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An Ex Situ Cadaver Liver Training Model Continuously Pressurized to Simulate Specific Skills Involved in Laparoscopic Liver Resection: the Lap-Liver Trainer

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► To cite this version:

Pierre-Guillaume Champavier, Laura Beyer-Berjot, Pierre-Jean Arnoux, Max Py, Rémy Casanova, et al.. An Ex Situ Cadaver Liver Training Model Continuously Pressurized to Simulate Specific Skills Involved in Laparoscopic Liver Resection: the Lap-Liver Trainer. *Journal of Gastrointestinal Surgery*, 2023, 27 (3), pp.521-533. 10.1007/s11605-022-05566-9 . hal-04502456

HAL Id: hal-04502456

<https://hal.science/hal-04502456>

Submitted on 29 Mar 2024

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Metadata of the article that will be visualized in OnlineFirst

ArticleTitle	An Ex Situ Cadaver Liver Training Model Continuously Pressurized to Simulate Specific Skills Involved in Laparoscopic Liver Resection: the Lap-Liver Trainer	
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Article Sub-Title		
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Article CopyRight	The Society for Surgery of the Alimentary Tract (This will be the copyright line in the final PDF)	
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Journal Name	Journal of Gastrointestinal Surgery	
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Schedule Received 3 Aug 2022
Revised
Accepted 17 Dec 2022

Abstract *Background:*
Laparoscopic liver resection (LLR) requires delicate skills. The aim of the study was to develop a training model mimicking as much as possible intraoperative bleeding and bile leakage during LLR. We also assessed the educational value of the training model.
Methods:
The Lap-liver trainer (LLT) combined a continuously pressurized ex situ cadaver liver and a customized mannequin. The customized mannequin was designed by computer-aided design and manufactured by 3D printing. The left lateral sectionectomy (LLS) was chosen to assess the feasibility of a LLR with the LLT. Eighteen volunteers were recruited to perform LLS and to assess the educational value of the LLT using a Likert scale.
Results:
The customized mannequin consisted of a close laparoscopic training device based on a simplified reconstruction of the abdominal cavity in laparoscopic conditions. Ex situ cadaver livers were pressurized to simulate blood and bile supplies. Each expert surgeon ($n = 3$) performed two LLS. They were highly satisfied of simulation conditions (4.80 ± 0.45) and strongly recommended that the LLT should be incorporated into a teaching program (5.00 ± 0.0). Eight novice and 4 intermediate surgeons completed a teaching program and performed a LLS. Overall, the level of satisfaction was high (4.92 ± 0.29), and performing such a procedure under simulation conditions benefited their learning and clinical practice (4.92 ± 0.29).
Conclusions:
The LLT could provide better opportunities for trainees to acquire and practice LLR skills in a more realistic environment and to improve their ability to deal with specific events related to LLR.

Keywords (separated by '-') Laparoscopic liver surgery - Simulation education - Ex situ pressurized liver - Cadaver liver - Specific events

Footnote Information The online version contains supplementary material available at <https://doi.org/10.1007/s11605-022-05566-9>.



An Ex Situ Cadaver Liver Training Model Continuously Pressurized to Simulate Specific Skills Involved in Laparoscopic Liver Resection: the Lap-Liver Trainer

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Received: 3 August 2022 / Accepted: 17 December 2022

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Introduction

Laparoscopic procedures have significantly progressed in the past decades and have become the standard approach in most surgical specialties, driven by the desire for less surgical

trauma, faster postoperative recovery, shorter hospital stay, and better cosmetic results.¹⁻³

Laparoscopic liver resection (LLR) has been progressively developed and gained worldwide acceptance during the past decade.⁴ Resections of lesions in the anterior liver segments or the left lateral segments can now be safely performed by laparoscopic approach.⁵ However, LLR requires delicate skills in both liver and laparoscopic surgery, and experts believe that only surgeons who do both advanced laparoscopic procedures and liver surgeries during daily practice should perform LLR.⁵ Although a steep learning curve (LC) exists for LLR, the postoperative outcomes should be improved by stepwise progression in skills.⁶⁻⁸ Because only few studies evaluated the educational value of LLR training programs,⁸ the Southampton meeting has recently emphasized the lack of evidence-based studies focusing on LLR education.⁵

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Procurement and Preparation of Ex Situ Cadaver Livers

The cadaver livers used in this study were from formalin-fixed cadavers preserved at the LBA, Aix-Marseille Université, France. Experimental activity on cadavers at the LBA is carried out within a strict, rigorous framework that respects the rules of ethics, quality, hygiene, and safety dictated by the French bioethics law (<https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000043884384>).

The removal of the cadaver liver was standardized. A large thoraco-phreno-laparotomy allowed easy access to the liver, to its arterial and portal inflow, to the hepatic veins and inferior vena cava, to the biliary tract, and to its anatomical attachments (Fig. 1A and B). The ex situ cadaver liver was thus pressurized by 4 systems of dedicated tanks and tubing by cannulation of the hepatic artery, the portal vein, the common biliary duct, and the inferior vena cava to simulate blood and bile supplies (Fig. 1C). Arterial pressure was maintained continuously at 65 mmHg (90 cmH₂O), comparable to a mean arterial pressure of 65 mmHg. Portal and hepatic venous pressures were maintained at 15 mmHg (20 cmH₂O) and 7.5 mmHg (10 cmH₂O) respectively.¹⁵ The main bile duct was pressurized with continuous pressure of 7.5 mmHg (10 cmH₂O) to simulate possible bile leakage during LLR. The hepatic model was pressurized with a fluid that best approximated the dynamic viscosity of blood. For this purpose, we used a colored preparation combining saline (70% saline) and liquid glycerin (30%) to obtain a dynamic viscosity of 3.73×10 to 3 Pa.S close to that of human blood.¹⁶

The first part of the study was to assess the usability of the ex situ pressurized cadaver liver as a training model for LLR. Two expert surgeons were asked to perform wedge

Unlike open surgery, several technical challenges such as limited tactile feedback, fulcrum effect, reliance on two-dimensional vision, and difficult hand-eye-coordination have contributed to the extended LC in acquiring laparoscopic skills.^{9,10} In the specific area of LLR, bleeding and bile leakage are the two major intraoperative risks and require sophisticated skills for hemostasis and suturing.¹¹ Learning and building these skills in the operating room is not ideal.¹² In addition, there is a shift in idea on the suitability of developing such skills during clinical practice regarding patient safety. Training outside of the operating room has proven its positive impact on surgical training because it eliminates the ethical concerns of learning laparoscopic skills on patients in clinical practice.^{13,14} A training model mimicking as much as possible a real liver organ and simulating intraoperative bleeding and bile leakage could greatly enhance the acquisition of specific skills in LLR.

We therefore hypothesized that an ex situ cadaver liver with simulated intraoperative bleeding and bile leakage should be anatomic, helpful, and practicable in LLR skill training. In the present study, we describe the development of the Lap-liver trainer, which combines a continuously pressurized ex situ cadaver liver training model and a customized mannequin. We also intended to assess the feasibility of a LLR using the Lap-liver trainer and the educational value of this training model to provide a more holistic and realistic environment for trainees to learn specific skills in LLR.

Materials and Methods

Experimentations were performed at the Laboratoire de Biomécanique Appliquée (LBA) and at the Center for Surgical Teaching and Research (CERC), Aix-Marseille Université, France. The study was approved by both center's institutional review board. Written consent was not required.

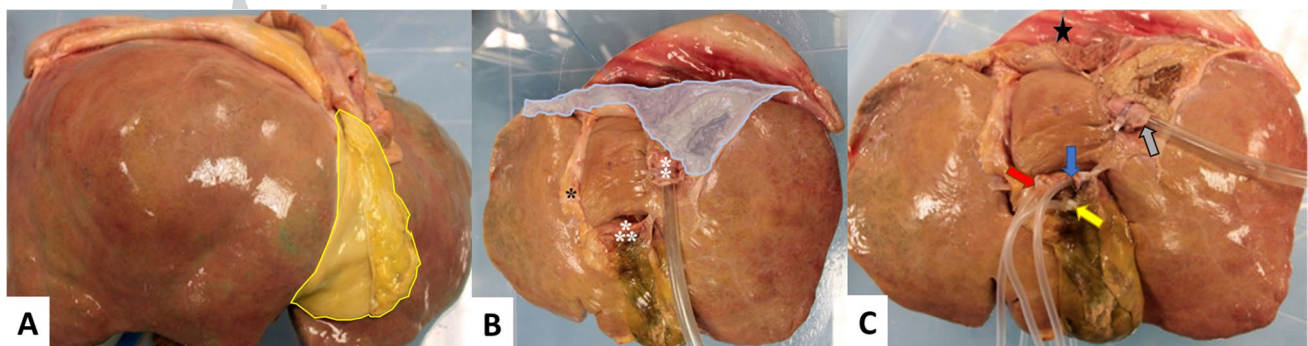


Fig. 10 Ex situ cadaver liver preparation. **A** Anterior aspect of the ex situ cadaver liver showing the falciform and round ligaments (yellow area). **B** Posterior aspect of ex situ cadaver liver. The hepatic pedicle (**), the cannulated inferior vena cava (‡), the Arantius ligament (*), and diaphragmatic attachments of the liver (blue area) are visualized.

C The hepatic artery (red arrow), the portal vein (blue arrow), the common biliary duct (yellow arrow), and the inferior vena cava (gray arrow) were cannulated. The supra-diaphragmatic end of the inferior vena cava was closed with running sutures (black star)

114 resections in anterior segments and a LLS to assess the
115 surgical relevance of the model, the vascular permeability
116 of the liver, and the efficacy of surgical devices during
117 liver resections.

118 Customized Mannequin Design

119 The customized mannequin should be able to host the ex situ
120 cadaver liver continuously pressurized model, whatever its
121 size or anatomy, and to provide laparoscopic conditions of
122 surgical training. Namely, the mannequin was designed to
123 maintain in a realistic and anatomical position for human
124 livers of different dimensions, in order to facilitate both the
125 reproducibility and scalability of the teaching model. These
126 included a working space obtained through the pneumoperi-
127 toneum in the operating room, a realistic insertion and
128 manipulation of laparoscopic devices through the anterior
129 abdominal wall, and the caudal approach of the liver model
130 during LLR.^{17,18} For a satisfying educational potential,
131 trocar placement should be free for each operator, to teach
132 novice surgeons how to correctly place them. To enhance
133 the simulation realism, the simulator and the liver should
134 be placed in an anatomical position (i.e., suspended by its
135 anatomical attachments, especially to the diaphragm), as in
136 the operating room where the operating table is placed in a
137 slightly sloping position.

138 Other specifications had to be met to facilitate the use of
139 the customized mannequin. It had to be liquid proof to han-
140 dle pressurization fluids losses and to be properly cleaned.
141 Pressurization fluid losses and smokes due to electrical or
142 ultrasonic instruments had to be drained from the custom-
143 ized mannequin for good visibility during the simulation.

144 The customized mannequin was designed by computer-
145 aided design on Rhinoceros 6 software (Robert McNeel &
146 Associates, Barcelona, Spain) based on a numerical finite
147 element model of the abdominal cavity.

148 Prototype Manufacturing

149 The main large prototype parts were manufactured by 3D
150 printing by the company INITIAL (Chavanod, Haute-Savoie,
151 France). The smallest parts were 3D printed thanks to the
152 Markforged® Mark Two printer (Watertown, Massachusetts,
153 USA) of the LBA.

154 A 10-mm thick RS Pro neoprene rubber plate (Corby,
155 UK) was used to simulate the skin space of the abdominal
156 anterior wall.

157 To be able to play with the orientation of the customized
158 mannequin and to allow the connection of the pressuriza-
159 tion liquid evacuations, four adjustable feet from Nu-Tech
160 Engineering (Poole, UK) were used.

Identification of LLR

162 The Southampton Guidelines advocated that the laparo-
163 scopic approach should be considered the standard practice
164 for the lesions of the left lateral and anterior segments at
165 the beginning of the LC.⁵ Indeed, laparoscopy has become
166 the standard surgical approach for left lateral sectionectomy
167 (LLS) (i.e., en-bloc resection of segments 2 and 3) due to its
168 anatomical accessibility.^{19–21} The LLS was the LLR chosen
169 to assess the educational value of the Lap-liver trainer. All
170 simulated procedures were done at the CERC, Aix-Marseille
171 Université, France. The CERC has the necessary laparo-
172 scopic surgical equipment (i.e., grasp, bipolar coagulation,
173 laparoscopic thunderbeat™ or LigaSure™ devices, liver
174 retractor, laparoscopic vacuum device, laparoscopic cam-
175 era, light source, and monitor) to perform a LLR with the
176 Lap-liver trainer (Supplementary Fig. 1).

Selection of Participants

178 Fifteen volunteers were recruited through personal commu-
179 nication as participants of the present study from a teaching
180 hospital (Hôpital Nord, Aix-Marseille Université, Marseille,
181 France). Among them, 3 were experts (surgeons experienced
182 both in laparoscopic and hepatobiliary surgery and with
183 prior experiences in LLR), 4 were intermediates (young
184 surgeons who had performed more than 30 laparoscopic
185 procedures but no LLR independently), and 8 were novices
186 (postgraduates who had little laparoscopic exposure).

Educational Value Assessment of the Lap-Liver Trainer

189 Expert surgeons were asked to each perform two LLS with
190 the Lap-liver trainer. A questionnaire designed to assess lap-
191 liver trainer was completed by all experts after each proce-
192 dure. The lap-liver trainer was evaluated using a Likert scale
193 (1 = strongly disagree/dissatisfied/constrained; 2 = disagree/
194 dissatisfied/constrained; 3 = indifferent; 4 = agree/satisfied/
195 not constrained; and 5 = strongly agree/satisfied/absolutely
196 not constrained) in terms of overall satisfaction, realism of
197 laparoscopic condition, realism of anatomical condition of
198 the model, realism of operative tactile properties, realism
199 of intraoperative bleeding and bile leakage, realism of suc-
200 cessive procedure steps, and in terms of gestural constraints
201 encountered during LLS with the lap-liver trainer (Table 1).

202 Prior to LLS with the lap-liver trainer, a standardized
203 teaching program with video was shown to instruct step by
204 step all novices and intermediates on techniques of LLR
205 and specific steps of the surgery¹¹. Then, novice and inter-
206 mediate surgeons were asked to each perform a LLS with
207 the lap-liver trainer and were supervised by one expert sur-
208 geon during the procedure. Similarly, the lap-liver trainer

Table 1 Criteria for evaluations of the lap-liver trainer by expert surgeons

Section 1. Satisfaction

- 1- Overall, were you satisfied with such a procedure in simulation condition on the lap-liver trainer?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 2- Does the educational value of the lap-liver trainer seem satisfactory to you?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 3- Do you think that the lap-liver trainer has its place in a practical teaching program of laparoscopic liver surgery?
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree

Section 2. Realism

- 4- Is the overall realism proposed by the lap-liver trainer satisfactory?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 5- Are the laparoscopic conditions proposed by the lap-liver trainer satisfactory?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 6- Is the pressurized ex situ liver model used by the lap-liver trainer realistic and relevant?
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 7- Does the positioning of the pressurized ex situ liver model within the lap-liver trainer seem appropriate for the performance of laparoscopic liver surgery?
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 8- Does the lap-liver trainer allow a realistic and satisfactory laparoscopic mobilization of the anatomical attachments of the left lateral lobe?
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 9- Is the realization of the parenchymal transection plan on the lap-liver trainer realistic?
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 10- Is the dissection of the Glissonian pedicle of segments 3 and 2 on the lap-liver trainer realistic?
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 11- Is the dissection of the left hepatic vein on the lap-liver trainer realistic?
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 12- Is the bleeding on the Lap-liver trainer, if it has occurred, realistic?
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 13- Is the leakage of bile on the Lap-liver trainer, if it has occurred, realistic?
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 14- Is the analysis of the parenchymal transection plan on the Lap-liver trainer at the end of the procedure realistic and satisfactory under laparoscopy conditions?
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree

Section 3. Procedure

- 15- Does the implementation and positioning of the trocars on the Lap-liver trainer seem satisfactory and appropriate to perform a left lateral sectionectomy?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 16- Is the available laparoscopic instrumentation suitable for performing a left lateral sectionectomy on the lap-liver trainer?
1: strongly disagree, 2: disagree, 3: indifferent, 4: agree, 5: strongly agree
- 17- Is the operating view and the positioning of the operative aid satisfactory?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 18- Is the realization of the parenchymal transection plan on the lap-liver trainer satisfactory with the available laparoscopy equipment?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 19- Is the control and section of the Glissonian pedicle of segment 3 and 2 on the lap-liver trainer satisfactory with the available laparoscopy equipment?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 20- Is the control and section of the left hepatic vein on the lap-liver trainer satisfactory with the available laparoscopy equipment?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 21- Is the control of bleeding and/or biliary leakage on the Lap-liver trainer, if it has occurred, satisfactory with the available laparoscopy equipment?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied

Section 4. Gesture

- 22- Overall, were you constrained in your gestures during the procedure?
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained

Table 1 (continued)

- 23- Were you forced into setting up the trocars?
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 24- Have you been constrained in your vision of the operating field?
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 25- Have you been constrained in your gestures for the mobilization of the left lateral lobe of its anatomical attachments?
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 26- Were you constrained in your gestures during parenchymal transection?
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 27- Have you been constrained in your gestures for the control and section of the vascular structures of the left lateral lobe?
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained

Table 2 Criteria for evaluations of the Lap-Liver trainer by residents and novice surgeons

Section 1. Satisfaction

- 1- Overall, were you satisfied with the directed teaching and such a procedure in simulation condition on the lap-liver trainer?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 2- Has the realization of a laparoscopic left lateral sectionectomy on the lap-liver trainer brought you a benefit for your clinical practice or your learning?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied

Section 2. Realism

- 3- Is the overall realism proposed by the Lap-liver trainer satisfactory?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied
- 4- Are the laparoscopic conditions proposed by the Lap-liver trainer satisfactory?
1: strongly dissatisfied, 2: dissatisfied, 3: indifferent, 4: satisfied, 5: strongly satisfied

Section 3. Gesture

- 5- Overall, were you constrained in your actions during the procedure?
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 6- Were you forced into setting up the trocars?
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 7- Have you been constrained in your vision of the operating field?
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 8- Have you been constrained in your gestures for the mobilization of the left lateral lobe of its anatomical attachments?
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 9- Were you constrained in your gestures during parenchymal transection?
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained
- 10- Have you been constrained in your gestures for the control and section of the vascular structures of the left lateral lobe?
1: strongly constrained, 2: constrained, 3: indifferent, 4: not constrained, 5: absolutely not constrained

209 was evaluated by novice and intermediate surgeons using
210 a Likert scale in terms of overall satisfaction, realism of
211 laparoscopic condition, and in terms of gestural constraints
212 encountered during LLS with the lap-liver trainer (Table 2).

213 Results

214 Usability of the Ex Situ Pressurized Cadaver Liver 215 Model for Surgical Training

216 On a back table, 10 ex situ pressurized cadaver liver models
217 could be prepared for experimentation. The preparation of
218 the liver model took an average of 35 min. A wedge resection
219 of segment 6 and an LLS was done by two expert surgeons

on each liver model (Supplementary Fig. 2). Peripheral and
220 deep vascular and biliary permeability of the model were
221 observed for the 10 ex situ pressurized livers. The texture
222 of the liver parenchyma was judged suitable for dissection,
223 parenchymal transection, and control of intra-parenchymal
224 vascular and biliary structures during the different proce-
225 dures. The laparoscopic instrumentation used allowed con-
226 trol of the occurrence of bleeding. 227

Customized Mannequin Conception 228

The customized mannequin consisted of a close laparoscopic
229 training device. To host the ex situ pressurized cadaver liver
230 model, the customized mannequin was based on a simpli-
231 fied reconstruction of the abdominal cavity in laparoscopic
232

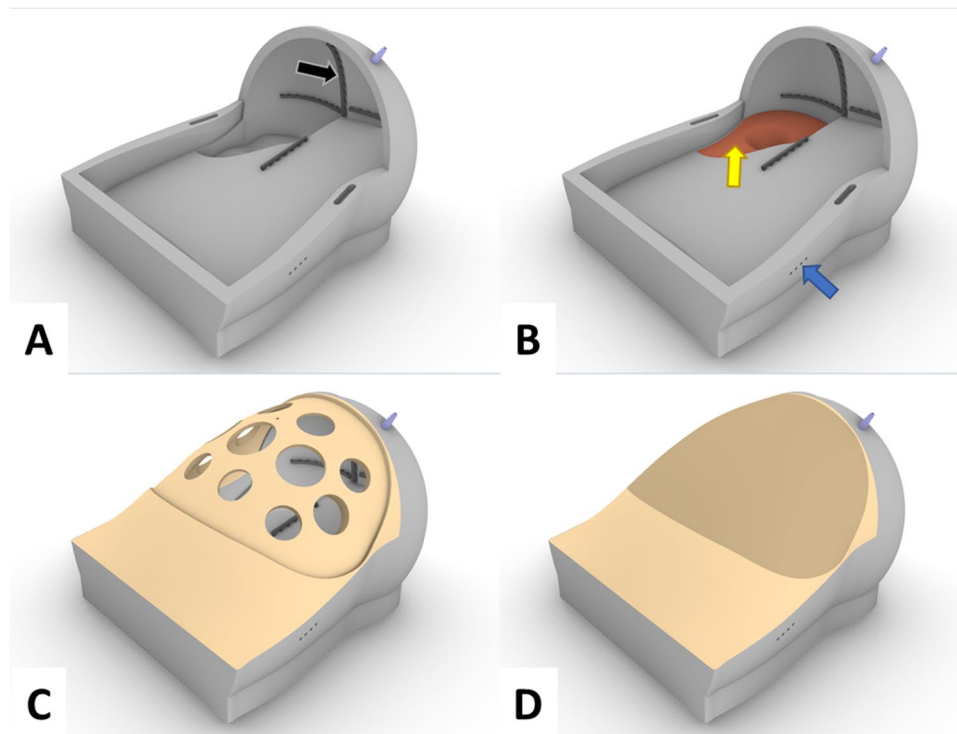


Fig. 2 Customized mannequin was designed by computer-aided design. **A** The base reconstructed, in a simplified way, the posterior abdominal wall and the diaphragm. The Liver model can be suspended by its anatomical attachments thanks to small bridges positioned at the corresponding locations on the base (black arrow). **B** To accommodate any liver size, three retroperitoneal wedges were developed to be placed in the right hypochondrium cavity (yellow area).

Four holes located on the right side allowed the passage of dedicated tubes for cannulation (blue arrow). **C** The cover was designed as a dome to simulate the pneumoperitoneum and to mimic the anterior abdominal wall in laparoscopic conditions. It was pierced with holes designed for the passage of trocars. **D** A recess was designed to receive a flexible neoprene-type material reproducing the skin space of the anterior abdominal wall

233 conditions. It consisted of two parts: a base and a cover
234 (Fig. 2).

235 The base rested on adjustable feet, allowing to adjust the
236 customized mannequin positioning. It reconstructed, in a
237 simplified way, the posterior abdominal wall and the dia-
238 phragm (Fig. 2A). The latter was designed by a hemisphere
239 shape. A cavity corresponding to the right hypochondrium
240 was dug to host the liver, and three funnel-shaped drain holes
241 for fluids and smoke losses were placed at the lowest points
242 of the base and at the diaphragm top. The liver model could
243 be suspended by its anatomical attachments (i.e., falciform,
244 round, and triangular ligaments) thanks to small bridges
245 positioned at the corresponding locations on the base. To
246 accommodate any liver size, three retroperitoneal wedges
247 were developed to be placed in the right hypochondrium
248 cavity (Fig. 2B). To pressurize the ex situ liver model, four
249 holes located on the right side allowed the passage of dedi-
250 cated tubes for cannulation. The latter could be hooked up
251 to a bridge to avoid unintentional movement.

252 The cover was developed to mimic the anterior abdominal
253 wall in laparoscopic conditions (Fig. 2C). Because real pneu-
254 moperitoneum is difficult to achieve, as it would require the

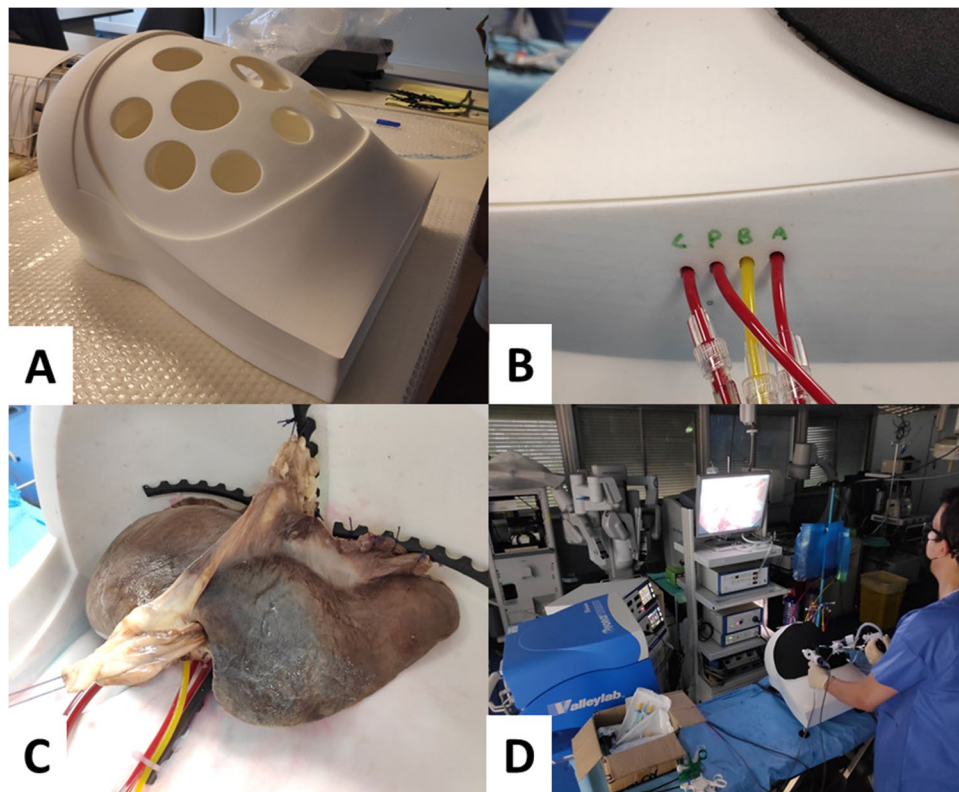
use of a CO₂ insufflator and related instruments, the cover
255 was designed as a dome to simulate the pneumoperitoneum.
256 It was pierced with holes designed in a honeycomb pattern,
257 respecting the triangulation principle, for the passage of
258 trocars and the free use of laparoscopic devices. The diam-
259 eters of the holes were determined to avoid any mechanical
260 stress between the trocars and the cover and between hands.
261 Another hole, smaller, allows the suspension of the liver
262 round ligament, as it would be to the umbilicus in humans.
263 A recess was designed to receive a flexible neoprene-type
264 material reproducing the skin space of the anterior abdomi-
265 nal wall (Fig. 2D).
266

267 Prototype Manufacturing

268 The 3D printing technology by powder sintering using poly-
269 amide PA2200 was chosen for the base and the cover manu-
270 facturing (Fig. 3A). A waterproofing varnish was applied
271 afterwards. The material used for the small bridges' manu-
272 facturing was Onyx, a nylon filled with carbon microfibers.

273 Prototype dimensions were 429 × 417 × 304 mm (height,
274 width, depth), allowing it to be moved and used easily on a

Fig. 3 The Lap-liver trainer. **A** Customized mannequin prototype. **B** The 5.2 mm diameter holes on the right side of the base let the dedicated tubes pass perfectly for cannulation. **C** After cannulation, the small bridges easily allowed suspension of the ex situ pressurized cadaver liver with interrupted sutures. **D** A novice surgeon performing a laparoscopic left lateral sectionectomy with the lap-liver trainer



275 surgical training table. The basal simulator proclivity is 15°,
 276 and adjustable feet could increase or reduce it. The flexible
 277 neoprene-type material was placed over the cover and held
 278 in place with a self-adhesive hook and loop tape. Magnets
 279 placed on both parts of the prototype satisfyingly held the
 280 base and the cover together.

281 The 5.2 mm diameter holes on the right side of the
 282 base let the dedicated tubes pass perfectly for cannulation
 283 (Fig. 3B). Drainage holes for fluids and smoke losses were
 284 linked to a basin and a suction system respectively. Small
 285 bridges easily allowed suspension of the ex situ pressurized
 286 cadaver liver with interrupted sutures (Fig. 3C). Thus, the
 287 liver was positioned realistically and could be mobilized like
 288 in the operating room.

289 On the cover, trocar holes had a diameter between 40 and
 290 80 mm to give the operator freedom for trocar placement and
 291 to avoid any mechanical stress. The flexible neoprene-type
 292 material allowed to hold the trocars in place and to learn
 293 trocar positioning with force feedback.

294 Feasibility of a Laparoscopic LLS with the Lap-Liver 295 Trainer and Educational Value

296 Each expert surgeon performed completely two LLS with
 297 the lap-liver trainer. All the experts gave positive scores
 298 in their questionnaire answers (Table 3). Expert surgeons
 299 were highly satisfied of the simulation conditions proposed

by the lap-liver trainer (4.80 ± 0.45), and they all strongly
 recommended that the lap-liver trainer should be incorporated
 into a teaching program of laparoscopic liver surgery
 (5.00 ± 0.0). The experts gave a positive evaluation of the
 laparoscopic condition and anatomic structures, in that the
 abdominal cavity had been well reproduced.

Furthermore, experts found that the overall realism proposed
 by the lap-liver trainer was satisfactory (4.60 ± 0.55)
 with a caudal approach of the liver during simulation.
 Although haptic feedback was slightly different from operations
 performed in the operating room, the usage of pressurized
 cadaver tissues made the experience realistic. Experts
 highlighted that blood and bile supplies made the surgical
 view identical to a real procedure (Fig. 4) and that demonstration
 of bleeding control and bile leakage was analogous
 to that of real surgery (Supplementary Fig. 3).

A total of 12 participants, including 8 novice and 4 intermediate
 surgeons, completed the teaching program and performed a
 LLS with the lap-liver trainer.

Overall, the level of satisfaction was high (4.92 ± 0.29),
 with 100% of the participants scoring 4/5 or 5/5 on question
 1 (Table 4). In addition, 100% of the participants found that
 performing such a procedure under simulation conditions benefited
 their learning and clinical practice (4.92 ± 0.29). Regarding
 the realism proposed by the lap-liver trainer, all the participants
 gave positive scores in their questionnaire answers (4.42 ± 0.51).
 Finally,

Table 3 Scores given by experts to the lap-liver trainer on a 5-point Likert scale

Items	Mean \pm SD
Section 1. Satisfaction	
1- Overall, were you satisfied with such a procedure in simulation condition on the Lap-liver trainer?	4.80 \pm 0.45
2- Does the educational value of the Lap-liver trainer seem satisfactory to you?	4.60 \pm 0.55
3- Do you think that the Lap-liver trainer has its place in a practical teaching program of laparoscopic liver surgery?	5.00 \pm 0.0
Section 2. Realism	
4- Is the overall realism proposed by the Lap-liver trainer satisfactory?	4.60 \pm 0.55
5- Are the laparoscopic conditions proposed by the Lap-liver trainer satisfactory?	4.60 \pm 0.55
6- Is the pressurized ex situ liver model used by the Lap-liver trainer realistic and relevant?	4.80 \pm 0.45
7- Does the positioning of the pressurized ex situ liver model within the Lap-liver trainer seem appropriate for the performance of laparoscopic liver surgery?	4.80 \pm 0.45
8- Does the Lap-liver trainer allow a realistic and satisfactory laparoscopic mobilization of the anatomical attachments of the left lateral lobe?	5.00 \pm 0.0
9- Is the realization of the parenchymal transection plan on the Lap-liver trainer realistic?	4.20 \pm 0.45
10- Is the dissection of the hepatic pedicle of segment 3 and 2 on the Lap-liver trainer realistic?	4.00 \pm 0.71
11- Is the dissection of the left hepatic vein on the Lap-liver trainer realistic?	4.40 \pm 0.55
12- Is the bleeding on the Lap-liver trainer, if it has occurred, realistic?	4.20 \pm 0.45
13- Is the leakage of bile on the Lap-liver trainer, if it has occurred, realistic?	4.20 \pm 0.45
14- Is the analysis of the parenchymal transection plan on the Lap-liver trainer at the end of the procedure realistic and satisfactory under laparoscopy conditions?	4.40 \pm 0.55
Section 3. Procedure	
15- Does the implementation and positioning of the trocars on the Lap-liver trainer seem satisfactory and appropriate to perform a left lateral sectionectomy?	4.40 \pm 0.55
16- Is the available laparoscopic instrumentation suitable for performing a left lateral sectionectomy on the Lap-liver trainer?	4.40 \pm 0.55
17- Is the operating view and the positioning of the operative aid satisfactory?	4.40 \pm 0.55
18- Is the realization of the parenchymal transection plan on the Lap-liver trainer satisfactory with the available laparoscopy equipment?	4.20 \pm 0.45
19- Is the control and section of the segment 3 and 2 hepatic pedicles on the Lap-liver trainer satisfactory with the available laparoscopy equipment?	4.60 \pm 0.55
20- Is the control and section of the left hepatic vein on the Lap-liver trainer satisfactory with the available laparoscopy equipment?	4.40 \pm 0.55
21- Is the control of bleeding and/or biliary leakage on the Lap-liver trainer, if it has occurred, satisfactory with the available laparoscopy equipment?	4.80 \pm 0.45
Section 4. Gesture	
22- Overall, were you constrained in your gestures during the procedure?	4.40 \pm 0.55
23- Were you forced into setting up the trocars?	4.80 \pm 0.45
24- Have you been constrained in your vision of the operating field?	4.40 \pm 0.45
25- Have you been constrained in your gestures for the mobilization of the left lateral lobe of its anatomical attachments?	4.60 \pm 0.55
26- Were you constrained in your gestures during parenchymal transection?	4.80 \pm 0.45
27- Have you been constrained in your gestures for the control and section of the vascular structures of the left lateral lobe?	4.00 \pm 1.00

327 concerning the gestures and possible constraints encountered during the simulation, none of the participants were
 328 constrained in the placement of the trocars (4.58 \pm 0.51)
 329 and the vision of the operating field (4.67 \pm 0.49). Two
 330 of the novice surgeons were constrained at the end of the
 331 parenchymal transection as well as for the dissection and
 332 control of the left hepatic vein. The macroscopic multinodular
 333 cirrhotic and fibrous aspect of the two liver models on
 334 which the procedure was performed explains the exposure
 335 difficulties encountered by these two participants.
 336

At the end of the teaching program and the simulation,
 participants expressed the wish to be able to repeat this
 experience to become more familiar with this approach
 in liver surgery. All emphasized the value of this training
 outside the operating room. Moreover, they highlighted the
 way that it allowed them to become aware of the anatomical
 proximity of the vascular elements of the liver and of
 their orientation in space.

Fig. 4 Laparoscopic left lateral sectionectomy with the Lap-liver trainer. **A** The parenchymal transection plan was begun at the left side of the round (blue arrow) and falciform (yellow arrow) ligaments. **B** Dissection and control of the Glissonian pedicle of segment 3 (dark blue lines). **C** Dissection and control of the Glissonian pedicle of segment 2 (light blue lines). **D** The parenchymal transection plan continued along the falciform and Arantius ligaments (green line and arrows). **E** Dissection and control of the left hepatic vein (purple lines). **F** Final mobilization of the left lateral lobe (orange arrow)

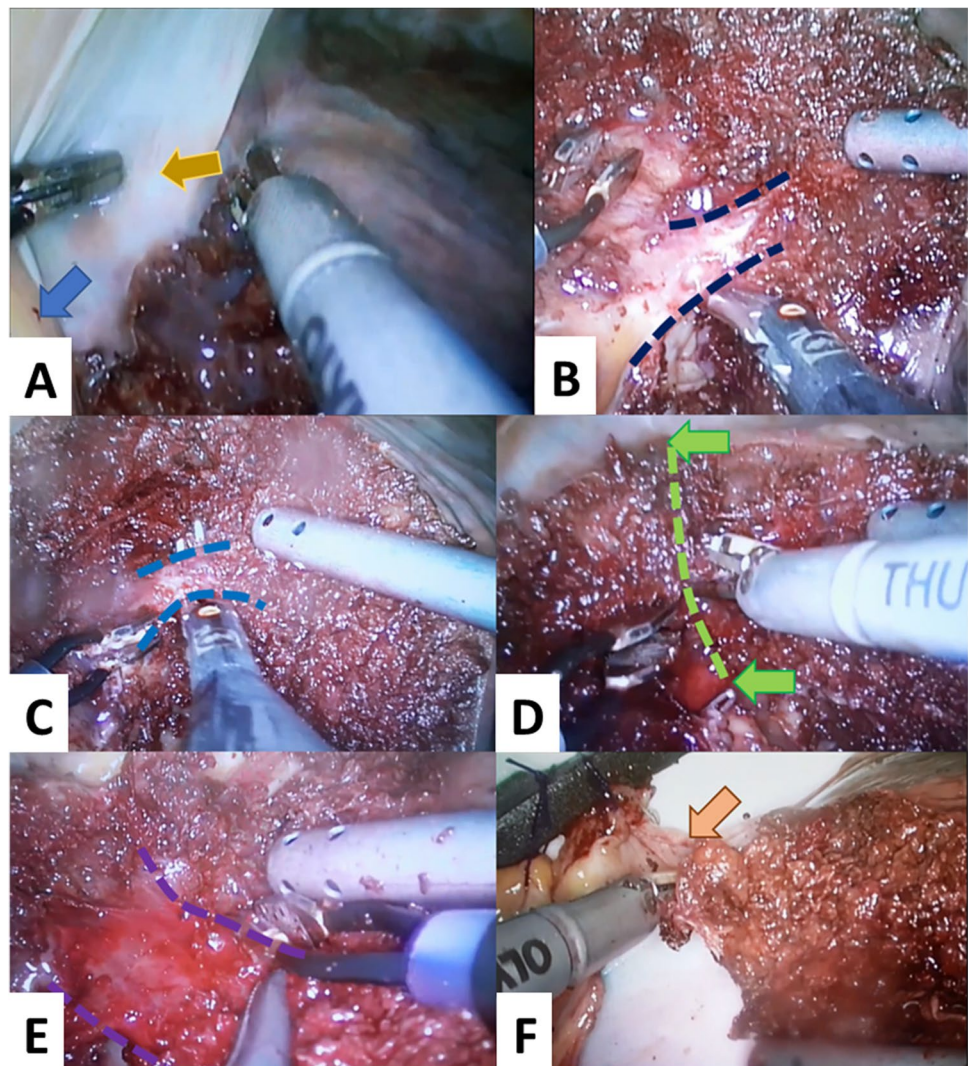


Table 4 Scores given by residents and novice surgeons to the Lap-liver trainer on a 5-point Likert scale

Items	Mean \pm SD
Section 1. Satisfaction	
1- Overall, were you satisfied with the directed teaching and such a procedure in simulation condition on the Lap-liver trainer?	4.92 \pm 0.29
2- Has the realization of a laparoscopic left lateral sectionectomy on the Lap-liver trainer brought you a benefit for your clinical practice or your learning?	4.92 \pm 0.29
Section 2. Realism	
3- Is the overall realism proposed by the Lap-liver trainer satisfactory?	4.42 \pm 0.51
4- Are the laparoscopic conditions proposed by the Lap-liver trainer satisfactory?	4.42 \pm 0.51
Section 3. Gesture	
5- Overall, were you constrained in your actions during the procedure?	4.33 \pm 0.49
6- Were you forced into setting up the trocars?	4.58 \pm 0.51
7- Have you been constrained in your vision of the operating field?	4.67 \pm 0.49
8- Have you been constrained in your gestures for the mobilization of the left lateral lobe of its anatomical attachments?	4.50 \pm 0.52
9- Were you constrained in your gestures during parenchymal transection?	4.33 \pm 0.98
10- Have you been constrained in your gestures for the control and section of the vascular structures of the left lateral lobe?	4.25 \pm 0.87

Discussion

Laparoscopic liver surgery has a steep LC, and safe implementation of it requires stepwise training.^{6–8} Competency in minor LLR is acquired after 15 to 60 cases, whereas 20 to 60 cases are needed to reach proficiency in major LLR, provided proficiency has been already reached for minor LLR.^{5,8} However, LC is a “moving target,” where, on the one hand, surgeons take on more difficult cases with increasing experience, and on the other hand, the LC may change from the self-taught pioneer to the master/apprentice timeline. This LC could be dramatically reduced with specific training and increased exposure of trainees to LLR.⁷ Indeed, the Southampton consensus guideline recommends fellowships in high-volume centers, proctored programs, and courses to facilitate training.⁵

This study presents a novel innovation using *ex situ* cadaver liver continually pressurized in a customized mannequin. The lap-liver trainer uses several sources to create a more holistic and realistic clinical scenario for laparoscopic liver surgery education at the beginning of the LC.⁵ Haptic feedback is an essential part of laparoscopic training.^{22,23} In our study, most of the participants spoke highly of the system, regarding it as a new, effective laparoscopic liver training model and considering the real tactile feedback to be one of the most attractive features. Furthermore, the caudal approach of the liver^{17,18} and specific events of LLR were successfully demonstrated including intraprocedural bleeding and bile leakage which were unattainable in other training models like human cadaver, conventional training simulators, or virtual reality. In addition, in comparison to animal models, the lap-liver trainer is free from specific logistic and ethical demands for managing animals and is easy to transport. Our system was patented under application number FR2200286 on 2022/01/14. The next step for us is to find a partnership with a manufacturer to disseminate our model in France first, then possibly internationally.

Human cadaveric livers are harvested from bodies donated for medical research that are used for other research purposes in the meantime. Hence, the mean cost for a cadaveric liver can only be estimated, around 1000€, and their availability relies on body donation regulatory aspects and necessitates the facilities of an anatomy lab. When it comes to the manufacturing of our model, its entire cost is estimated at around 3431€. Moreover, liver collection from bodies donated for medical research constitutes a potential educational session in itself. As for LLR, apart from LLS, only wedge resection of the anterior segments (WRAS) has been taught to novices with this model. Indeed, until now, the purpose was to train novices in laparoscopic liver surgery. Forthcoming studies should assess our model for more complex LLR, such as right hepatic lobectomy.

The rapid expansion and acceptance of laparoscopic surgery have increased the demand of laparoscopic training for advanced surgeries. Many new techniques for laparoscopic training have been explored and have demonstrated the positive impact of simulation on technical skills for basic laparoscopic procedures.^{24–28} Moreover, simulation-based training programs have shown benefits in shortening the LC of young surgeons and reducing the number of adverse events in the operating room.^{29,30} However, simulation for complex laparoscopic procedures has been assessed to a lesser extent.^{8,31} These procedures are associated with a longer LC and are not easily accessible by young surgeons. In hepatobiliary surgery, the average number of hepatic resections performed by postgraduates at the completion of their general surgery training is estimated to be five cases (range 0–20), which are predominantly open surgery.^{32,33} A training model mimicking as much as possible a real organ and simulating intraoperative bleeding and bile leakage could greatly enhance the acquisition of specific skills in LLR.

Systematic reviews on laparoscopic training curriculums found that the use of live animal models or *ex vivo* simulators was preferred because other modalities cannot realistically reproduce the specific events.^{31,34–38} In LLR, the main training models used were live animal models, *ex vivo* simulators, and human cadavers.⁸ LLR requires surgeons to be trained in managing hemostasis and bile leakage control during parenchymal transection. Recently, efforts have been made to improve the experience of *ex vivo* simulators to overcome organizational constraints rendered by animal-based training curriculums.^{38–41} Red fluid^{14,38,41} or porcine blood⁴⁰ was used to simulate bleeding control during LLR, but data regarding bile leakage simulation are lacking. However, bile leakage is a specific event in LLR that requires special attention during parenchymal transection plan assessment at the end of the procedure to optimize patient outcomes.¹¹ Moreover, *ex vivo* simulator models using animal organs demonstrate one crucial drawback: animal organs cannot resemble human anatomy in its entirety which is necessary in advanced surgery to identify anatomical landmarks.

Our augmented reality simulator combines a continuously pressurized *ex situ* cadaver liver training model and a customized mannequin to improve laparoscopic surgical skills and to help participants to climb the inherent LC of LLR in a more realistic environment without the restrictions of anatomical differences, exorbitant expenses, and ethical issues of animal models. Our study showed that our system can be reproducibly used in laparoscopic training and that wedge resection and LLS are feasible with the lap-liver trainer. The educational value of the lap-liver trainer was highlighted by all participants and provides a more holistic and realistic environment for trainees to learn specific skills in both laparoscopy surgery and LLR. Most importantly,

449 participants can improve their ability to deal with unex-
 450 pected events intraoperatively using the lap-liver trainer, as it
 451 is currently unattainable in other inanimate training models.
 452 Specific events (such as bleeding and bile leakage) initiated
 453 during simulation serves to further refine the scenarios and
 454 techniques involved to optimize patient outcome in clinical
 455 practice. In addition, our system can be used in an open liver
 456 resection training program thanks to the removable capaci-
 457 ty of the customized mannequin's cover. In case of ethical
 458 restrictions on the use of cadaver organs, an animal liver can
 459 be used for simulation.

460 Despite the potential advantages of the lap-liver trainer
 461 and the contributions of our study, there are some limita-
 462 tions. First, anatomical features around the liver such as dia-
 463 phragmatic movements cannot be reproduced completely.
 464 Second, the macroscopic aspect of the cadaver liver is dif-
 465 ficult to predict before procurement and could impair the
 466 reproducibility of LLR simulation between participants.
 467 Before training, the procurement and preparation of cadaver
 468 livers were standardized. Some techniques relevant to liver
 469 transplantation could involve a specific transplantation train-
 470 ing program and should benefit young surgeons. Third, the
 471 study's aim was to assess the feasibility of a LLR on the
 472 lap-liver trainer and its educational value but did not pro-
 473 vide a robust evaluation of trainees' skill acquisition. In this
 474 prospective and the will to determine objective data related
 475 to the acquisition of skills, the lap-liver trainer seems to be
 476 a suitable platform for the motion analysis of psychomo-
 477 tor skills in LLR. To recognize and assess each instrument
 478 individually irrespective of instrument exchanges, which
 479 allows the characterization of the motions of multiple surgi-
 480 cal instruments simultaneously in complex training tasks, it
 481 seems better than basic procedures data to digitize the level
 482 of surgical competency and to provide a clear feedback of
 483 motion parameters to trainees.⁴² Finally, for now, our model
 484 has only been developed to host a liver. Other organs could
 485 be implemented in this simulator in the future, provided that
 486 the same method is used to design its anatomical attaches
 487 and to prove its educational value.

488 In summary, the lap-liver trainer developed in the pre-
 489 sent study could provide better opportunities for trainees to
 490 acquire and practice LLR skills in a more realistic environ-
 491 ment. Most importantly, trainees can improve their ability
 492 to deal with unexpected specific events related to LLR. The
 493 lap-liver trainer is a feasible and effective training system
 494 and could be used efficiently to improve skill teaching and
 495 learning in laparoscopic liver surgery. We are currently
 496 working to improve our novel system and for a better under-
 497 standing of motion parameters of psychomotor skills related
 498 to the inherent LC. Furthermore, a subsequent step in our
 499 research will be to demonstrate improvement following a
 500 training session on the lap-liver trainer in the junior surgeons
 501 and transfer of skills in the operating room setting.

Supplementary Information The online version contains supplemen- 502
 tary material available at <https://doi.org/10.1007/s11605-022-05566-9>. 503

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 of the work in ensuring that questions related to the accuracy or integri- 513
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 the work. Final approval of the version to be published. Agreed to 516
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 related to the accuracy or integrity of any part of the work are appro- 518
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 the accuracy or integrity of any part of the work are appropriately 523
 investigated and resolved. 524

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 or integrity of any part of the work are appropriately investigated and 528
 resolved. 529

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 the work. Final approval of the version to be published. Agreed to 531
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 related to the accuracy or integrity of any part of the work are appro- 533
 priately investigated and resolved. 534

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 be published. Agreed to be accountable for all aspects of the work in 537
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 of the version to be published. Agreed to be accountable for all aspects 542
 of the work in ensuring that questions related to the accuracy or integri- 543
 ty of any part of the work are appropriately investigated and resolved. 544

Declarations 545

The present liver training model named lap-liver trainer was patented 546
 under application number FR2200286 on 2022/01/14. 547

Competing Interests The authors declare no competing interests. 548

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