The Innovation Medicine

Enhancing robotic-assisted surgery training with 3D-printed bio-models: A new era

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Received: May 10, 2023; Accepted: October 11, 2023; Published Online: October 24, 2023; https://doi.org/10.59717/j.xinn-med.2023.100031

Citation: Amadi S. and Wang Z. (2023). Enhancing robotic-assisted surgery training with 3D-printed bio-models: A new era. The Innovation Medicine 1(3), 100031.

Robotic surgery, in the vernacular, has become synonymous with the telerobotic execution of Minimal Invasive Surgery (MIS), wherein the surgeon is physically distanced from the patient while the surgical instruments are directly maneuvered and controlled by a human operator. Termed Robotic Assisted Surgery (RAS), this clinical approach aligns well with the contemporary and increasingly prevalent paradigm of MIS performed through minimal incisions, supplanting numerous conventional open surgery procedures. The inherent advantage of reduced tissue trauma directly benefits patients, while simultaneously providing surgeons with improved ergonomics. Furthermore, it integrates a multitude of technological components specifically tailored for employment within the operative setting.[1]

BACKGROUND

Over the past decade, the field of robotic surgery has experienced exponential growth, as evidenced by the notable escalation in the volume of procedures performed. Notably, the "Da-Vinci surgical system," developed by Intuitive Surgical Inc., headquartered in Sunnyvale, CA, USA, has emerged as the predominant platform for RAS. This system has attained an unparalleled level of popularity, with an annual growth rate of 15%, leading to an impressive annual aggregate of 1.5 million procedures. As of present, it remains the most extensively utilized and esteemed RAS system to date.[2] The remarkable success can be attributed to several key factors:

1. Advancement in technological features; Encompassing enhanced visual acuity and refined instrumentation. Emphasis on ergonomics and safety: Incorporation of features like EndoWrist for suturing, tremor filtering mechanisms, and heightened situational awareness.
2. Compelling clinical evidence: Tangible improvements in patient outcomes associated with robotic surgery. Focusing on procedures enhancing Quality of Life.
3. Development of multiple programs that incorporate comprehensive training modalities, including simulators for basic training, and advanced training that includes wet and dry lab simulations.
4. Preservation of surgeon responsibility and absence of high-level autonomy; Fostering a sense of accountability among the medical community and patients.

The utilization of robotic technology has enabled surgeons to conduct intricate procedures within confined anatomical spaces. However, it is important to acknowledge that the proficiency of the operators continues to be a critical factor in determining favorable clinical outcomes. Consequently, there is a burgeoning interest in evaluating the skill levels of trainees who engage in robotic surgery. The training process for robotic surgery encompasses a multifaceted approach that utilizes diverse simulation platforms and didactic methods. Considering the reported extended learning curves associated with RAS as compared to Laparoscopic Minimally Invasive Surgery, the current recommended pathway proposed by Intuitive may be deemed insufficient in adequately preparing surgeons for the complexities of RAS procedures.

The objective of procedural simulation is to foster the acquisition of advanced surgical skills prior to engaging in live surgeries, thereby mitigating the potential risks to patients. The utilization of various simulation tools, such as virtual and augmented reality, live animal models, and cadavers, has been instrumental in cultivating robotic surgical competency.[3] However, the existing practice of employing these simulation methods to demonstrate the substantial advantages of simulation is constrained by the absence of a truly realistic platform capable of imparting comprehensive procedural knowledge necessary for performing operations. While wet lab models may offer more realistic experiences, their practical implementation is impeded by challenges such as high costs, limited availability, concerns related to transmissible diseases, and potential ethical considerations.[4]

To address this situation, the advent of novel synthetic organ models generated through the utilization of 3D-printing technology has emerged as a promising avenue, presenting an additional and viable approach for proficiency-based procedural training preceding the transition to live surgical interventions. By replicating the anatomical and physiological characteristics of human organs, these 3D-printed models provide a realistic and hands-on learning experience. The integration of these synthetic organ models into training curricula represents a significant advancement with the potential to enhance the preparedness and self-assurance of surgeons.

The progress achieved in 3D printing technology, combined with software capable of converting patient Digital Imaging and Communications in Medicine (DICOM) imaging data into stereo-lithography (STL) files,[5] have facilitated the replication of intricate morphological characteristics of human anatomy to create procedural models. These models serve as tangible reproductions of organs, providing not only a platform for surgical skills training but also enabling surgeons to make more informed assessments, enhance preoperative planning, and refine their stereognostic abilities (Figure 1).[5]

BENEFITS OF 3D PRINTING

Anatomical accuracy and mimic pathological variations

An innovative breakthrough has led to the development of 3D models that simulate the texture, imaging characteristics, and bleeding responses of organs. These models capture the comprehensive essence of the operative experience. A study by A. Ghazi et al. showcased the successful creation of procedural hydrogel 3D bio-models, accurately replicating the intricate anatomical features of the kidney. These models hold great potential for surgical training.[6]

Training platform

The integration of lifelike tissue characteristics, accurate human anatomy, and 3D printing technology has created a more controlled training environment, that offers trainees repeated practice opportunities in a realistic procedural setting, surpassing the limitations of VR simulations and providing a comparable experience to wet lab models.[3]

Cost-effective

It is important to consider that replicating the authentic parameters of dissection with hemostasis using human cadavers necessitates artificial perfusion, resulting in increased costs. Similarly, conducting experiments on animal subjects requires the utilization of a separate robotic system. In contrast, the utilization of 3D-printed models proves to be a cost-effective alternative. These models are biodegradable and reusable, eliminating the requirement for a dedicated teaching robot.[7]

Customizable

The development and validation of these models as innovative training tools in robotic surgery have been widely acknowledged across various surgical specialties. Our emphasis lies in general surgery. This discipline has been identified as one of the foremost beneficiaries of robotic assistance, making it the primary focus of our research and model implementation efforts.[6]

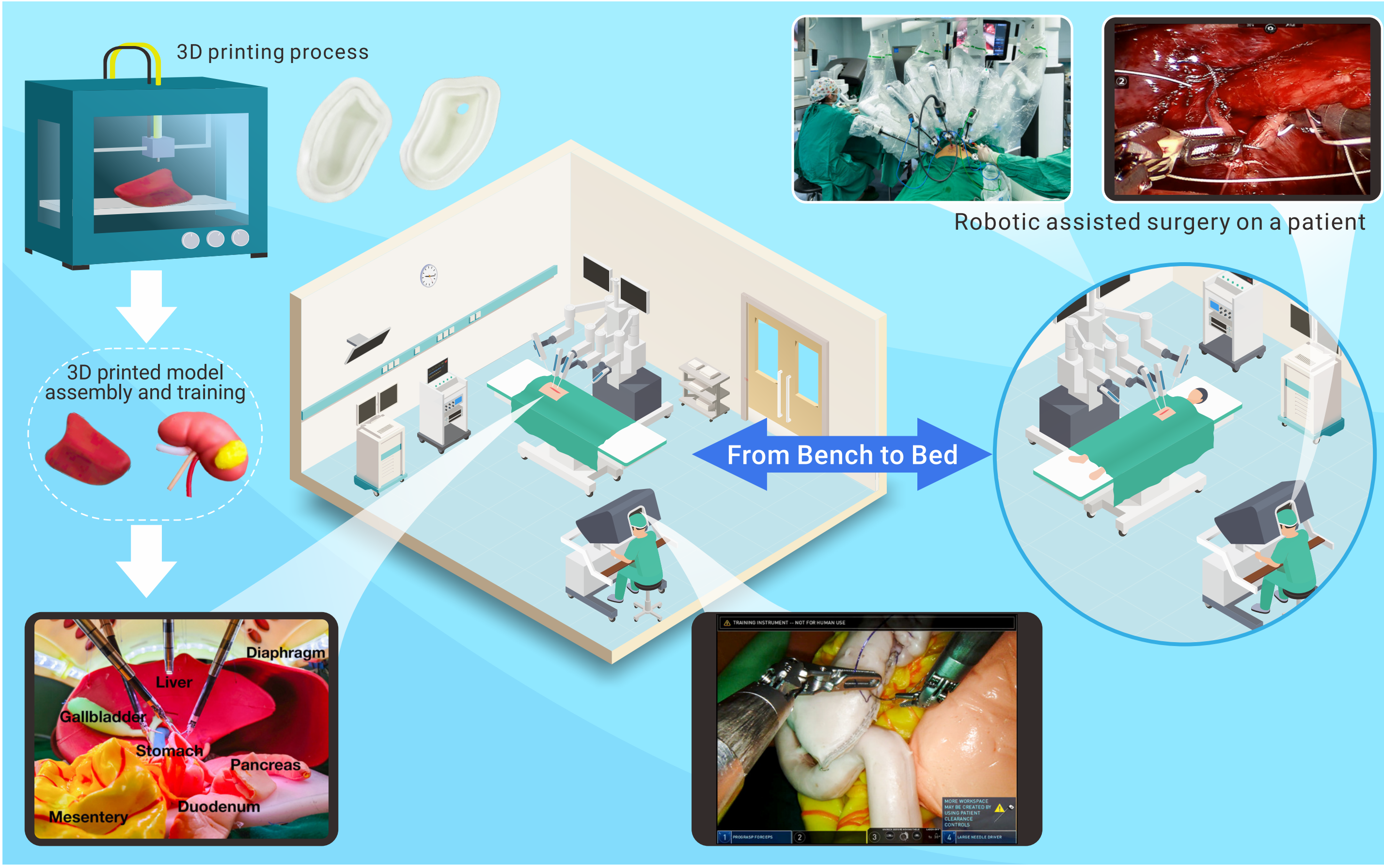

Figure 1. The illustration of Bench to Bed study of a 3D-printed model in aiding robotic surgery training In this scenario, patient information is first converted into 3D-printed models, which are then utilized in various training scenarios, and thus promoting intraoperative surgery performance eventually.

Skill assessment

Dry laboratories have demonstrated their effectiveness in enhancing robotic technical proficiency. Furthermore, specific benchmark competency metrics, such as the Global Evaluative Assessment of Robotic Skills (GEARS) and the Robotic–Objective Skills Assessment Test (R-OSATS), have been established for evaluating performances. These metrics serve as standardized tools for assessing and measuring skill levels in the field of robotic surgery, providing valuable insights into the proficiency of surgeons.[3]

Personalized surgical planning for complex procedures

Anatomical organ replicas created through 3D printing technologies represent the primary and prevalent application of this innovation. These replicas are generated directly from axial images of patients, accurately depicting the underlying pathology. As illustrated by the bench to bed study in Figure 1, they serve as valuable guides and templates, facilitating the preoperative planning of intricate surgical procedures. By leveraging these 3D-printed models, surgeons can enhance their understanding of the patient's specific anatomical intricacies, enabling them to develop comprehensive and tailored surgical strategies.[8]

POTENTIAL IMPROVEMENTS IN 3D PRINTED MODELS AND ROBOTIC-ASSISTED SURGERY TRAINING

Cost

The primary consideration revolves around cost. As is typical with emerging technologies, the initial costs tend to be highly variable and relatively expensive. However, with affordable 3D printers and open-source modeling software on the rise, 3D printing is becoming a standard in academic centers. Its increasing accessibility and adoption promise widespread integration across various fields.

Small sample size

The availability of substantial evidence, consisting of high-quality research studies incorporating rigorous methodologies and long-term follow-up, is currently limited within various surgical branches and their application to 3D printing in RAS training. To fully harness the potential of 3D printing, it is crucial for the scientific community to actively engage in research and exploration, cultivating an atmosphere of optimism and anticipation.

Learning curve

Evaluating 3D-printed organ models in real-use cases across diverse environments is crucial for accurate assessment. Statistical surveys of surgical outcomes and patient safety, using comprehensive data criteria, are necessary. Although limited data exist on the transfer of robotic skills from dry labs to operating rooms, there is optimism about the potential of 3D-printed biomaterials and advanced training platforms. These innovations, combined with existing laparoscopic surgery knowledge, hold promise for improving the accessibility and ease of learning RAS, leading to enhanced surgical proficiency and patient outcomes.

Realism levels limited

Most 3D-printed organ models currently available exhibit static characteristics, lacking the capability to simulate dynamic conditions that organs undergo, such as the pulsations of the heart. Consequently, the inclusion of convenient and precise dynamic functionalities, such as actuation mechanisms, within these organ models would greatly enhance their value for realistic surgical rehearsal purposes.[8]

Limited availability and accessibility

Similar to wet laboratories, the establishment of a dry laboratory necessitates the availability of a robotic system and appropriate robotic training instruments. However, it is important to acknowledge that such resources may not always be readily accessible or feasible to acquire at many training institutions. Despite infrastructure limitations, there is hope to make robotic surgical training more accessible. Innovative solutions are being sought to overcome these challenges and expand the availability of dry laboratory programs.[9]

ADVANCEMENTS IN ARTIFICIAL INTELLIGENCE (AI) IN ROBOTIC SURGERY TRAINING

Objective assessment of robotic surgery training

Current assessment methods rely on subjective human ratings, which can introduce biases and demand substantial time and resources from educators or assessors. The emergence of automated performance metrics (APMs), presents an opportunity to assess surgical techniques objectively and analytically. This advancement enables surgical trainees to receive a fair and quantifiable evaluation. A novel data recorder known as the "dVLogger" has been developed to directly capture data from the DaVinci Surgical System, facilitating automatic data collection. Assessment tools employing automation and self-learning computer algorithms offer a sustainable approach for large-scale evaluation of surgeries. The implementation of such systems allows for comprehensive analysis and enhances learning by examining recorded surgical training procedures or rehearsals. Furthermore, the development of benchmarks and installation of sensors that can only be utilized in training scenarios would revolutionize RAS training.

AI to enable patient-specific 3D printed models

In the realm of surgical training, a computer network can be trained to learn the key descriptors of the intraoperative scene, such as texture, blood, peculiarity, instruments, and suture application. This process, known as hyperrealism involves transforming frames between different domains by altering object appearances. It generates simulated realities with augmented details, derived from actual procedures without altering details existing in the original model, this approach will in turn enhance the realism of RAS training.

The deep learning ability of AI

AI can revolutionize robotic surgical practice by organizing and sharing extensive surgical data, including videos, training procedures, imaging, and medical records. This enables the identification of rare cases and facilitates data integration across the patient care journey. Real-time monitoring and analysis of diverse data types during surgery can predict and prevent adverse events.

Telemedicine and Remote Robotic Surgery

Drawing a parallel to air traffic control towers, telementoring represents a similar domain of support and enhanced feedback, akin to the assistance provided to pilots. It encompasses a feature of live proctoring; wherein expert surgeons can remotely provide real-time guidance and support throughout a surgical case. This has the potential to serve as an additional valuable tool in offering novice surgeons immediate intraoperative feedback, thereby facilitating their skill development.[9] SurgSmart is an AI-assisted remote surgical guidance system that automatically detects critical phases and events during surgery. It notifies surgical experts for real-time guidance and utilizes dynamic anatomical markers to assist in accurate procedures.[10]

CONCLUSION

Since its inception, the robot has transformed various fields including surgery with its known benefits. However, a learning curve exists in RAS. 3D printed models have emerged as valuable tools, benefiting patients, trainees, and experienced surgeons. These models enhance robotic surgical outcomes, reduce errors, and expedite the learning curve. Innovation in robotic education, coupled with AI integration and 3D printing bio-model technology, appears to have limitless possibilities, and we find ourselves amid a dynamic and paradigm-shifting era.

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FUNDING AND ACKNOWLEDGMENTS

We would like to thank Zhejiang Provincial Peoples Hospital and Zhejiang Chinese Medicine University for supporting this work. The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.