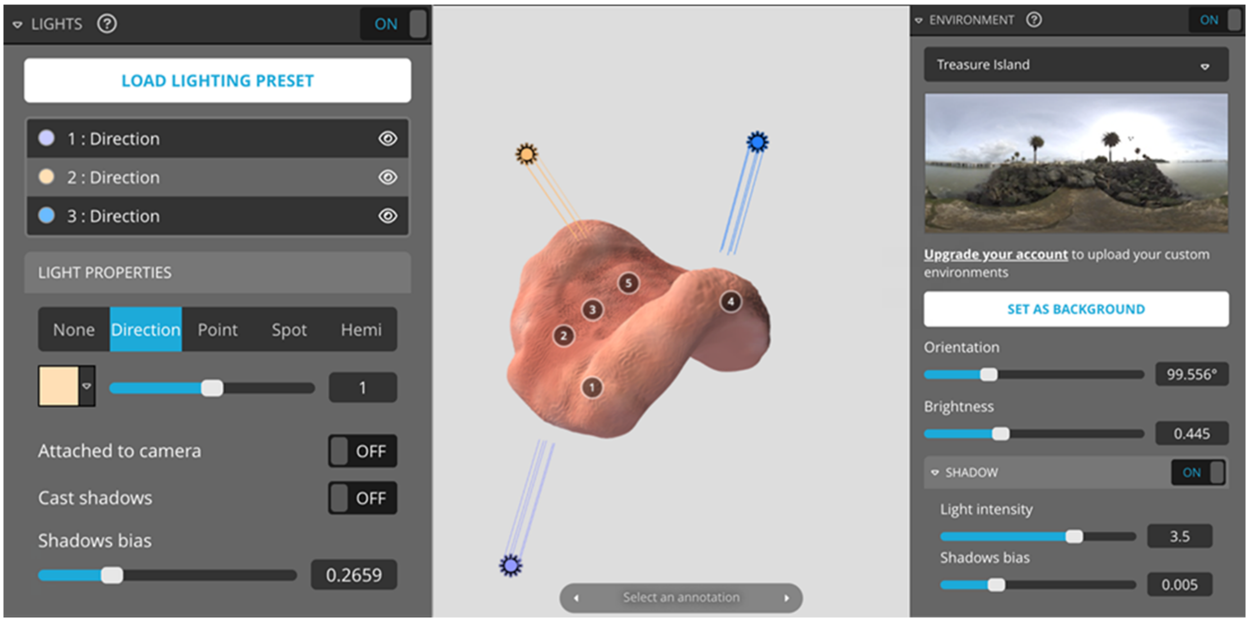


Figure 12. Screenshot of lighting setting adjustments used in Sketchfab.

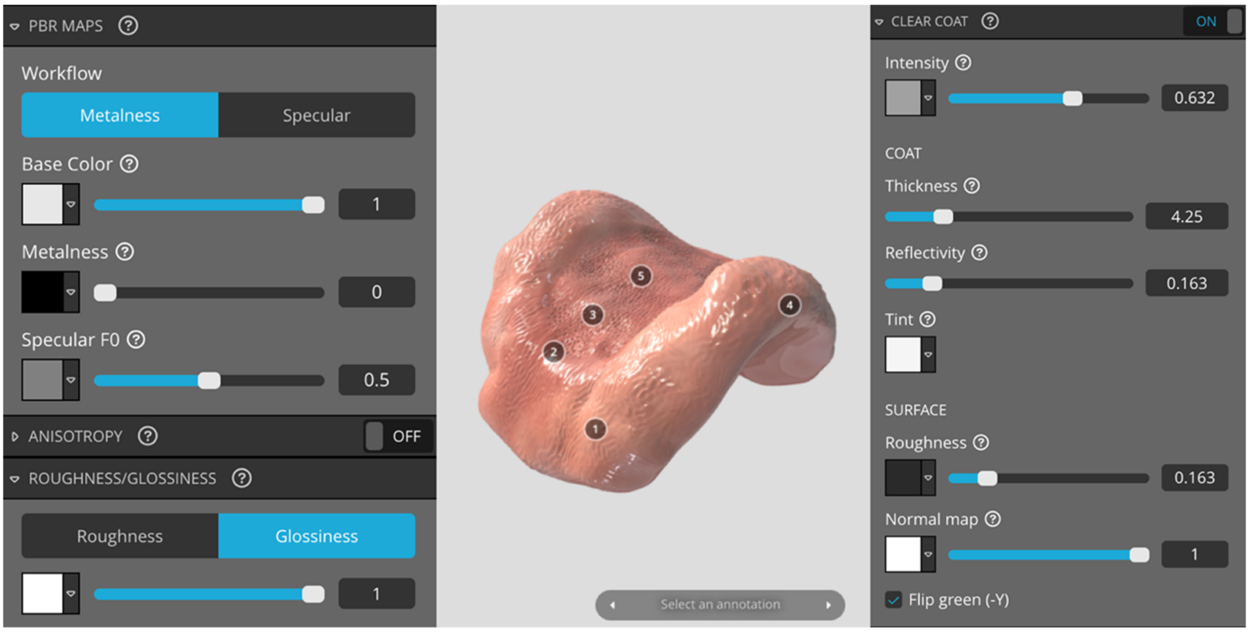


Figure 13. Screenshot of material adjustment settings used in Sketchfab.

here: https://skfb.ly/oRFJo. Figure 18 shows all models produced.

## Evaluation of the suitability of the 3D digital polyp models as educational training resources

An online survey was conducted to assess the suitability of the 3D polyp models as educational training resources. The aim was to evaluate the potential usefulness of the 3D digital polyp models as teaching aids for large colorectal polyp assessment. Participants were presented with the URLs linked to the models on Sketchfab to allow them to examine each model, then asked a series of statements using a Likert scale (strongly agree – strongly disagree):

- The background (title) information is clear, helpful and sufficient.
- The polyp morphology (general shape and appearance) is realistic.
- Enough detail is available to allow morphological classification.
- The pit patterns are realistic and sufficiently visible.
- Enough detail is visible to allow an estimation of malignancy risk.
- The colour and lighting are realistic.

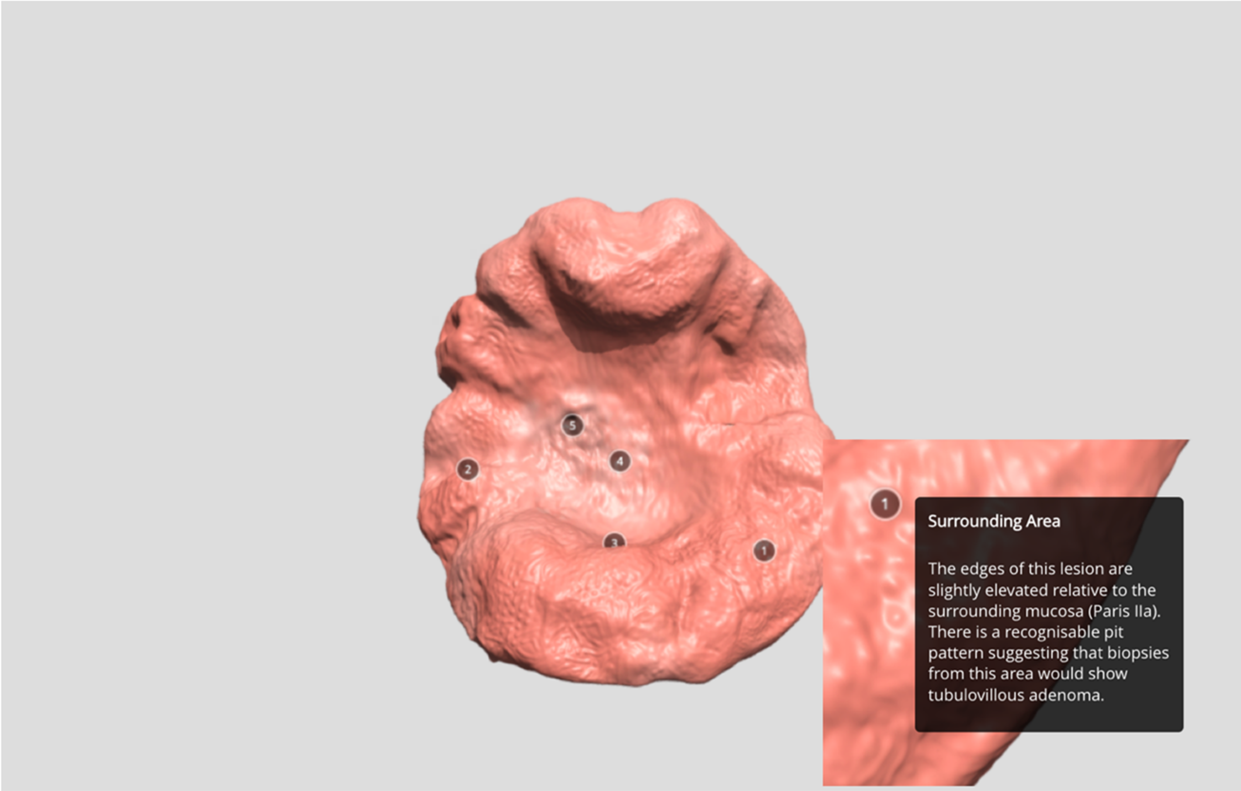


Figure 14. Annotated description of flat non-granular lesion with depression in Sketchfab.

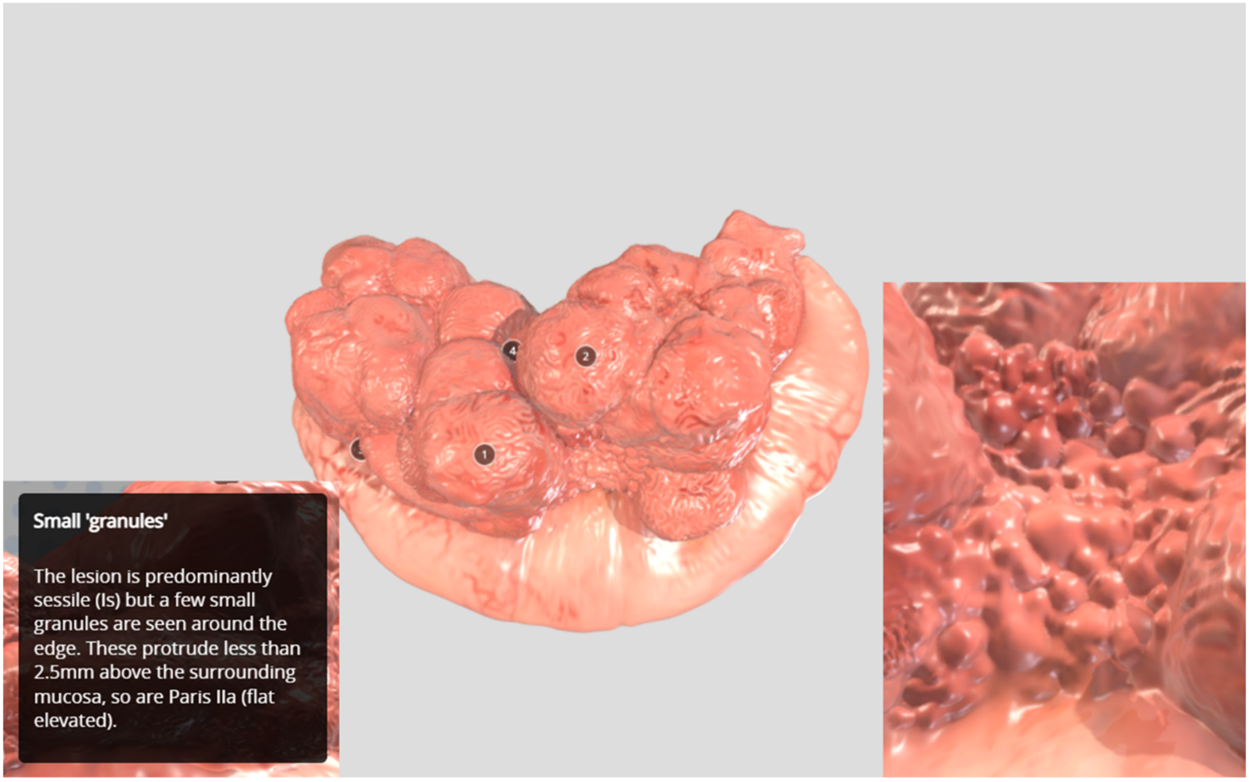


Figure 15. Annotated 3D model in Sketchfab of a lateral spreading lesion demonstrating the granular patterning around the skirt of the polyp lesion.

- The polyp is easy to manipulate (rotating/ zooming in).
- Information provided on hot spots is clear, helpful, and sufficient.
- Overall, the polyp appears sufficiently realistic.
- Overall, the polyp would be useful as a teaching aid.

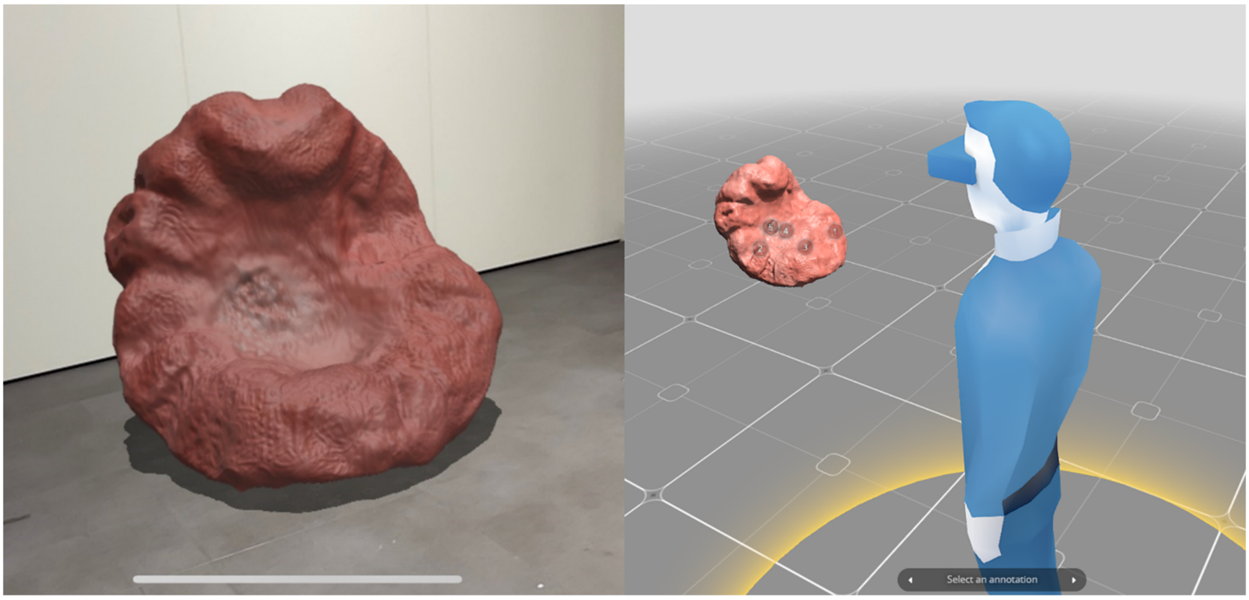


Figure 16. Viewing a polyp model in a classroom in augmented reality using Sketchfab's AR feature.

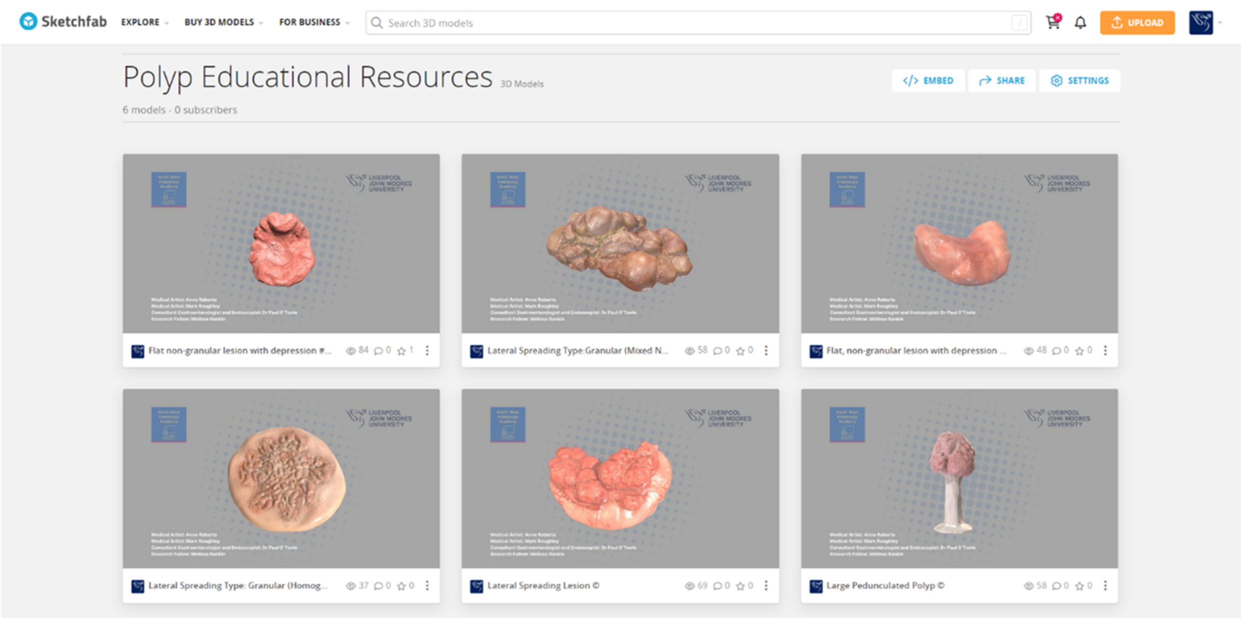


Figure 17. The 3D digital model models hosted on Sketchfab as a 'Collection'.

The survey was distributed to 5 experienced colonoscopists from the Northwest of England after approval by the Research Ethics Committee at Liverpool John Moores University (Ref: 29/NAH/029) and was conducted according to minimal ethical risk guiding principles. All participants were presented with the participant information sheet and gave their informed consent through participation in the survey.

## Results

The survey results, shown in Figures 19 and 20, demonstrated that 4.5/5 participants of the colonoscopists surveyed found the 3D digital polyp models to be useful as teaching aids for large colorectal polyp assessment. On average, 4/5 colonoscopists found the models easy to manipulate and examine on Sketchfab. When considering the morphology, 4/5 colonoscopists 'strongly agreed' and 'agreed' that the models had a realistic shape, however, the realism of the pit pattern garnered mixed results; with a median of 1.5/5 colonoscopists disagreeing with the accuracy of the pit pattern. This variance signified a lack of detail or potential inaccuracy of the pit pattern with a need for further refinement. This impacted further results, as 1/5 colonoscopists disagreed that the models retained sufficient detail for the assessment of malignancy risk.

Based on these results, there was clear discernment of the polyps' quality as teaching aids (Figure 20), however, some areas of realism required refinement (Figure 19), through re-defining the pit pattern and altering the colour.

Figure 18. Six polyp models were created including a range of pedunculated, sessile and flat polyps.

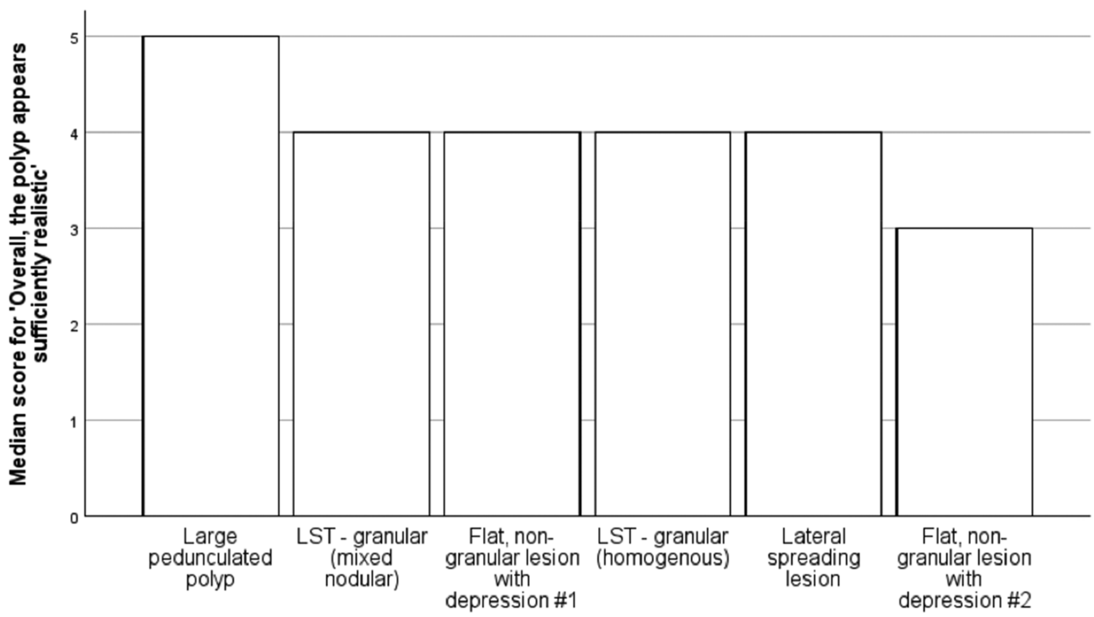


Figure 19. Bar chart detailing the survey results of the polyps' realism. Participants' results were displayed in a median value.

## Discussion

Competence in basic polyp assessment is considered a vital component of colonoscopy practice (Siau et al., 2023) and endoscopists wishing to learn more advanced polypectomy require greater skill in interpreting the subtle morphological and surface features of larger polyps (Tate et al., 2023). The challenge for trainee endoscopists, is to develop these assessment skills despite a limited exposure to clinical cases and a lack of high-fidelity medical images.

Digital visualisation is widespread within medical education, and 3D digital models can act as key resources for complementary learning, including the reproduction of pathology seen in clinical environments (Erolin, 2019). The ability to interrogate simulated, anatomical forms independently supports key assessment skills, critical decision making and psychomotor abilities (Ardila et al., 2023).

This project aimed to create and evaluate 3D digital polyp models for use in polypectomy training. To achieve this, it was necessary to create polyp models with realistic morphology, and detailed pit patterns that covered the entire surface. By using advanced digital sculpting tools like ZBrush, detailed surface textures could be accurately represented.

Hosting the 3D polyp models on an interactive and open-source website like Sketchfab allows users

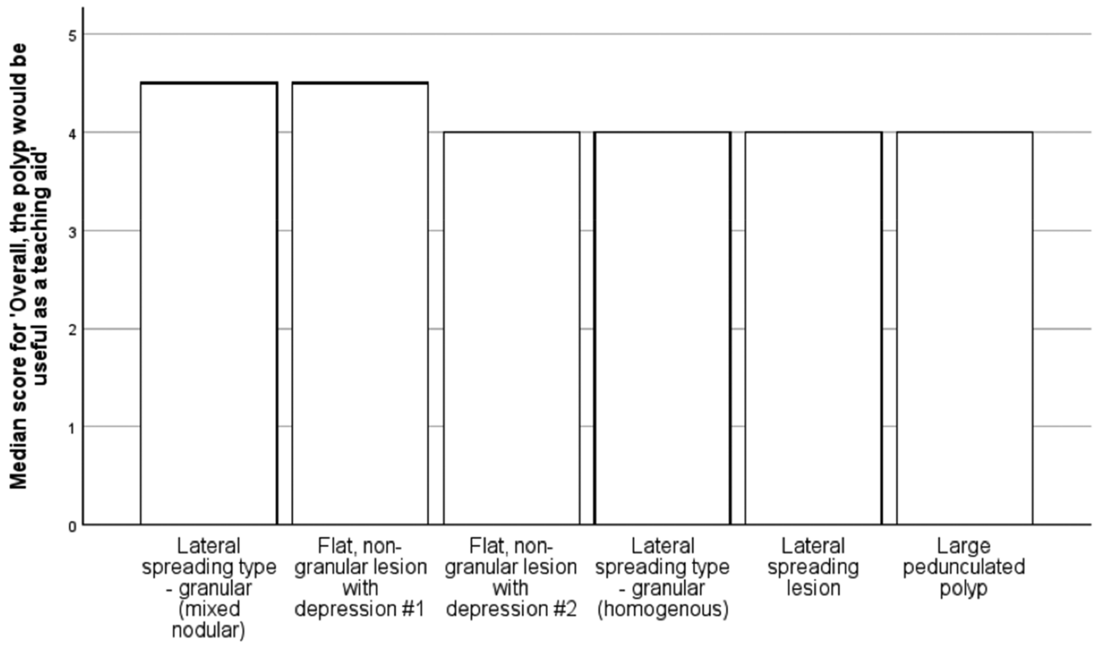


Figure 20. Bar chart detailing the survey results of the polyp assessment as a useful teaching aid. Participants' results were displayed in a median value.

to get a three-dimensional impression of the polyp models' morphology and to interrogate the entire surface, so they can find important areas of pit pattern variation. In addition, online hosting enables users from international institutions to use the models within their training programmes.

Based on the results of the evaluation survey, respondents generally agreed that the 3D colorectal polyp models would be useful as teaching aids. They approved of the possibilities for interactivity that were offered by the hosting site, Sketchfab, allowing zooming and rotating of the model that mimics real-world polyp assessment during colonoscopy. Around 3/5 respondents also 'strongly agreed' on the clarity of the background information provided through hot-spots and descriptions of each polyp model. The aim of these hot spots is to provide users with information about the way an expert colonoscopist would undertake polyp assessment in clinical practice: what they would look for, and how they would describe and classify their observation.

In terms of overall realism, our evaluation produced a mixed response; whereas 4.5/5 of experts 'strongly agreed' or 'agreed' that the morphology of the polyps showed a high degree of realism, 1.5/5 experts found that the pit pattern lacked accuracy, suggesting the need for further refinement. We used the pre-set parameters in a free 'Reaction-Diffusion playground' to generate our basic pit patterns. It is possible that by adjusting the seed patterns and parameters using mathematical programming, more accurate pit pattern renderings could have been achieved.

In practice, colonoscopists use enhanced imaging when assessing pit patterns, because they are not always visible when viewed endoscopically under white light. These enhancements include various forms of narrow-band imaging (NBI) that work by highlighting small blood vessels running around the pits, making the pit pattern more obvious. NBI appearances were not recreated in our models, but this is a possibility for further work to support classification and improve the estimation of malignancy risk (Lopez-Ceron et al., 2014).

An immediate solution would be to allow the hot-spot function to superimpose genuine pit pattern images over the areas of interest if they are selected by the user. These could demonstrate both white light and NBI appearances. Representative pit pattern images are somewhat easy to acquire during endoscopy if only small areas of the relevant pattern are required. Unfortunately, Sketchfab does not allow a photographic overlay function.

Evaluation of the colour and lighting of the polyp also produced a mixed response. This is a challenge for the medical artist because the colour tone, brightness and contrast of endoscopic images will vary depending on the manufacturer and model of the endoscope used. The reference images were compiled over several years and were captured using a variety of different colonoscopes. Colonoscopists tend to become familiar with the instrument which they most often use and their interpretation of the colour of our polyp models was likely to be somewhat subjective. (Bardhi et al., 2021).

It would be useful to understand the reasons for the mixed response to some of the questions in our survey. Using a Likert scale allowed us to rank each aspect of the product, but including open-ended questions would have permitted the expert panel to elaborate on why they considered the pit pattern to be unrealistic or how the colour and lighting could have been improved. This contextual understanding will be important for the development of the future polyp models.

When addressing the realism of the surface features for the models displayed online, it is important to acknowledge the limitations of the 3D modelling workflow used in this project. Using ZBrush enabled the creation of high –polygon, complex, organic polyp shapes with detailed pit patterns, forming indentations and bumps across the surface of the polyp that create contrast between the capillaries and surrounding surface. Despite duplicating the high polygon model and re-topologising to a lower polygon count using the Dynamesh tool, then projecting details onto the lower polygon model using the 'Project' tool and adding in further geometry in targeted areas using the 'Topology' brush, ultimately details were lost in the final models, especially visible when uploading to Sketchfab. More subdivisions and projections and the use of normal maps would have better prepared the models for online publication.

As emphasised by Webster (2017) creating low polygon duplicates of high polygon models and using normal maps will help to retain sculpted detail while also maintaining low-polygon models for effective rendering. Erolin (2023) describes a recommended workflow that includes using ZRemesher to re-topologise the high polygon models to have lower polygon counts, then subdivide (approx. 3 times) and project details from the high to low polygon models a number of times until the desired appearance was reached; at each subdivision, use the 'Project' tool to transfer details from the high polygon model to lower polygon version (Erolin, 2023). Normal maps can then be created and baked onto the low polygon versions of the models in the 'Multi-map exporter'. The process of baking normal maps allows for high resolution details to be captured into an image. With the low polygon version of the model exported at the lowest subdivision with a baked normal map, when the model is uploaded to Sketchfab, the high-resolution details are preserved when rendered (Versalius, 2023). This workflow would be more appropriate than the one we adopted and would allow for seamless online rendering of higher resolution details.

Materiality is another crucial proponent of realistic polyp training models. Colonic mucosa, when viewed endoscopically has a distinct glossy, wet look; this is an important factor when representing human tissue realistically. The quality of texturing in ZBrush is advanced, but there is a lack of post-processing functions that could recreate the desired glossy effect. We were able to achieve this appearance within Sketchfab, as the software has built-in post-processing settings. Working between ZBrush and Sketchfab allowed us to utilise the advantages offered by each software platform. For future work, we plan to explore other texturing software such as Blender or Adobe Substance Painter, to generate more exportable models that could function within game-based interfaces.

It is also important to note the small survey pool. Although only five respondents participated, all were polypectomy experts able to consider the validity of the models of simulations of real polyps. The overall findings showed that the models were judged to be reasonably realistic and suitable tools for training, and this is reassuring. Further evaluation, incorporating new criterion to assess validity, will require a wider survey of experienced endoscopists with more detailed questions to assess how successful the models prove when used by endoscopists at various stages of training.

## Conclusion and future plans

Despite the limitations discussed, this study has shown that sufficiently realistic 3D digital polyp models can be created using ZBrush and be used as teaching aids for colonoscopy trainees. However, further refinement of the six models we created is required to enhance their pit pattern appearances, lighting, and colour.

Following further refinement, we plan to incorporate our models into training programmes offered by the Northwest Endoscopy Training Academy, UK. This will allow for the evaluation of the models as educational tools using trainees as participants. Additionally, 3D printing physical representations of these polyps can be undertaken. This will allow trainees tactile exploration of polyp surfaces, which may further enhance understanding and knowledge retention (Jones et al., 2006).

Finally, although we believe these digital 3D models will prove valuable as a complementary resource to support colonoscopists' learning, they are not designed to replace clinical polyp assessment training. Our hope is that they will augment the acquisition of diagnosis skills and allow trainees to practice clinical decision-making in a safe, low-stress environment. Hosting the models on an open-source online platform, like Sketchfab, enables collaboration beyond the boundaries of institutions, and will allow access to training materials for healthcare professionals worldwide.

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## ORCID

Paul O'Toole http://orcid.org/0009-0000-1686-854X
Mark Roughley http://orcid.org/0000-0002-7483-859X
Melissa Rankin http://orcid.org/0000-0002-5905-4965

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