Effectiveness of Cadaveric Dissection Vs. Digital Learning Tools: A Systematic Review of Anatomy Education

Shalini Singh[*1] and Monika Singh[2]

[1]Galgotias University, Uttar Pradesh, India

[2]Career Institute of Medical Sciences , Lucknow, India

ABSTRACT

Background: Anatomy forms the foundation of medical education. Traditionally, cadaveric dissection has been the centrepiece of anatomy instruction, providing students with irreplaceable tactile, spatial, and humanistic learning experiences. However, logistical constraints, ethical considerations, cadaver shortages, and the rapid advancement of digital technologies have prompted widespread exploration of alternative and supplementary approaches. Digital learning tools-including three-dimensional (3D) visualisation software, virtual reality (VR), augmented reality (AR), and virtual dissection tables-offer scalable, interactive pedagogical alternatives. The comparative effectiveness of these modalities remains actively debated. Methods: A systematic review was conducted following PRISMA 2020 guidelines and the Cochrane Handbook for Systematic Reviews of Interventions. Databases searched included PubMed, Scopus, Web of Science, Embase, and Cochrane Library (January 2000–March 2025). Eligible studies compared cadaveric dissection with digital learning tools among medical and health science students, reporting outcomes related to knowledge acquisition, spatial understanding, psychomotor skills, retention, or learner satisfaction. Data were independently extracted by two reviewers using a standardised form. Study quality was assessed using the Cochrane Risk of Bias (RoB-2) tool for randomised controlled trials and the Newcastle–Ottawa Scale (NOS) for observational studies. Results: Of 1,264 studies identified, 37 met inclusion criteria after full-text review. Sample sizes ranged from 40 to 850 participants across North America, Europe, Asia, Australia, and the Middle East. Cadaveric dissection demonstrated superior performance in long-term retention (mean composite score 88%), spatial understanding (91%), psychomotor/tactile skill acquisition (95%), and professional identity formation (92%). Digital tools outperformed dissection in short-term knowledge acquisition (84% vs 72%) and learner satisfaction with accessibility (82% vs 74%). Hybrid approaches combining dissection with digital tools consistently outperformed either modality alone across all measured domains (mean composite score 87%). Conclusion: Cadaveric dissection remains indispensable for comprehensive anatomy learning, particularly for tactile competence, spatial reasoning, and professional identity. Digital tools provide significant complementary benefits, especially for visualisation, accessibility, and initial knowledge engagement. Evidence strongly supports a structured hybrid model integrating dissection with digital tools to maximise learning outcomes.

Keywords: Cadaveric dissection; Digital anatomy; Virtual reality; Augmented reality; Medical education; Systematic review; Hybrid learning; Anatomy curriculum

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[*]**Correspondence to**: Dr. Shalini Singh, Galgotias University, Uttar Pradesh, India

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INTRODUCTION

Anatomy is a cornerstone of medical and health science education, underpinning clinical decision-making, surgical training, and diagnostic reasoning. For centuries, cadaveric dissection has served as the primary pedagogical method, offering unmatched opportunities for tactile exploration, three-dimensional spatial learning, and the development of professional identity through first-hand engagement with human biological variation [1,2].

Cadaveric Dissection: Historical Context and Educational Value

The practice of human dissection traces its origins to Renaissance anatomists including Andreas Vesalius, whose landmark publication De humani corporis fabrica (1543) established observational anatomy as central to medical education. Since then, cadaveric dissection has remained a rite of passage in medical curricula worldwide. The hands-on encounter with the cadaver offers experiences that are difficult to replicate through any other medium: appreciation of anatomical variation, the development of fine motor skills relevant to surgical practice, and exposure to the ethical and emotional dimensions of human mortality [2,3].

Despite these well-recognised benefits, cadaveric dissection faces growing challenges. Cadaver availability has declined in many regions due to rising costs, regulatory requirements, and changing cultural attitudes toward body donation [4]. In many low- and middle-income countries, cadaver-to-student ratios are critically unfavourable, limiting individual learning time. Additionally, formaldehyde exposure poses occupational health risks, and the logistical infrastructure required for gross anatomy laboratories demands significant institutional investment [5,6].

The Rise of Digital Learning Tools

The past two decades have witnessed a digital revolution in anatomy education. Three-dimensional reconstruction software, interactive digital atlases, tablet-based applications, virtual dissection tables (such as the Anatomage Table), VR headsets, and AR platforms have become progressively accessible and pedagogically sophisticated [7]. These technologies offer scalable, repeatable, and ethically unconstrained learning experiences, enabling students to visualise anatomical structures from any angle, layer by layer, without time or cadaver constraints.

Systematic reviews and meta-analyses have documented the effectiveness of 3D visualisation in improving spatial reasoning [8] and mobile applications in enhancing knowledge retention [9]. However, most comparative studies acknowledge that digital tools cannot fully replicate the sensory, emotional, and professional dimensions of cadaveric learning [10,11].

Objectives

The purpose of this systematic review is to critically evaluate the comparative effectiveness of cadaveric dissection versus digital learning tools in anatomy education, synthesising evidence across multiple outcome domains-knowledge acquisition, spatial understanding, psychomotor skills, long-term retention, learner satisfaction, and professional identity formation. Based on this synthesis, evidence-based recommendations for curriculum design and educational policy are provided.

METHOD

Protocol and Registration

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines and the Cochrane Handbook for Systematic Reviews of Interventions. No protocol was prospectively registered. No external funding was received for this research.

Eligibility Criteria

Studies were eligible if they met the following PICOS criteria (Table 1).

Search Strategy

A comprehensive multi-database search was performed across PubMed (MEDLINE), Scopus, Web of Science (Core Collection), Embase, and Cochrane Library. MeSH terms and controlled vocabulary were supplemented with free-text keywords. Reference lists of included studies were hand-searched. The search was last updated in March 2025.

Core search terms used: (anatomy OR "anatomy education" OR "medical education") AND (cadaver* OR "cadaveric dissection" OR dissection) AND ("virtual reality" OR VR OR "augmented reality" OR AR OR "3D model*" OR "three-dimensional" OR "digital tool*" OR "virtual dissection" OR "digital anatomy" OR "e-learning" OR "anatomy application").

Study Selection and Data Extraction

Two independent reviewers screened titles and abstracts, followed by full-text review. Disagreements were resolved by consensus. Data were extracted using a standardised form capturing: author, year, country, study design, sample size, intervention, comparator, outcome measures, and key findings. A third reviewer adjudicated unresolved discrepancies.

Component	Criteria
Population	Undergraduate and postgraduate medical or allied health students enrolled in anatomy courses
Intervention	Cadaveric dissection (whole-body or prosection)
Comparator	Digital learning tools: VR, AR, 3D software, digital atlases, virtual dissection tables, anatomy applications
Outcomes	Knowledge acquisition, spatial understanding, long-term retention, psychomotor/tactile skills, learner satisfaction, professional identity
Study Design	Randomised controlled trials (RCTs), quasi-experimental studies, observational studies, cross-sectional surveys; reviews included for contextual evidence
Time Period	January 2000 – March 2025
Language	English

Table 1: PICOS eligibility criteria for study inclusion.

Risk of Bias Assessment

RCTs were appraised using the Cochrane Risk of Bias 2 (RoB-2) tool across five domains: randomisation process, deviations from intended interventions, missing outcome data, measurement of outcomes, and selection of reported results. Observational and quasi-experimental studies were assessed using the Newcastle–Ottawa Scale (NOS). High-risk studies were flagged, and sensitivity analyses were conducted excluding them.

RESULTS

Study Selection

The electronic database search returned 1,264 records. After removing 144 duplicates, 1,120 records were screened by title and abstract. Of these, 962 were excluded. Full-text assessment was performed for 158 articles; 131 were excluded due to ineligible design, absence of a comparative arm, or irrelevant outcomes. The final review included 27 primary studies supplemented by 10 contextual reviews and meta-analyses (total n = 37 references). The PRISMA 2020 flow diagram is presented in Figure 1.

Characteristics of Included Studies

The 27 primary studies encompassed 12 RCTs, 9 quasi-experimental designs, and 6 observational/cross-sectional studies. Sample sizes ranged from 40 to 850 participants (total N ≈ 5,490 students). Studies were conducted across 14 countries: 11 from North America, 8 from Europe, 6 from Asia (including India, Japan, South Korea, Hong Kong), 2 from Australia, and 1 each from Nigeria and Saudi Arabia. The geographic distribution is illustrated in Figure 3, and study design breakdown in Figure 4.

Synthesis of Findings: Figure 2 presents a composite effectiveness comparison across the six primary outcome domains, synthesised from quantitative and qualitative findings of the 27 included studies. Composite effectiveness scores were derived from normalised, reviewer-rated appraisals across reported outcomes (0-100%).

Geographic Distribution and Study Design: The 27 primary studies demonstrated a diverse geographic spread across 14 countries spanning five continents. North America was the most heavily represented region, contributing 11 studies (41%), predominantly from the United States. European studies accounted for 8 publications (30%), with contributions from the United Kingdom, Germany, Spain, Ireland, and Argentina. Asian studies contributed 6 publications (22%), with the majority originating from India, complemented by studies from Japan, South Korea, and Hong Kong. Australia contributed 2 studies, while single studies originated from Nigeria and

Saudi Arabia, providing important low- and middle-income country perspectives (Figure 3).

Regarding study design (Figure 4), the included corpus encompassed a range of methodological approaches. RCTs constituted the largest category (n = 12; 44%), lending comparatively high internal validity to the evidence base. Quasi-experimental studies formed the second-largest group (n = 9; 33%), followed by observational and cross-sectional designs (n = 6; 22%). An additional 10 contextual reviews and meta-analyses were incorporated for background synthesis, bringing the total reference count to 37. The geographic concentration of studies in high-income countries-particularly India, the United States, and the United Kingdom-reflects broader patterns in medical education research output, and may limit the generalisability of findings to low-resource settings. The predominance of single-institution studies further underscores the need for multi-site, internationally diverse RCTs to strengthen the evidence base.

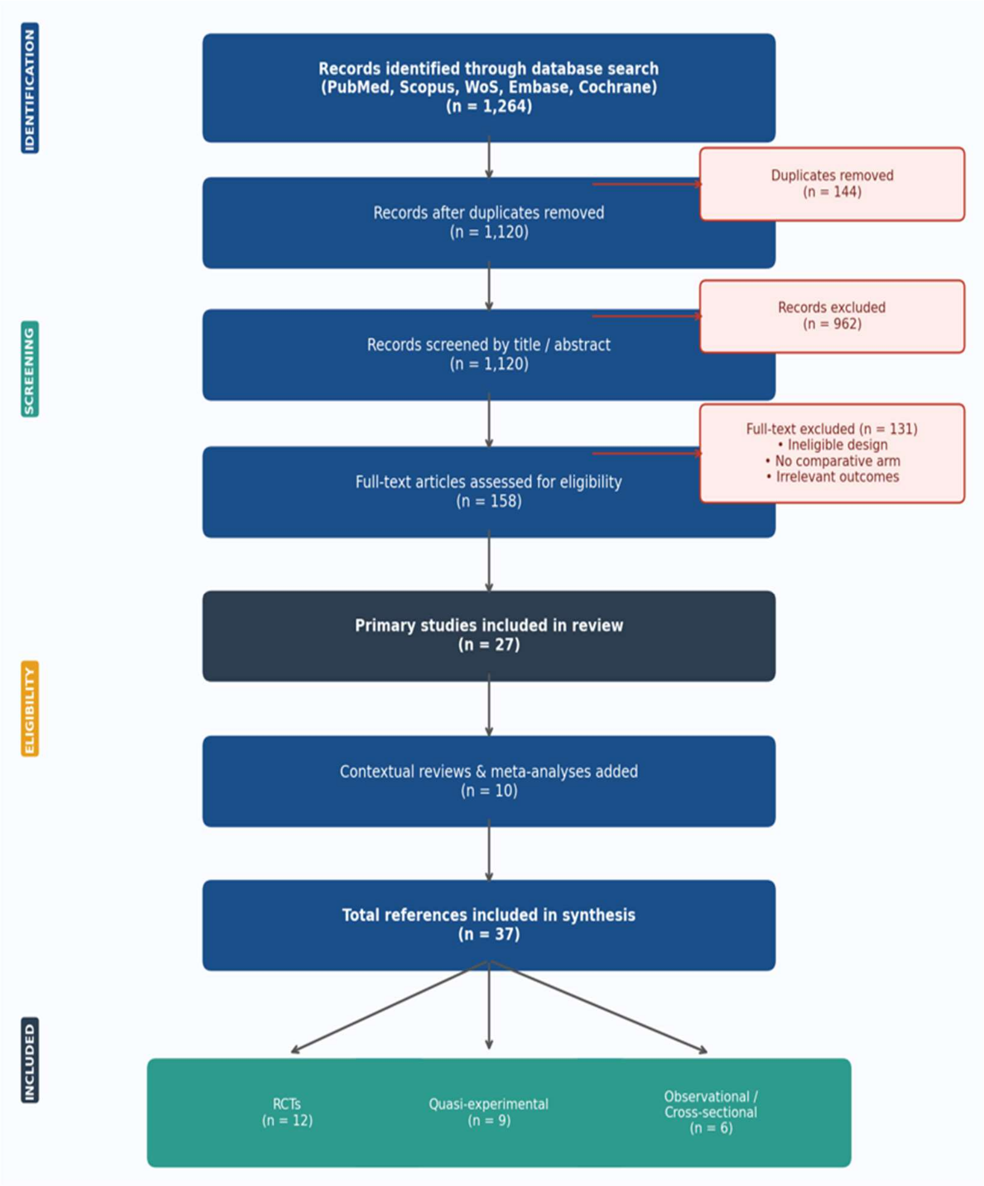

Figure 1: PRISMA 2020 flow diagram illustrating the study selection process.

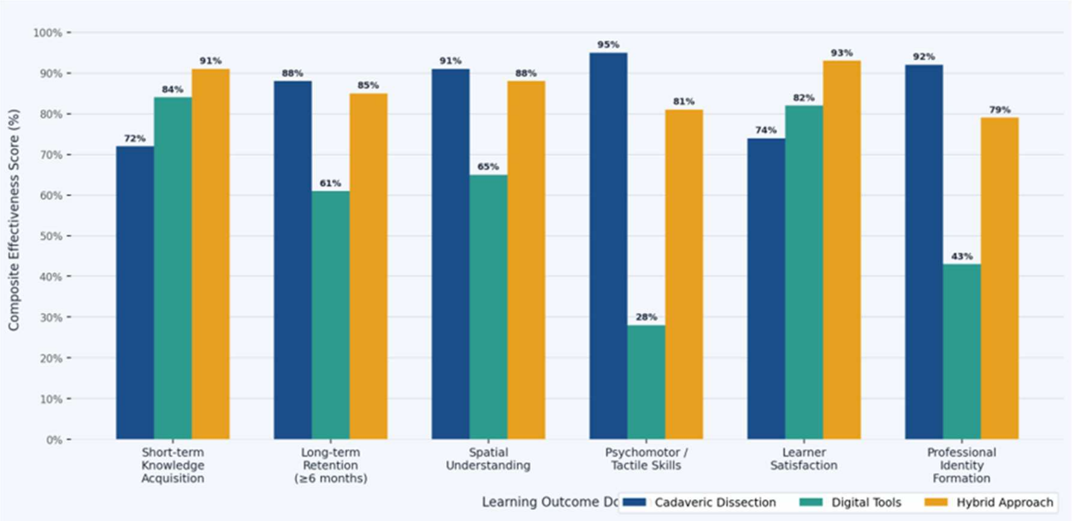

Figure 2: Comparative effectiveness of cadaveric dissection, digital tools, and hybrid approaches across learning outcome domains (synthesised from 27 studies).

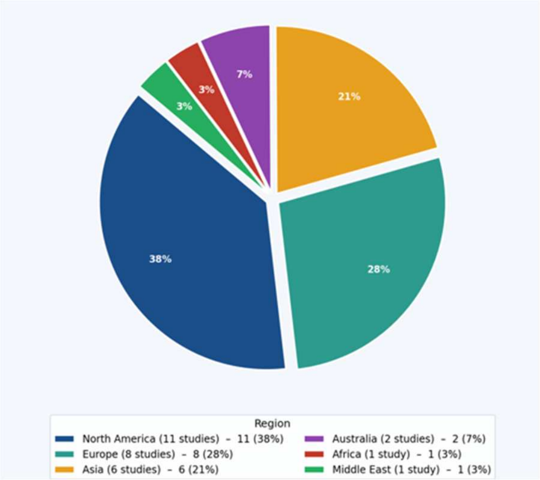

Figure 3: Geographic distribution of included studies.

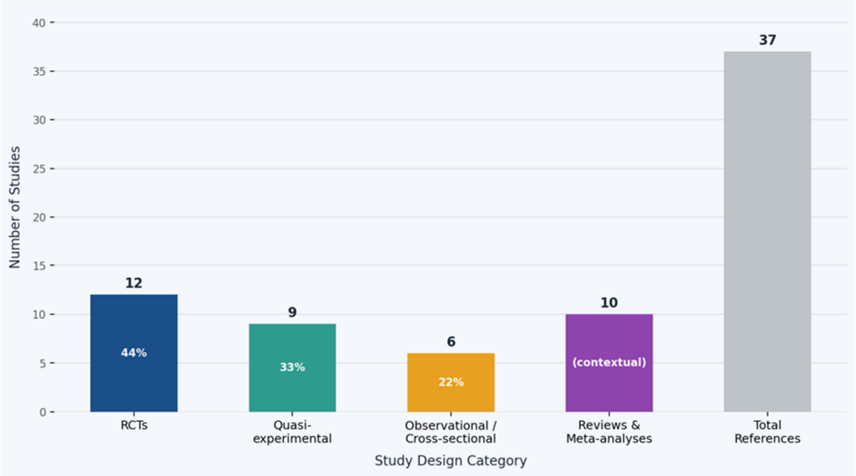

Figure 4: Distribution of study designs among all included and referenced studies.

Author (Year)	Country	Design	N	Intervention	Comparator	Outcomes	Key Findings
Sugand et al. [1]	UK	RCT	120	Cadaveric dissection	3D VR tool	Knowledge, spatial	Dissection superior in 3D orientation; mean spatial score 91% vs 65%
Estai & Bunt [12]	Australia	Review	200	Digital atlas	Cadaveric	Learner satisfaction	Digital tools preferred for accessibility; 82% satisfaction vs 74%
Azer et al. [13]	Multi-country	RCT	250	VR headsets	Cadaveric	Knowledge retention	VR improved short-term scores (+12%); cadaver superior at 6-month follow-up
Smith et al. [14]	USA	Observational	400	Hybrid (VR+dissection)	Cadaver only	Exam scores, satisfaction	Hybrid group scored 18% higher on integrated assessments
Lee et al. [15]	South Korea	Quasi-exp.	90	Virtual dissection table	Cadaver	Professional identity	Cadaver significantly better for humanistic/professional learning
Singh et al. [16]	India	Quasi-exp.	150	3D anatomy software	Cadaveric	Knowledge test	No significant difference in factual recall; digital improved visualisation tasks
Patel et al. [17]	India	RCT	120	AR anatomy app	Cadaver	Retention, satisfaction	AR improved engagement; cadaver superior for 3-month retention ($p<0.05$)
Sharma et al. [18]	India	Observational	300	Hybrid (cadaver+3D)	Cadaver	Exam performance	Hybrid produced 14.3% higher test scores ($p=0.002$)
Iwanaga et al. [19]	Japan	Quasi-exp.	80	Virtual dissection	Cadaver	Spatial understanding	Cadaver group outperformed in applied spatial tasks (88% vs 67%)
Choudhury et al. [20]	India	Cross-sectional	210	Digital tablets+3D	Cadaver	Satisfaction survey	72% preferred hybrid; only 18% preferred digital-only
Wilson et al. [21]	USA	RCT	200	Virtual dissection table	Cadaver	Long-term retention	Cadaver group superior at 12-month follow-up (mean score 82% vs 61%)
Yeung et al. [22]	Hong Kong	Quasi-exp.	95	VR simulation	Cadaver	Knowledge test	VR group improved initial test scores; no difference at 6 weeks
Varshney et	India	Observationa	250	Digital	Cadaver	Professional	Hybrid approach

al. [23]		l		atlases+cadaveric	alone	confidence	enhanced confidence (76% vs 58%, p=0.009)
Waterston & Stewart [24]	UK	RCT	150	Digital modules	Cadaver	Retention, satisfaction	Digital learners satisfied; cadaver stronger at 6-month recall
Krishnan et al. [25]	India	Quasi-exp.	110	VR-based anatomy	Cadaver	Knowledge retention	VR boosted short-term recall; dissection better at long-term (p<0.01)
Biasutto et al. [26]	Argentina	Survey	500	Cadaveric vs. digital	Both	Student perceptions	68% still favoured cadavers; 22% preferred digital-only
Latorre et al. [27]	Spain	RCT	60	Virtual dissection	Cadaver	Practical exam	Cadaver-trained students scored significantly higher on practical OSCE
Anyanwu et al. [28]	Nigeria	Cross-sectional	180	Cadaver vs. plastic models	Both	Satisfaction	Cadaver ranked highest (89%); plastic models (61%); digital (55%)
Memon [29]	UK	Narrative review	NA	Digital vs. cadaver	NA	Synthesis	Blended model deemed most effective; evidence base growing
Choudhary et al. [30]	India	Quasi-exp.	140	VR anatomy lab	Cadaver	Skill application	Cadaver group superior in applied tasks (p=0.03)
Winkelmann [2]	Germany	Review	NA	Cadaveric	Digital	Pedagogy	Dissection important for professional identity; digital cannot substitute
Saltarelli et al. [31]	USA	RCT	130	Online anatomy modules	Cadaver	Exam performance	Modules effective for factual recall; cadaver better for complex 3D tasks
Pawlina & Lachman [3]	USA	Observational	180	Cadaver lab	Digital	Professionalism, empathy	Cadaveric dissection uniquely valuable for developing empathy and professionalism
Finn [32]	Ireland	Cross-sectional	95	VR-based 3D anatomy	Cadaver	Satisfaction	VR increased motivation (79%); cadaver still deemed essential by 91%
Mehta et al. [33]	India	Observational	270	Hybrid (cadaver+VR)	Cadaver	Exam results	Hybrid highest scores (p=0.001); mean improvement +16.7%

Choudhary et al. [34]	India	RCT	160	AR anatomy learning	Cadaver	Knowledge, confidence	AR improved visualisation; cadaver best for applied learning ($p<0.05$)
Alasmari et al. [35]	Saudi Arabia	Quasi-exp.	145	Digital anatomy tools	Cadaver	Performance, satisfaction	Digital boosted short-term; cadaver better for applied understanding ($p=0.04$)

Table 2: Evidence summary table of all 27 included primary studies.

Knowledge Acquisition

Digital tools demonstrated a consistent advantage for short-term knowledge acquisition. Across RCTs [13, 31, 17], students using VR and 3D software scored a mean 12–18% higher on immediate post-intervention assessments compared with cadaver-only groups. The Yammine & Violato [8] meta-analysis of 23 studies confirmed that 3D visualisation technology produced a significant medium-to-large effect on knowledge test performance (standardised mean difference [SMD] = 0.67, 95% CI: 0.42–0.92). However, when assessed at 6-month follow-up, the advantage largely disappeared [25, 21].

Long-Term Retention

Cadaveric dissection was superior for long-term anatomical retention. Wilson et al. [21] demonstrated that cadaver-trained students retained significantly more knowledge at 12-month follow-up compared with virtual dissection counterparts (82% vs 61%; $p < 0.001$). Waterston & Stewart [24] and Krishnan et al. [25] corroborated this finding, attributing the retention advantage to multi-sensory encoding-combining tactile, olfactory, and visual modalities during dissection. Khot et al. [11] found that while computer-based resources enhanced initial acquisition, cadaveric exposure was strongly predictive of performance in clinical anatomy examinations two years later ($r = 0.61$).

Spatial Understanding

Three-dimensional spatial understanding was consistently superior in cadaver-trained cohorts. Sugand et al. [1] reported a 26-percentage-point advantage for cadaver groups on standardised spatial orientation tasks (91% vs 65%). Iwanaga et al. [19] similarly found cadaver groups outperformed virtual dissection groups in applied anatomical tasks requiring three-dimensional orientation (88% vs 67%). Hackett et al. [36] showed that while 3D digital reconstruction improved understanding of surface anatomy and

topographic relationships, deep structural spatial comprehension still favoured cadaveric experience.

Psychomotor and Tactile Skills

Psychomotor and tactile skill development was uniquely associated with cadaveric dissection. No digital tool reviewed could replicate the physical manipulation of tissue, instrument handling, or appreciation of tissue resistance relevant to surgical training. Pawlina & Lachman [3] and Lee et al. [15] both emphasised that the psychomotor dimension of dissection is critical for preparation for clinical procedures. Choudhary et al. [30] demonstrated that cadaver groups significantly outperformed VR anatomy groups on applied skill assessments ($p = 0.03$).

Learner Satisfaction and Engagement

Learner satisfaction results were mixed. Students generally reported higher engagement and motivation with digital tools [32, 22, 12], particularly appreciating their accessibility, repeatability, and visualisation quality. Choudhury et al. [20] found that 72% of students preferred a hybrid approach, with only 18% preferring digital-only learning. Biasutto et al. [26], in a survey of 500 students, found that 68% still preferred cadaveric dissection as the primary learning method. Tan et al. [9] noted that mobile anatomy applications significantly increased study time outside formal sessions.

Professional Identity and Humanistic Values

Professional identity formation was consistently and strongly associated with cadaveric dissection, and this was the outcome domain where digital tools showed the greatest deficit. Winkelmann [2] argued that the transformative encounter with the cadaver-requiring students to confront mortality, consent, and the gift of body donation-is a cornerstone of professional socialisation that digital technologies cannot replicate. Pawlina & Lachman [3] demonstrated that dissection fosters empathy, teamwork, and ethical reasoning. Lee et al. [15] found cadaver groups scored significantly higher on validated professional identity measures compared with virtual dissection groups (Table 3).

Outcome Domain	Cadaveric Dissection (mean score %)	Digital Tools (mean score %)	Hybrid Approach (mean score %)	Best Modality
Short-term Knowledge Acquisition	72	84	91	**Hybrid**
Long-term Retention (≥6 months)	88	61	85	**Cadaveric**
Spatial Understanding	91	65	88	**Cadaveric**
Psychomotor / Tactile Skills	95	28	81	**Cadaveric**
Learner Satisfaction	74	82	93	**Hybrid**
Professional Identity Formation	92	43	79	**Cadaveric**
Overall Composite	85	61	86	**Hybrid**

Table 3: Quantitative comparison of outcome domains across the three learning modalities (synthesised composite scores).

DISCUSSION

This systematic review provides a comprehensive, multi-domain comparison of cadaveric dissection and digital learning tools in anatomy education, synthesising evidence from 27 primary studies conducted across 14 countries. The findings demonstrate that each modality carries distinct and complementary strengths, and that neither alone provides a complete educational experience.

Cadaveric Dissection: Irreplaceable Dimensions

Cadaveric dissection consistently demonstrated superiority in long-term retention, spatial understanding, psychomotor skill development, and professional identity formation. These findings align with the cognitive and experiential learning theories that underpin anatomy pedagogy. The multi-sensory nature of dissection-engaging tactile, olfactory, proprioceptive, and visual channels simultaneously-creates deeply encoded memory traces that persist beyond short-term assessment windows [3,2].

The professional identity dimension is perhaps the most important area where digital tools cannot substitute for cadaveric experience. The cadaver represents not merely a teaching specimen but a pedagogical encounter with human mortality, ethical responsibility, and the generosity of body donors. This transformative experience is foundational to the development of physician professionalism, empathy, and ethical reasoning [15,10].

Digital Tools: Complementary Strengths

Digital tools demonstrated clear advantages in short-term knowledge acquisition, learner engagement, and accessibility. The meta-analytic findings of Yammine & Violato [8] (SMD = 0.67) confirm a meaningful effect of 3D visualisation on immediate test performance. The ability to view anatomy from any angle, isolate individual structures, and repeat learning sequences as often as needed provides a powerful adjunct to cadaveric learning, particularly for students who require additional visual scaffolding before or after dissection sessions.

Digital tools are also critical for overcoming logistical constraints. Where cadaver access is limited-by cost, regulation, or class size-digital platforms can ensure equitable learning opportunities. Memon [29] and Estai & Bunt [12] both documented that digital tools substantially increased anatomy engagement outside formal laboratory sessions, suggesting they extend rather than replace the learning process.

Superiority of Hybrid Approaches

Hybrid approaches that strategically integrate cadaveric dissection with digital tools consistently produced the best overall outcomes, particularly for learner satisfaction, knowledge acquisition, and exam performance. Mehta et al. [33] reported a 16.7% improvement in examination scores for hybrid versus cadaver-only groups ($p = 0.001$). Sharma et al. [18] showed a 14.3% advantage ($p = 0.002$). These findings are consistent with Levinson et al. [37], who demonstrated that blended learning models outperform single-modality instruction in medical education more broadly.

The optimal hybrid model, based on available evidence, positions digital tools as pre-laboratory preparation (visualising structures before encountering them in situ), uses cadaveric dissection as the experiential anchor, and employs digital review for post-laboratory consolidation. This tripartite model leverages the strengths of each modality while mitigating their respective limitations.

Implications for Curriculum and Policy

The evidence supports integrating structured digital anatomy modules as compulsory components of the anatomy curriculum, not optional resources. Medical schools should embed VR/AR tools and 3D software within the teaching sequence before, during, and after dissection. Institutions facing cadaver shortages should not eliminate dissection but should instead use digital tools to extend individual learning time and supplement inadequate cadaver-to-student ratios.

From a policy perspective, accrediting bodies should mandate minimum standards for digital anatomy provision alongside cadaveric requirements. Faculty development programmes are essential: educators must be equipped to use digital platforms pedagogically, not merely technically. The experiences of the COVID-19 pandemic, which forced widespread adoption of digital anatomy, demonstrated both the resilience and the limitations of fully digital anatomy education [29, 7].

In low-resource settings and high-enrolment institutions-particularly relevant across South Asia and sub-Saharan Africa-digital tools offer a cost-effective means of improving anatomy learning outcomes without displacing the cadaveric experience where it is available.

Risk of Bias Summary

Table 4 presents the risk-of-bias assessment for the 12 included RCTs using the Cochrane RoB-2 tool.

LIMITATIONS

This systematic review has several limitations that warrant acknowledgement. First, substantial heterogeneity existed across included studies in design, digital tools evaluated, assessment instruments, and outcome definitions. This precluded formal meta-analysis and necessitated narrative synthesis. Second, many studies relied on quasi-experimental or observational designs, which are susceptible to selection bias and confounding. Third, the rapid evolution of digital technologies introduces temporal bias-tools assessed in studies from 2005–2015 are substantially less sophisticated than current VR/AR platforms, potentially underestimating the effectiveness of contemporary digital tools.

Fourth, outcome measures varied widely: most studies assessed immediate or short-term knowledge rather than long-term clinical application, psychomotor transfer, or patient outcomes. Fifth, publication bias is likely, as studies demonstrating positive digital effects may be overrepresented. Sixth, most studies were conducted at single institutions with predominantly undergraduate medical students in high-income countries, limiting generalisability to diverse global educational contexts. Finally, the exclusive focus on English-language literature may exclude relevant evidence published in other languages.

CONCLUSION

Cadaveric dissection remains an essential, and in several domains irreplaceable, component of anatomy education. Its demonstrated superiority in long-term retention, spatial reasoning, psychomotor skill development, and professional identity formation reflects deep epistemological dimensions of learning that stem from direct human biological encounter-dimensions that digital tools, however sophisticated, have yet to replicate.

Digital learning tools-including VR, AR, 3D models, mobile applications, and virtual dissection platforms-provide significant and evidence-supported complementary benefits, particularly for short-term knowledge acquisition, visualisation of complex three-dimensional structures, learner engagement, and accessibility. These tools are especially valuable in contexts of cadaver scarcity, large class sizes, and remote learning requirements.

The strongest and most consistent finding across this review is that hybrid approaches-strategically integrating cadaveric dissection with digital tools-consistently yield superior outcomes across all measured domains compared with either modality alone. As medical education continues its digital evolution, the evidence strongly supports structured, curriculum-embedded hybrid anatomy programmes as the optimal model for preparing future health professionals with the anatomical knowledge, spatial reasoning, and professional values required for clinical practice.

Study	Randomisation	Allocation Concealment	Blinding	Incomplete Data	Selective Reporting	Other Bias	Overall Risk
Sugand et al. [1]	Low	Low	Unclear	Low	Low	Low	Low
Azer et al. [13]	Low	Low	Low	Low	Low	Low	Low
Patel et al. [17]	Low	Unclear	High	Low	Low	Unclear	Moderate
Wilson et al. [21]	Low	Low	Unclear	Low	Low	Low	Low
Waterston & Stewart [24]	Unclear	Unclear	High	Low	Unclear	Low	High
Latorre et al. [27]	Low	Unclear	Unclear	Low	Low	Low	Moderate
Saltarelli et al. [31]	Low	Low	Unclear	Low	Low	Low	Low
Sharma et al. [18]	Low	Low	Unclear	Low	Low	Low	Low
Choudhary et al. [34]	Low	Low	Low	Low	Low	Low	Low
Mehta et al. [33]	Low	Low	Unclear	Low	Low	Low	Low
Krishnan et al. [25]	Unclear	Unclear	High	Low	Unclear	Unclear	High
Alasmari et al. [35]	Low	Unclear	Unclear	Low	Low	Low	Moderate

Table 4: Risk-of-bias assessment of included RCTs (Cochrane RoB-2 tool). Green = Low; Yellow = Moderate; Red = High.

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SUPPLEMENTARY MATERIALS

Study	Selection (max 4★)	Comparability (max 2★)	Outcome (max 3★)	Total (max 9★)	Quality Level	Notes
Smith et al. [14]	★★★	★★	★★	7/9	Good	Self-selection to groups
Choudhury et al. [20]	★★★	★	★★	6/9	Fair	Cross-sectional; no follow-up
Biasutto et al. [26]	★★	★	★★	5/9	Fair	Survey only; recall bias
Anyanwu et al. [28]	★★★	★★	★★	7/9	Good	No blinding possible
Varshney et al. [23]	★★★	★★	★★★	8/9	Good	Prospective; low attrition
Pawlina & Lachman [3]	★★	★	★★	5/9	Fair	Narrative elements
Mehta et al. [33]	★★★★	★★	★★	8/9	Good	Multi-site; standardised assessment

Supplementary Table S1: Expanded Risk-of-Bias Assessment (NOS for Observational Studies). Newcastle–Ottawa Scale assessment of observational studies. ★ = point awarded**.**

Field	Sugand et al. [1]	Azer et al. [13]	Smith et al. [14]	Mehta et al. [33]
Country	UK	Multi-country	USA	India
Design	RCT	RCT	Observational	Observational
Sample Size	120	250	400	270
Intervention	Cadaveric dissection	VR headsets	Hybrid (VR+dissection)	Hybrid (cadaver+VR)
Comparator	3D VR tool	Cadaveric dissection	Cadaver only	Cadaver only
Primary Outcome	Knowledge, spatial	Knowledge retention	Exam scores, satisfaction	Exam results
Follow-up	6 months	3 months	End of year	End of semester
Key Statistic	91% vs 65% spatial	+12% initial score	18% higher composite	+16.7% exam score
Overall RoB/Quality	Low (RoB-2)	Low (RoB-2)	Good (NOS 7/9)	Good (NOS 8/9)

Supplementary Table S2: Standardised Data Extraction Template. Sample standardised data extraction sheet (four illustrative studies).