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Clay-Based Modeling in the Anatomist's Toolkit: A Systematic Review

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Anatomical education has suffered from reduced teaching time and poor availability of staff and resources over the past thirty years. Clay-based modeling (CBM) is an alternative technique for teaching anatomy that can improve student knowledge and experience. This systematic review aimed to summarize and appraise the quality of the literature describing the uses, advantages, and limitations of CBM compared to alternative methods of teaching human gross anatomy to students or qualified healthcare professionals. A systematic search of Embase, MEDLINE, Scopus, and Web of Science databases was conducted, and the Medical Education Research Quality Instrument (MERSQI) was used to assess study quality. Out of the 829 studies identified, 12 papers met the inclusion criteria and were eligible for this review. The studies were of high quality, with a mean MERSQI score of 11.50/18. Clay-based modeling can be used to teach all gross anatomical regions, and 11 studies demonstrated a significant improvement in short-term knowledge gain in students who used CBM in comparison to other methods of learning anatomy. Eight studies that included subjective assessment showed that CBM is rated highly. However, some studies showed that students viewed CBM as juvenile and experienced difficulty making the models. Additionally, there is no evidence to suggest that CBM improves long-term knowledge. Clay-based modeling is an effective learning method for human gross anatomy and should be incorporated into the anatomists' toolkit. In the future, more randomized controlled studies with transparent study designs investigating the long-term impact of CBM are needed. Anat Sci Educ 14: 252–262. © 2020 The Authors. Anatomical Sciences Education published by Wiley Periodicals LLC on behalf of American Association for Anatomy.

Key words: anatomical sciences education; medical education; gross anatomy education; undergraduate medical education; postgraduate medical education; clay-based models; three-dimensional models; systematic review

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INTRODUCTION

Despite anatomy traditionally being viewed as the "cornerstone" of education for all healthcare students and qualified healthcare professionals (Sugand et al., 2010), there has been a significant reduction in anatomical teaching hours within modern curricula (Turney, 2007). The undergraduate medical curriculum, in particular, has significantly reduced anatomical teaching (Gogalniceanu et al., 2009). In the United Kingdom (UK), this reduction followed the publication of the Tomorrow's Doctors policy by the General Medical Council (GMC, 2009), which emphasized the need for a transition of the medical curriculum toward the inclusion of more holistic and clinical content (Smith et al., 2016a). Similar curricular trends can be identified globally (Papa and Vaccarezza, 2013).

The use of human tissue within anatomical education has also significantly decreased in popularity (McMenamin et al., 2018). For instance, only a minority of UK medical schools still use cadaveric dissection as part of their anatomy teaching (Memon, 2018), and some have stopped using human tissue completely (Collett et al., 2009).

This, it is argued, has led to substantial concern about the decline in undergraduate medical students' knowledge of anatomy (Turney, 2007). Subsequently, the development of alternative pedagogic techniques that are time efficient and effective in teaching anatomy has been a focus of anatomical education research over the last decade (Finn, 2015). In particular, these alternative pedagogic techniques tend to be methods that focus on using active learning, which was first defined by an American educator Malcom Knowles as problem-centered learning that is driven by internal motivators, as opposed to memorization (Knowles et al., 2015; Inra et al., 2017). With the implementation of a problem-based learning curriculum widespread across modern medical schools, there is a demand for appropriate pedagogic techniques that can be incorporated into this format of teaching (Holen et al., 2015).

These alternative techniques for teaching anatomy can be broadly categorized into technologies such as virtual reality and mobile applications, three-dimensional (3D) models, such as 3D printing, and art-based approaches, such as body painting and clay-based modeling (Sugand et al., 2010). Although there is a plethora of literature describing the uses of these approaches, there have been few systematic reviews conducted on these alternative methods of anatomy teaching (Sugand et al., 2010). As a consequence of this, it is difficult at this stage to interpret which of these pedagogic strategies are effective and suitable for teaching different aspects of anatomy. This systematic review aims to address this limitation with the current literature, focusing on clay-based modeling.

Clay-based modeling (CBM) is an alternative method for teaching anatomy that is becoming increasingly popular (Kooloos et al., 2014). It was first documented as a method of teaching anatomy to medical students, specifically the central nervous system, in 1904 (Herring, 1904). Plasticine models were used by Fitzgerald et al. (1979) for teaching gross anatomical structures to medical students to address the reduction in dedicated anatomy teaching and availability of cadavers, highlighting the fact that these issues have been long-standing (Turney, 2007; Gogalniceanu et al., 2009). Within the last decade, clay-based modeling has continued to be used for teaching multiple anatomical regions, including the upper respiratory tract and the musculoskeletal system (Skinder-Meredith, 2010; Naug et al., 2011). These innovative models are typically composed of clay, clay-based materials such as Play-Doh and plasticine, or a combination of these (Bareither et al., 2013; Akle et al., 2018). They can be made entirely out of clay-based materials or use other materials such as plastic as a foundation upon which clay-based materials can be incorporated. Figure 1 displays an example of clay-based modeling used by the authors for teaching the anatomy of the basal ganglia to medical and Physician Associate students.

The continued popularity of CBM may be due to the advantageous physical properties of clay-based materials which enable the production of 3D malleable models (Akle et al., 2018). These models can be used for the visualization of 3D anatomy and can also be adapted to produce anatomical and embryological cross-sections (Oh et al., 2009; Endres Howell and Endres Howell, 2010), introduce pathology (Eftekhar et al., 2005; Manners et al., 2017), and replicate surgical approaches (Asp et al., 2013). This is a unique feature of CBM that cannot be easily replicated by other 3D models that are typically made out of non-malleable, inflexible, or permanent materials such as plastic. Additional advantages of the clay-based materials include their ease of accessibility and low cost (Akle et al., 2018).

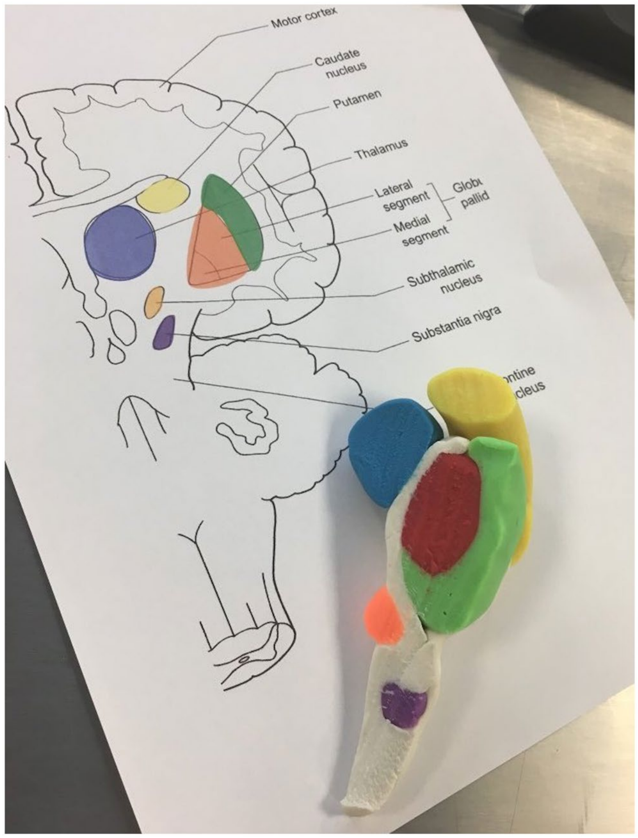

Figure 1.

An example of clay-based modeling used by the authors for teaching the basal ganglia to medical and physician associate students.

Another benefit of CBM, which has promoted its use in general and art education for some time, is that it provides the benefit of providing tactile discernment (Hill, 1988). Mayer's cognitive model of multimedia learning explains the link between clay exercises and the cognitive aspect of learning and performance (Hill, 1988; Wilson, 2015). This model explains information processing, based upon the assumption that visual and auditory processing occurs separately yet simultaneously to a learner with limited capacity (Wilson, 2015). Haptic feedback is provided to students when the models are made and adds another channel for information processing (Hill, 1988; Wilson, 2015).

Constructivist learning theories explain the benefits of CBM. A key concept behind these theories is that learning is constructed, with learners building upon previous knowledge (Fosnot and Perry, 2005). By introducing the appreciation of pathology to normal anatomical structures (Eftekhar et al., 2005; Manners et al., 2017) and creating cross-sections (Oh et al., 2009; Endres Howell and Endres Howell, 2010), clay is a creative medium that easily allows learners to progress their knowledge. Constructivist theories also suggest that learning is an active process, as information can be passively received but understanding relies on connections to be made through active engagement (Fosnot and Perry, 2005; Schunk, 2019). Clay-based modeling requires learners to build and manipulate the models and therefore directly employs the active learning process. Learning can occur in groups using CBM (Herur et al., 2011; Bareither et al., 2013) which aligns with the constructivist perspective of learning as a social activity (Schunk, 2019).

Furthermore, Kolb's Experiential Learning Cycle describes how learning is provided by new experiences through a four-stage cycle (Kolb, 1984). This cycle is relevant to CBM as it explains how learners can make links between theory (knowledge) and practice (experience), starting with an understanding of a gross anatomical structure which can be built upon through the process of making an anatomical model and adapting it, allowing learners to reflect how this experience links to theory (Kolb, 1984).

This systematic review aimed to summarize and appraise the available research on the uses, advantages, and limitations of CBM to teach human gross anatomy to students or qualified healthcare professionals. Subset analysis, including exploration of the relationship that sex, knowledge retention, curriculum design, and student self-selected learning preferences have with CBM at an aggregate level, was recorded and analyzed. This analysis provided further information on the suitability of the CBM within healthcare professional education providers, including medical schools and universities with heterogeneous curricula, assessment methods (Devine et al., 2015), and student populations (Kumwenda et al., 2017).

MATERIALS AND METHODS

Search Strategy

The protocol for this review was registered in PROSPERO, an international database of systematic reviews (Centre for Reviews and Dissemination, University of York, York, UK; registration number CRD42019134170). Following this, an electronic literature search of Embase® (Ovid Technologies, Inc., New York, NY), MEDLINE (United States National Library of Medicine, Bethesda, MD), Scopus (Elsevier, Amsterdam, The Netherlands), and Web of Science (Clarivate Analytics, Philadelphia, PA), employing a search strategy derived from Medical Subject Headings (MeSH) terms, was performed on 4th September 2019. The search strategies used are listed in the Supporting Information Appendix 1. The findings of this search are displayed in the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) flow-chart, seen in Figure 2 (Moher et al., 2009).

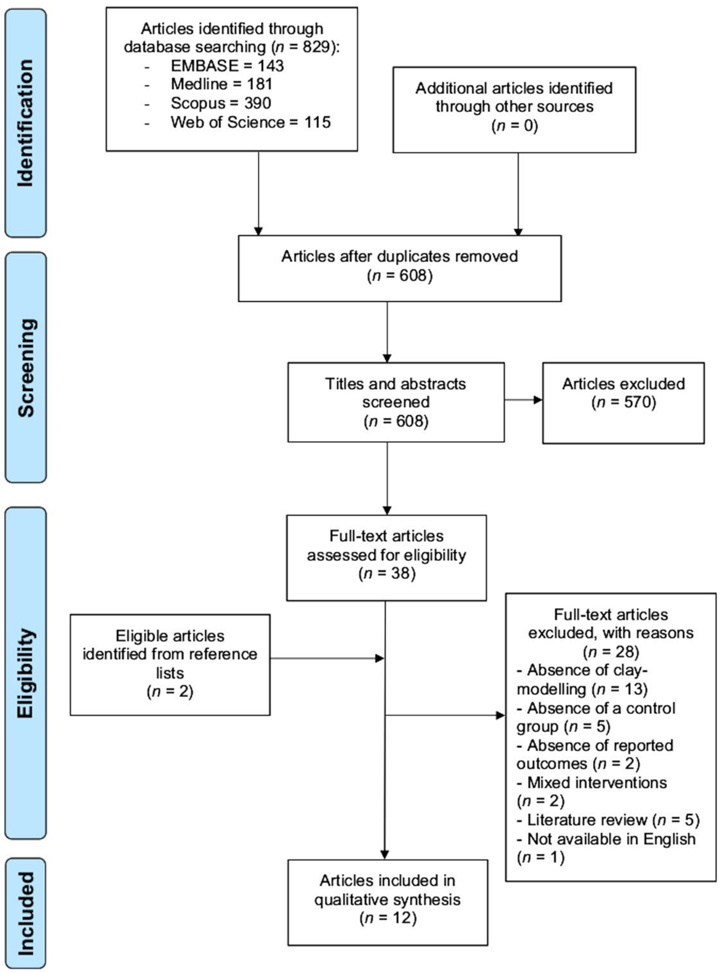

Figure 2.

A diagram of the article selection process shown in the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) flow diagram (Moher et al., 2009).

Screening of Citations and Full-Text Articles

The search identified 829 articles. Following the removal of duplicates, 608 articles were left for review. These first underwent title and abstract review for relevance, which left 38 articles for full-text review. To be eligible for this systematic review, the articles had to include and describe the following: the use of CBM; the advantages of CBM; and the limitations of CBM for teaching students or qualified healthcare professionals. All studies had to have a control group that utilized a different method of teaching anatomy for comparison to be included. Citations and full-text screening were comprehensively reviewed by two independent reviewers (K.C., M.P.), with a third reviewer (K.S.) resolving any discrepancies to ensure a consensus was met. Lateral searching of included articles was performed, and reference lists were screened for potentially relevant citations by the two independent reviewers (K.C., M.P.).

Quality Appraisal and Data Extraction

Study quality was assessed using the Medical Education Research Quality Instrument (MERSQI) for quantitative studies, which is a validated tool widely used in education research (Cook and Reed, 2015). This quality assessment tool comprises six domains: "study design," "sampling," "type of data," "validity of evaluation instrument," "data analysis," and "outcomes." The minimum score within five of the domains is = 1, and the maximum score across all domains is = 3. Accordingly, MERSQI scores range from 5 to 18. The MERSQI scale is based on Kirkpatrick's hierarchy of levels (Sullivan, 2011). This conceptual framework consists of four points and is used to characterize levels of outcome in educational interventions (Sullivan, 2011). Higher scores in the six domains of the MERSQI scale map onto higher levels of outcomes according to Kirkpatrick's hierarchy of levels (Sullivan, 2011).

To achieve the highest MERSQI scores, studies would exhibit the following qualities: Randomized control trials sampling three institutions or more with a response rate greater than 75% that measure outcomes through objective data would score maximum points from study design, sampling, and type of data domains of the MERSQI scale (Cook and Reed, 2015). The evaluation instrument for the study would be valid with internal structure, content, and relationships to other variables reported (Cook and Reed, 2015). The highest scoring studies would perform appropriate data analysis for the study design that go beyond descriptive statistics and have outcomes that map onto patient care (Cook and Reed, 2015).

Comparatively, a single group cross-sectional study sampling a single institution with a response rate of less than 50% that measures outcomes through assessment by participants would score minimum points from study design, sampling, and type of data sections of the MERSQI scale (Cook and Reed, 2015). If the evaluation instrument was not valid, through a lack of reported clarity, the study would score minimum points (Cook and Reed, 2015). The lowest scoring studies would perform inappropriate data analysis that is limited to descriptive statistics and that map onto participant-reported measures such as satisfaction and perceptions (Cook and Reed, 2015).

For data extraction, the following data items were extracted from the included studies: study design, population information (country, sample size, average age and sex of participants), anatomical region studied, intervention, control, and conclusions.

Two independent reviewers (K.C., B.L.) extracted these data and performed MERSQI scoring. Discrepancies were resolved by a third reviewer (K.S.).

Narrative Synthesis

Only aggregate-level data were analyzed. A narrative synthesis was followed in the discussion for all studies that meet the eligibility criteria. This included an investigation into the similarities and differences between the results of different studies and an exploration of the patterns in the data. The four major steps in conducting a narrative synthesis as defined by the Cochrane Consumers and Communication Review Group (Ryan, 2013) were followed, namely: (1) Developing a theory of how the intervention works, why, and for whom; (2) Developing a preliminary synthesis of the findings of included studies; (3) Exploring relationships in the data within and between studies; and (4) Assessing the robustness of the synthesis.

RESULTS

The article selection process is outlined in Figure 2. Of the 38 articles that underwent full-text review, 28 were excluded for the reasons documented in Figure 2. This resulted in 10 articles that met the inclusion criteria and were suitable for inclusion in this review. Two additional papers were identified as eligible for inclusion following a screen of the reference lists of the 38 papers that underwent full-text review. This ultimately left 12 articles that were critically examined within this systematic review.

Study Characteristics

The characteristics of the included studies are described in the Supporting Information Appendix 2. The studies included utilized heterogeneous study designs and a variety of interventions making a comparison between the studies challenging. Of the 12 studies included, six were non-randomized controlled trials, which introduce uncertainty regarding their reliability. Confounding bias may be present in these studies. The heterogeneous study designs meant that some did not clarify or quantify the additional teaching and assessment received by the control group alongside CBM. Therefore, there may be a spurious association between CBM and improved knowledge. From the remaining studies, four were prospective cohort studies and two were randomized controlled trials.

The range of countries in which the studies were undertaken demonstrates that CBM can be used in different educational settings with a diverse range of resources. Although the majority (n = 11) of studies were conducted within the United States (US), these were conducted in a variety of educational institutions including community colleges and medical schools. There was one study each identified from Colombia, the Netherlands, India, and Korea.

Clay-based modeling was mostly used as a teaching tool for medical or healthcare professional students. All but one study (n = 11) investigated the population of undergraduate students or postgraduate students. The other study investigated a population of practicing healthcare professionals (obstetrics and gynecology residents).

Clay-based modeling was used for teaching all major anatomical regions and systems. Although the studies often considered more than one system (see Supporting Information Appendix 2); the musculoskeletal system (n = 7) and the nervous system (n = 5) were the most popular systems studied. Specifically, the periventricular system was a recurring concept that was taught using the CBM within neuroanatomy (n = 3).

Eleven of the twelve included studies demonstrated objective improvement measured by assessment results in those who used CBM, compared to alternative methods of learning anatomy that included models, textbooks, dissection, and lectures. Only one study (Bareither et al., 2013) showed no difference in assessment scores between CBM and another active intervention, completing worksheets. Out of the eleven studies that showed an objective improvement, two demonstrated mixed results (Motoike et al., 2009; DeHoff et al., 2011).

Eight studies included student feedback into their results, with all emphasizing that students enjoyed CBM and found it useful. Other recurring advantages of CBM identified across all included studies include the active learning process that they utilize, the haptic feedback provided by the models, the incorporation of different colors, and the malleability of the clay-based materials.

It was highlighted in one study that students initially felt disengaged from CBM and viewed it as a distraction from other work due to their implicit connotations of clay-based materials being juvenile (Akle et al., 2018). Furthermore, other studies stated that students had difficulties with making the models, which may have resulted in them potentially having poor anatomical accuracy (Oh et al., 2009; Akle et al., 2018).

Regarding the suitability of CBM, the majority of included studies appear to suggest that it is only more effective than alternative methods in improving short-term knowledge. Six studies included both *short-* and *long-term* assessments into their study design but had differing definitions of what constituted short term and long term. Of these six, four provided evidence that there was an improvement in short-term knowledge only (Motoike et al., 2009; Oh et al., 2009; Estevez et al., 2010; Bareither et al., 2013). One study provided mixed evidence on knowledge retention associated with CBM in 33 medical doctors (Myers et al., 2001). The final study of the six that included both types of assessment into their study design suggested that long-term knowledge retention can be improved as a result of CBM, in a population of 100 medical students (Herur et al., 2011).

Only one study investigated the relationship that sex had with outcomes of CBM, meaning that no reasonable conclusions can be drawn on this relationship (Akle et al., 2018). Therefore, there are limited conclusions that can be made on the potential benefits that CBM can have on sex differences in anatomical education in this review, and this should be a focus for future studies.

Further, there was considerable heterogeneity in how these models were incorporated within the curricula. Some allowed for only a few hours for teaching (Oh et al., 2009; Estevez et al., 2010; Akle et al., 2018), whereas others used CBM longitudinally over a whole term (Bareither et al., 2013; Haspel et al., 2014). These approaches tended to depend on the amount of time allocated for CBM-based teaching used; those dedicating only a short amount of time required students to make the models independently with teaching subsequently taking place on the completed model, and those allowing for a considerably longer time required the modeling to be performed within the classroom and incorporated it directly as a teaching method.

Students self-declared their learning preferences by completing Visual, Auditory, Reading/Writing, Kinaesthetic (VARK) questionnaires in two of the studies, containing 101 medical students and 39 healthcare professional students respectively (Estevez et al., 2010; Bareither et al., 2013). Although this small number reduces confidence in the ability to make an appropriate conclusion, it appears that there is no difference in student self-declared learning preferences and their results on knowledge assessments when using CBM.

Some studies used animal dissection for teaching human anatomy in their control groups (Waters et al., 2005; Motoike et al., 2009; DeHoff et al., 2011; Waters et al., 2011; Haspel et al., 2014). These studies were conducted in community colleges, where the practical difficulties and expense of using human tissue likely limited the use of cadavers. The inclusion of these studies is useful, as it allows for the exploration of the suitability of CBM in environments with economic barriers, and for comparisons to be made with alternative strategies for teaching anatomy that aim to be cost efficient and effective.

The MERSQI scores for all 12 studies are displayed in Table 1. The mean total MERSQI score was 11.50 (±SD) = 1.04, range = (10.5-13.5). The study with the highest MERSQI score was a randomized controlled trial showing that color-coded clay models of the periventricular system compared to two-dimensional (2D) slices of preserved human brain tissue improved knowledge and satisfaction with neuroanatomy (Estevez et al., 2010). This study earned the highest score as it was a randomized controlled study, had a high number of participants (n = 101) that followed through with the study until completion, and utilized an evaluation instrument that had good validity, with the authors performing appropriate reliability and factor analysis to determine its validity (Estevez et al., 2010). However, the outcomes were limited to the level of knowledge and skills, and only one institution was studied which impeded a higher overall score (Estevez et al., 2010).

There were four studies with a shared lowest MERSQI score. These were non-randomized studies that scored low for sampling, studying only one institution and not reporting their response rate (Waters et al., 2005; Motoike et al., 2009; DeHoff et al., 2011; Haspel et al., 2014). Furthermore, all four studies used evaluation instruments that were not validated (Waters et al., 2005; Motoike et al., 2009; DeHoff et al., 2011; Haspel et al., 2014).

DISCUSSION

A narrative synthesis of these twelve articles based upon the steps outlined by the Cochrane Consumers and Communication Review Group follows.

The literature demonstrates that CBM can be used for teaching all major anatomical regions and systems including the integument, nervous, musculoskeletal, cardiorespiratory, gastrointestinal, urinary, and reproductive systems. The uses of CBM will first be explored to provide context on the extent of its use as a teaching tool for gross anatomy. Subsequently, to allow for sufficient breakdown of the advantages of CBM, these will be split into the objective and subjective results. The limitations of CBM will then be analyzed before the suitability of teaching anatomy using CBM is discussed.

Use of Clay-Based Modeling

Clay-based modeling can be used for teaching all major gross anatomical regions due to the intrinsic properties of

Table 1.

Medical Education Research Study Quality Instrument (MERSQI) Scores for the Included Studies, with a Breakdown of Domain Scores and the Total Score for Each Study

		Domain Score						
Study	Country	Study Design	Sampling	Type of Data	Validity of Evaluation Instrument	Data Analysis	Outcomes	Total Score
Akle et al. (2018)	Columbia	2	1.5	3	2	3	1.5	13
Bareither et al. (2013)	US	2	1.5	3	0	3	1.5	11
DeHoff et al. (2011)	US	2	1	3	0	3	1.5	10.5
Estevez et al., 2010	US	3	2	3	1	3	1.5	13.5
Haspel et al. (2014)	US	2	1	3	0	3	1.5	10.5
Herur et al. (2011)	India	3	1	3	0	3	1.5	11.5
Kooloos et al. (2014)	The Netherlands	2	1	3	1	3	1.5	11.5
Motoike et al. (2009)	US	2	1	3	0	3	1.5	10.5
Myers et al. (2001)	US	2	2.5	3	1	3	1.5	13
Oh et al. (2009)	South Korea	2	1.5	3	0	3	1.5	11
Waters et al. (2005)	US	2	1	3	0	3	1.5	10.5
Waters et al. (2011)	US	2	1	3	1	3	1.5	11.5

The MERSQI is a quality appraisal tool widely used in education research (see Cook and Reed, 2015). The minimum score within five of the domains is = 1, and the maximum score across all domains is = 3. Accordingly, MERSQI scores range from 5 to 18. Two independent reviewers (K.C., B.L.) extracted these data and performed MERSQI scoring. Discrepancies were resolved by a third reviewer (K.S.) to ensure a consensus was met. US, United States of America.

clay-based materials, namely the malleability, adaptability, and the range of colors available. These properties allow for modeling and subsequent cross-sectional anatomy to be explored. Anatomical models made from clay can be easily and accurately sectioned to display internal structures, such as the internal structures of the brain and basal ganglia demonstrated in the study conducted by Oh et al. (2009). This aspect of CBM is particularly important for medical students for the understanding and interpretation of CT and MRI scans (Oh et al., 2009). Despite being an important skill for a graduating doctor, many medical students feel unprepared for interpreting scans (Wentzell et al., 2018). To address this, it has been suggested that radiology can be taught alongside anatomy due to the close relationship these topics share (Caswell et al., 2015). Clay-based models are a unique pedagogic tool as they can be sectioned at any point and easily rebuilt due to their malleability to allow for a deeper understanding of cross-sectional anatomy.

The range of different colors of clay-based materials allows for students to make components within their models distinguishable. The ability to make structures discernible due to contrasting colors favors the creation of models of varying complexity, delineating the variety of anatomical regions taught using CBM. Furthermore, given that color may aid memory, this property of the clay-based materials may partially explain the improvement in student performance seen in 11 studies within this review (Finn and McLachlan, 2010).

The intrinsic properties of clay-based materials allow for different anatomical regions to be created, yet it is noteworthy that musculoskeletal anatomy and neuroanatomy were the most popular topics investigated. Neuroanatomy may be particularly suitable for teaching using CBM due to "neurophobia" stemming from the reported difficulty students have with understanding and enjoying neuroanatomy (Javaid et al., 2018). The brain is also time consuming and challenging to dissect, meaning that human tissue may not be the most appropriate method to use when teaching neuroanatomy (Akle et al., 2018). The included studies that mentioned exact times for making clay-based models of the brain suggested that they took on average between three to five hours, which is less than the time required for a novice to dissect this region (Oh et al., 2009; Akle et al., 2018). Thus, clay-based modeling allows for the creation of 3D structures that are otherwise difficult to visualize in human tissue, such as the periventricular system.

Musculoskeletal anatomy has traditionally been taught using human tissue, although, with the modern shift toward alternative pedagogic techniques, body painting and CBM have been recognized as useful teaching methods. A Delphi panel developed a core syllabus for musculoskeletal anatomy for medical students and highlighted that knowledge of the majority of muscles is compulsory however only to the level required to understand their function (Webb et al., 2018), a view reinforced by the Anatomical Society core regional anatomy syllabus (Smith et al., 2016a). Clay-based modeling allows this knowledge to be achieved at the appropriate level by concentrating on only the vital knowledge required subsequently allowing students to build upon this through the use of other pedagogic approaches. As its efficacy in active learning of musculoskeletal anatomy has been demonstrated to be as good as other active learning resources (Bareither et al., 2013), clay-based modeling should particularly be considered for teaching this aspect of anatomy.

Objective Results

Clay-based modeling was found to improve assessment scores in all but one of the studies included in this review. This highlights that it is a valuable pedagogic tool that all anatomy educators should consider implementing into their teaching.

The improvement in objective results may be attributable to CBM reducing cognitive load. Cognitive overload occurs when learning is significantly impaired by the presence of multiple "drains" on the cognitive resources of the student (Wilson, 2015). Clay-based modeling creates anatomically simple models, which allows for students to understand and process information more easily and removes additional stimuli and unwanted anatomical detail that may be present on other 3D models, therefore preventing cognitive overload (Wilson, 2015). This *less is more* approach with CBM permits students to link pre-knowledge with new information and bring it all together, thus yielding more productive learning (van Merriënboer and Sweller, 2010). It has been argued by van Merriënboer and Sweller (2010) that decreasing the demand posed by both the learning environment and content may result in improved learning outcomes and therefore improved short-term learning. Consequently, the apparent limitation of CBM lacking anatomical detail should rather be perceived as a positive, especially when involving inexperienced learners.

In addition to its simplicity, CBM may achieve its success by making use of the sense of touch. Clay-based modeling models provide haptic feedback when being made and used by the students; and this feedback adds another channel for information processing. Haptic feedback has been demonstrated to improve surgeon performance and decrease cognitive loading in laparoscopic surgical trainers (Zhou et al., 2012), and it may explain the particular improvement in 3D understanding when participating in CBM as opposed to watching a video of the activity (Kooloos et al., 2014).

Active learning is an engaging process that focuses on problem-solving through emphasizing student responsibility and direct participation in the learning process (Michael, 2006; Deslauriers et al., 2019). By requiring students to make the anatomical structures themselves, manipulate them, or place them on plastic apparatus, CBM is an active learning tool (Deslauriers et al., 2019). There are other alternative pedagogic approaches used for teaching anatomy that are based upon active learning, most notably body painting, and so this is not a unique feature of CBM (Finn, 2015). Moreover, there is no literature available that compares the efficacy of active approaches to teaching anatomy, let alone the efficacy of active learning approaches to learning specific anatomical regions. Such studies would be useful to address whether particular active learning approaches are more suited to certain anatomical regions. This would provide useful clarification for the two papers with mixed results within this review. These studies suggested that CBM is superior to dissection only for specific anatomical regions and in certain assessments, such as the identification of muscles in human models (Motoike et al., 2009) and written questions regarding the peripheral nervous system (DeHoff et al., 2011).

This is particularly important as Bareither et al. (2013) showed that there was no difference in outcomes between another active learning approach, completing worksheets in groups, and CBM. Therefore, the literature may contain spurious conclusions advocating the use of CBM. Poor study designs may have resulted in investigators measuring the effect of active learning (CBM) against a passive traditional format. As there is widespread evidence to the effect that active learning is superior to passive learning, this is unsurprising and may suggest that the benefits of CBM are solely due to it using an active learning approach (Michael, 2006; Inra et al., 2017). Furthermore, it is unclear whether the overwhelming objective improvement in student performance is actually due to CBM, or the additional teaching and assessment that the students received alongside the intervention in some of the studies (Herur et al., 2011; Bareither et al., 2013). These supplementary learning opportunities were not typically quantified or described in great detail, and, as they were often based around the clay-based models, were not available for the control groups. The MERSQI scores for these papers were 11 and 11.5 respectively. Although relatively low when considering MERSQI scores are out of 18, they were equivalent to the mean MERSQI score across all papers of 11.5. Additionally, assessment drives learning and provides students the occasion to acknowledge gaps within their knowledge and focus their future learning (Wormald et al., 2009). Therefore, these supplementary learning opportunities may be acting as a confounder in improving students' knowledge. The studies included in this review incorporated different assessments (such as multiple-choice and single-best-answer questions, and practical assessments) and at different times (such as immediately after CBM or at the end of term). This is expanded upon in the Supporting Information Appendix 2.

Clay-based modeling is still an active-learning approach that has proven benefits and is rated higher by students than alternative active learning techniques (Waters et al., 2005; DeHoff et al., 2011; Haspel et al., 2014; Akle et al., 2018). The possibility that CBM is not the direct cause of the improved outcomes does not matter, as it provides an opportunity for educators to incorporate different teaching and assessment methods that students enjoy. The associated benefits of CBM still arise from implementing it as a teaching method, although whether it is directly due to the process remains to be determined.

Subjective Results

Clay-based modeling was rated highly from students in all studies that included subjective assessment, suggesting that the benefits of the pedagogic tool go beyond improving exam performance.

As well as being an active learning approach that engages students, CBM shares advantages with other art-based approaches, which explains the overwhelmingly positive feedback provided by students. Firstly, it promotes a positive learning environment by being a "non-traditional" learning activity that encourages communication between students (Akle et al., 2018). Secondly, students view the activity as fun (DeHoff et al., 2011). This may be because, like body painting, clay-based modeling offers the opportunity for students to engage in respite from traditionally passive learning methods, such as lectures and textbooks (Finn, 2015). Thirdly, it is a useful alternative to human tissue. The majority of students do not have significant negative experiences when encountering cadaveric material, yet there remain some students who struggle with working with human tissue and the notion of death (Sándor et al., 2015). Clay-based modeling may be more beneficial to these students who may not engage as much with human tissue.

Only one study documented the subjective results from faculty on CBM (Haspel et al., 2014). Accordingly, it is difficult to determine how generalizable these findings are, yet the large number of faculty surveyed ($n = 26$) from a single institution assert that the activity is useful and a positive learning experience for their students (Haspel et al., 2014).

Limitations of Clay-Based Modeling

A theme highlighted within the only study in this review that included a focus group was that some students felt disengaged from CBM when first introduced to the activity (Akle et al., 2018). Clay-based materials were viewed as juvenile and associated with "kindergarten", leading some students to express feelings that the activity was patronizing (Akle et al., 2018). Increased student satisfaction has been shown to improve student's motivation to learn (Eagleton, 2015). Therefore, as students did not initially rate the activity highly, it is unsurprising that many felt that the activity was inappropriate and taking away from other learning opportunities (Akle et al., 2018).

Despite the initial negative feelings about CBM, students do overwhelmingly enjoy the activity and find it useful to their learning. Nevertheless, some students may be disengaged throughout the activity due to poor artistic ability and thus struggle to find the benefits in the task (Oh et al., 2009). As individual learners, students will naturally have variation within their artistic ability, and some may regard the activity as a major challenge (Newton and Miah, 2017). Although anatomical accuracy is important, the objective of CBM is not to directly replicate human anatomy, with the emphasis rather on the actual process of making the models and understanding spatial relationships. Therefore, students should not be discouraged if they are not artistically talented.

Suitability

The study conducted by Akle et al. (2018) was the only study that investigated the relationship between sex and performance in students who used CBM. The authors investigated the use of CBM compared to 2D images and preserved brain sections for teaching periventricular anatomy in a population of 151 medical students. The authors found that in the students who used CBM there were significantly higher scores in knowledge assessments and student satisfaction ($P < 0.0001$) (Akle et al., 2018). This study obtained a MERSQI score of 13, the highest score of all studies included in this review suggesting that the study findings are likely to be representative of the wider literature.

Although no valid conclusion can be made due to only one study investigating this variable, it would appear that no relationship exists between sex and performance after using CBM. The authors' findings reinforced common gender stereotypes with females rating their spatial ability lower, yet the authors found no actual difference existed. Indeed, it is ambiguous whether males do have a better spatial ability than females (Akle et al., 2018). This result does, however, draw attention to the common phenomenon of imposter syndrome, which is particularly present in females (Villwock et al., 2016). If females are less confident in their ability, they may perform worse, reflecting a negative view of their ability, which is a significant problem (Akle et al., 2018). Deslauriers et al. (2019) found that while active engagement in class leads to reduced confidence in learning, actual learning increases. As CBM uses active engagement, this may in part account for the lack of confidence in females.

The time frames used for assessing short- and long-term knowledge varied considerably between studies, likely due to the lack of a clear definition of these terms within the wider literature (Cowan, 2008). Although determining cut-offs for these terms is arduous, it would appear that CBM is only as effective as traditional methods in retaining knowledge over months or terms. Only two studies showed a significant difference between CBM and control over a period of 30 days and 8 weeks respectively, which may be defined as medium-term knowledge (Myers et al., 2001; Herur et al., 2011). The other papers that investigated long-term knowledge found that over months and terms, there was no significant difference (Myers et al., 2001; Motoike et al., 2009; Oh et al., 2009; Estevez et al., 2010; Herur et al., 2011; Bareither et al., 2013). This would imply that in terms of knowledge retention, CBM is only as useful as traditional didactic approaches. It could also be argued that CBM provides a useful learning "stepping-stone" that enables students to engage with content and thus learn it faster, but other active learning methods also effectively teach the content albeit in a slower fashion.

The considerable variability in how CBM can be incorporated into the curriculum and how it may be used further demonstrates the diversity of CBM, another advantage of this teaching method. Clay-based modeling offers a dry-laboratory alternative to teaching with human tissue and can be used in any setting. Most of the studies used CBM in small groups and all used it away from human tissue in a classroom setting. As it is fundamentally an active-learning approach, it is suitable for inclusion within a PBL curriculum, but it could be used within a traditional curriculum to provide respite from lectures.

When considering overall suitability, the range of countries that the studies were conducted in should be acknowledged. Some, such as Colombia and India, have significant economic barriers and poor access to human tissue (Herur et al., 2011; Akle et al., 2018). Also, while the majority of studies were conducted in institutions within the United States, some were conducted within community colleges (Waters et al., 2005; Motoike et al., 2009; DeHoff et al., 2011; Waters et al., 2011; Haspel et al., 2014) which may also have significant economic barriers and poor access to human tissue. Overall, the low cost and ease of accessibility of these materials are another benefit of CBM, which is a suitable pedagogic tool for a variety of institutions with different resources (Akle et al., 2018).

Implications for Anatomy Teaching

This systematic review provides sufficient evidence to suggest that CBM is a useful adjunct for teaching human gross anatomy to students or qualified healthcare professionals. The limitations with this review and the studies analyzed should be made clear to anatomy educators before they incorporate CBM into their teaching toolkit. These findings may not translate to other student populations such as postgraduates, including medical students within the United States, who may favor deep and strategic learning approaches that may not be fully compatible with CBM (Samarakoon et al., 2013). Only one study in this review explicitly focused on postgraduate medical students, and although the results correlated with the other findings, further work should seek to clarify the efficacy of CBM in postgraduate students (Estevez et al., 2010).

Alternative pedagogic techniques do not seek to take away from methods of teaching that use human tissue. Clay-based modeling could not replace human tissue as it lacks the anatomical detail that is required. However, it is a useful tool to use alongside human tissue, particularly to improve 3D understanding and student satisfaction with difficult anatomical concepts. Clay-based modeling may be more suitable for Physician Associates, nursing students, and other healthcare professionals who do not require as in-depth a level of anatomical knowledge as compared to medical students, and these populations should be used for future research (RCP, 2012; Smith et al., 2016b).

Limitations of the Review

The most significant limitation of this review was the heterogeneity of the studies included in the analysis. The differences in study designs, study settings, and particularly study methodology with dissimilar assessments, interventions, and populations meant that a meta-analysis could not be conducted. Consequently, a narrative synthesis was performed, which is dependent on author interpretation, and the analysis and interpretation of findings are both subjective and non-reproducible. In an attempt to mitigate this issue, Cochrane guidelines on conducting a narrative synthesis were followed rigorously (Ryan, 2013). However, there still exists the potential for bias to be present within this review.

There were notable limitations with the studies included within this review. The most significant of these is that the significant majority of studies scored 0 for the validity of evaluation instrument on MERSQI scoring. This means that the methods used for assessing knowledge after using CBM were often not based on experts, existing instruments, or guidelines, did not include reliability and factor analysis, and did not investigate relationships to other variables (such as predictive correlation with other variables) (Cook and Reed, 2015). Accordingly, the assessments used could have been highly biased or discriminated against either the control or intervention groups. This should be taken into account when contextualizing the conclusions of this review.

CONCLUSIONS

Clay-based modeling is one example of an art-based alternative pedagogic approach that can be used to teach all gross anatomy. Although most of the literature focuses on its use in teaching undergraduate healthcare professional students it can additionally be used for practicing healthcare professionals (Myers et al., 2001). Clay-based modeling has been demonstrated to improve short-term anatomical knowledge when compared to traditional passive learning approaches and is rated highly by students who have used it. These benefits are largely due to the properties of clay-based materials, in particular their malleability, adaptability, ability to provide haptic feedback, and the active learning approach.

With this review demonstrating that the many benefits of CBM significantly outweigh the limitations and that it can be used alongside human tissue to improve anatomical knowledge, the consideration should not be whether to implement CBM, but how best to incorporate it into the anatomists' toolkit. This is especially current, given that research in anatomical education is progressively focusing on incorporating technology into learning and simpler approaches for teaching anatomy like CBM may be overlooked (Clunie et al., 2018). The findings of this review can be used to determine how CBM can be incorporated into individual institutions' curricula, and for what anatomical regions, to access the many advantages of using CBM for teaching gross anatomy and therefore addressing the previous concerns of the standard of current anatomy teaching.

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