

Humanoid robots in surgery: Preclinical evidence and translational priorities

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Humanoid robots in surgery: Preclinical evidence and translational priorities

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INTRODUCTION

Robotic surgery has largely developed through specialization. Purpose-built systems combine dedicated manipulators, mechanically defined remote centers of motion (RCMs), proprietary wristed instruments, and standardized workflows. This integration supports precise teleoperation and links each platform to particular instruments, procedures, and operating-room layouts. Liang et al. took a different approach by adapting a general-purpose humanoid to manipulate manual wristed laparoscopic instruments.[1] Their study examines whether one robotic form can use clinical tools and workspaces while meeting the control requirements of minimally invasive surgery. Established surgical robots provide the relevant benchmark.[2]

A surgeon controlled the humanoid from a stereo console. Inverse kinematics converted hand motion into robot-wrist commands, and a vision-localized virtual RCM kept each instrument near its trocar pivot. The experiments evaluated workspace, trajectory regularity, dry-laboratory task performance, and selected operative steps in two porcine procedures. Instrument motion remained under continuous surgeon control throughout the study. No autonomous surgical function was evaluated. The work therefore offers a preclinical demonstration of laparoscopic manipulation by a teleoperated humanoid under physiological conditions (Figure 1).

The broader interest in humanoid platforms lies in their possible compatibility with clinician-operated tools and human-designed workspaces. Compared with purpose-built surgical robots, a multipurpose platform could offer more flexible deployment across operative manipulation and bedside support. Safe switching between these roles could improve resource utilization. The study did not systematically evaluate this versatility, and each robot, instrument, software and task combination requires separate technical and workflow validation.

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EVIDENCE FROM THE STUDY

Benchtop experiments defined the platform's mechanical limits. Reachable workspace changed with trocar placement, and straight trajectories were more regular than circular trajectories. The reported motion values require careful interpretation. Because the OptiTrack and robot coordinate frames were not registered directly, the values describe residuals relative to fitted trajectories. They do not measure absolute target-to-tool error or establish overall positional accuracy. The results identify calibration, curved-motion control, workspace, and responsiveness as current limitations.

Dry-laboratory tasks provided operator-level comparisons. In the 18-participant ring-transfer task, the humanoid and da Vinci Research Kit (dVRK) produced similar weighted error scores, although the

humanoid required more time. In the 13-participant peg-transfer task, the humanoid outperformed manual wristed instrumentation on the study-specific composite score but remained below the da Vinci Xi. The tasks used different robotic comparators, and the peg-transfer score was normalized within the study cohort. These findings apply only to the tested tasks and do not establish overall superiority or equivalence.

The animal evidence comprised two planned hybrid porcine cholecystectomies. One senior surgeon performed all console-controlled steps, and the procedures were neither randomized nor blinded. Both cases were completed without an unplanned conversion. The shorter active console time in the second case offers little evidence of a learning effect because interruptions were excluded and only two cases were studied. Robot redeployment, recalibration, and prolonged pauses interrupted workflow. Minor biliary spillage and liver-bed bleeding in the second case were managed intraoperatively. Conventional laparoscopy was used for cystic duct clipping and cystic artery ligation because a compatible clip applier was unavailable.

Human assistants provided most bedside support. A second humanoid briefly held the camera and retracted tissue during the first procedure. The post-procedure survey included four respondents, with only one console operator. These observations support feasibility for selected operative steps in a controlled preclinical setting. They do not establish readiness for human surgery.

CURRENT LIMITATIONS

In this study, 'humanoid' referred to the robot's morphology. The surgeon continuously commanded instrument motion, which functionally aligns the system with Level 1 (Robot Assistance) in the Levels of Autonomy in Surgical Robotics (LASR) framework.[3] The experiments did not evaluate autonomous perception, planning, or action. Higher levels of autonomy would introduce additional requirements for uncertainty management, human oversight, and safe handover.

Technical performance also depended on conditions that are difficult to control during surgery. Respiration and robot-base drift displaced the fiducial-based virtual RCM, leading to recalibration and repositioning. Compact arms restricted reach, intermittent overheating occurred, and gloves over the robot arms did not constitute a validated sterile interface. Safety evaluation based on International Electrotechnical Commission (IEC) standards identifies motion quality, unintended collision, excessive heat, emergency management and software integrity as relevant domains.[4] The platform would also need validated recovery procedures for communication loss and rapid conversion to manual surgery.

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Whether humanoid morphology offers a practical advantage over other robotic designs remains uncertain. The study did not isolate the contribution of human-like kinematics or test bipedal mobility as a surgical capability. It also provided no comparison with wheeled, table-mounted, or modular dual-arm systems for staffing, reliability, or life-cycle cost. Proposed roles in flexible endoscopy, arthroscopy, endoscopic spine surgery, and instrument exchange therefore require direct evaluation. Each application will need evidence on force, access, sensing, sterility, and failure recovery.

PRIORITIES FOR TRANSLATION

Translation should proceed through explicit technical and workflow gates. The first priority is reliable instrument control, especially geometric calibration, absolute pose accuracy and RCM stability under respiratory motion and robot-base drift. Control latency, force control, adequate reach, thermal endurance, sterile interfaces and fault recovery must also meet prespecified bench criteria. Once these criteria are met, integrated simulation and comparative animal studies can assess docking, instrument exchange, emergency access, team workload and total procedure time. Multicenter testing with independent operators can then assess reproducibility. Surgeons, engineers and regulatory specialists should jointly define intended use, autonomy level, performance thresholds, configuration control and cybersecurity from the outset.

Within the Idea, Development, Exploration, Assessment and Long-term monitoring (IDEAL) framework for surgical robotics, the current work is best regarded as preclinical Stage 0.[5] Progression toward human evaluation should depend on reproducible performance and predefined safety thresholds in comparative animal studies. Tissue injury, conversion, interruptions and fault recovery should be assessed alongside completion of selected operative steps.

If these preclinical requirements are met, early human evaluation should focus on narrowly defined, procedure-specific tasks with immediate manual takeover. Camera holding may be a tractable starting point; predefined tissue-manipulation steps would require additional task-specific safety evidence. Takeover plans should specify safe instrument withdrawal or disengagement and a trained bedside team able to continue the procedure. New functions, including instrument exchange or learned subtasks, would change the risk profile and require renewed assessment.

Liang et al. provide an important preclinical demonstration of surgeon-controlled laparoscopic manipulation by a general-purpose humanoid. In the longer term, validated platforms could support multiple operative and bedside tasks within existing clinical workspaces. This flexibility could broaden robotic assistance, provided comparative studies show reproducible safety, practical workflow gains and a clear advantage over alternative designs.

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AUTHOR CONTRIBUTIONS

All authors contributed to and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

FIGURE LEGEND

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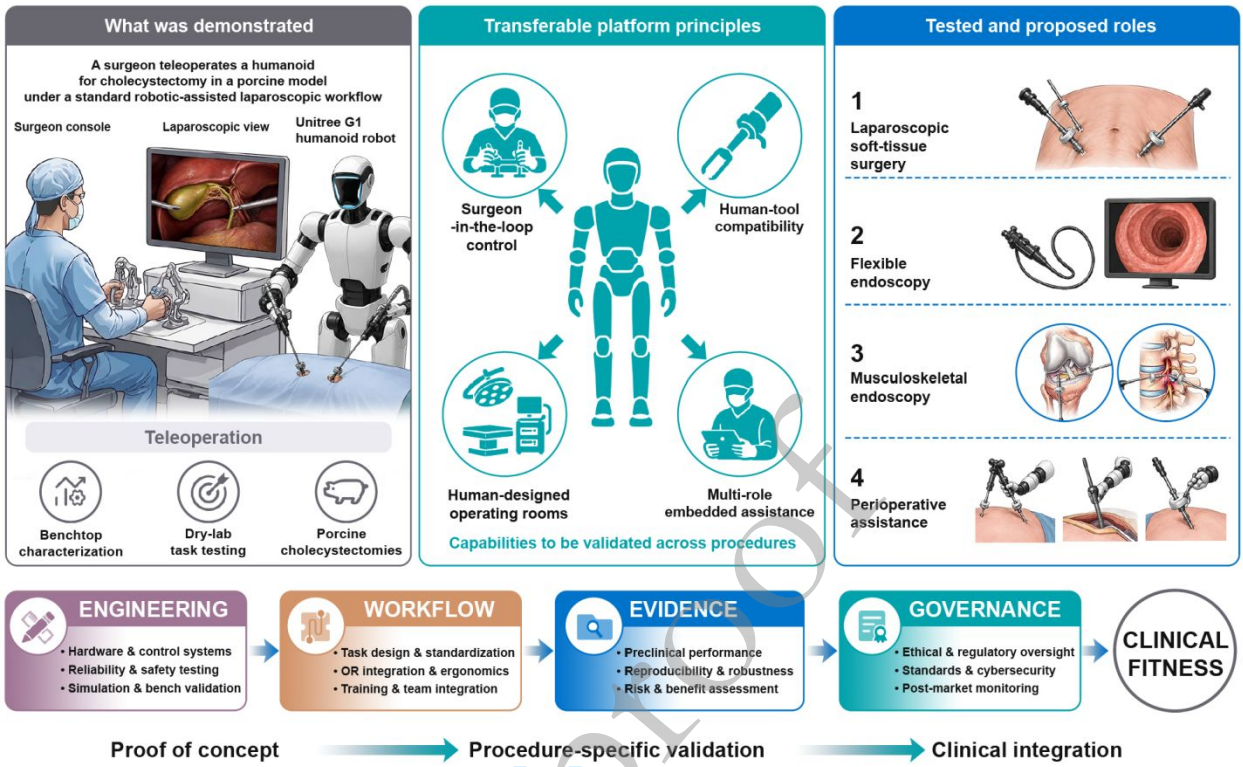

Figure 1. Humanoid robotic surgery from preclinical feasibility to broader clinical evaluation. Left, the preclinical study evaluated benchtop performance, dry-laboratory tasks and selected operative steps in two hybrid porcine cholecystectomies under continuous surgeon teleoperation. Conventional laparoscopy was used for cystic duct clipping and cystic artery ligation. Center, humanoid morphology may support compatibility with clinician-operated tools and human-designed operating rooms, alongside surgeon-in-the-loop control and potential assistance across multiple roles. Right, the illustrated roles span tested laparoscopic manipulation and proposed extensions. The lower pathway summarizes engineering, workflow, evidence and governance requirements for progression from proof of concept through procedure-specific validation toward clinical integration. Governance and multidisciplinary collaboration should accompany all stages of development and evaluation.

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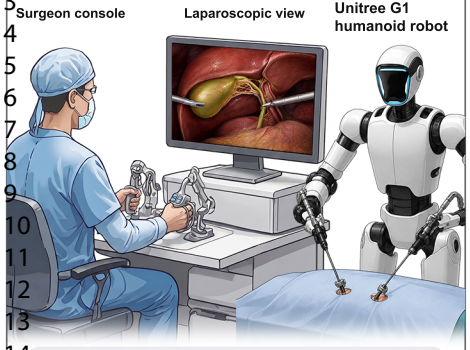
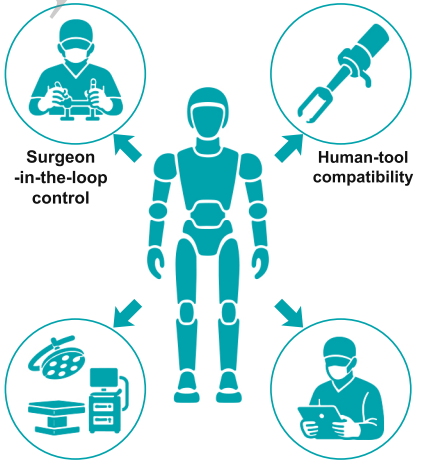
What was demonstrated

A surgeon teleoperates a humanoid for cholecystectomy in a porcine model under a standard robotic-assisted laparoscopic workflow



- Benchtop characterization
- Dry-lab task testing
- Porcine cholecystectomies

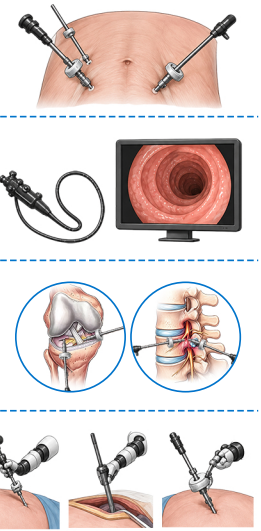
Transferable platform principles



Capabilities to be validated across procedures

Tested and proposed roles

1. Laparoscopic soft-tissue surgery
2. Flexible endoscopy
3. Musculoskeletal endoscopy
4. Perioperative assistance



ENGINEERING
- Hardware & control systems
- Reliability & safety testing
- Simulation & bench validation

WORKFLOW
- Task design & standardization
- OR integration & ergonomics
- Training & team integration

EVIDENCE
- Preclinical performance
- Reproducibility & robustness
- Risk & benefit assessment

GOVERNANCE
- Ethical & regulatory oversight
- Standards & cybersecurity
- Post-market monitoring

CLINICAL FITNESS

Proof of concept → **Procedure-specific validation** → **Clinical integration**

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