Supplementary Materials

Hierarchical quantification of operative workflow in laparoscopic left lateral sectionectomy using step-task-action triplets and automated recognition

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Supplementary Table 1. Recorded step counts and task labels in the LLS48 dataset

Clinical task group	Step label	Step frame count	Task	Task label	Task frame count
S1	Trocar placement	605	T1	Trocar placement	520
S2	Left liver mobilization	2030	T2	Dissection of the falciform ligament	440
			T3	Dissection of the left coronary ligament	430
			T4	Dissection of the left triangular ligament	775
			T5	Dissection of the hepatogastric ligament	75
S3	Parenchymal transection	5015	T6	Pringle maneuver	310
			T7	Demarcation of left lateral section	240
			T8	Parenchymal transection	2910
			T9	Inflow control-division of G2 and G3	680
			T10	Outflow control-division of left hepatic vein	470
S4	Hemostasis after transection	1065	T11	Hemostasis of the transected liver surface	935
			T12	Hemostasis of the perihepatic tissue	540
S5	Extraction and drainage	845	T13	Package of the specimen	260
			T14	Hemostatic agents placement	185

			T15	Anti-adhesive agents placement	85
			T16	Drainage tube placement	245
Events	Step-independent event	—	T17	Adhesiolysis	450
			T18	Liver cyst aspiration	10

Step frame counts use the recorded step labels and sum to 9,560. Tasks are arranged by primary clinical association, so task counts within each group need not sum to the corresponding step count. The 460 frames containing step-independent tasks retain their recorded step labels and are included in the five step counts. No separate event step is defined.

Supplementary Table 2. Distribution of triplet components in the LLS48 dataset

Instrument	Count	Verb	Count	Target	Count
anti-adhesive agents	70	aspirate	1130	G2 and G3	295
bipolar	705	clamp	110	aberrant left hepatic artery	5
bulldog	125	clip	340	adhesion	370
bulldog applicator	70	coagulate	695	blood	885
clipper	350	cut	175	bulldog	90
grasper	6105	dissect	3570	clip	20
Hem-o-lok clip	45	divide	395	diaphragm	20
hemostatic agents	175	examine	10	diaphragm vein	25
hook	1770	grasp	3330	drain tube	165
needle holder	25	irrigate	195	duodenum	20
right angle	155	null verb	2250	falciform ligament	325
scissor	235	pack	85	fluid	55
Sonicision	2740	place	265	gallbladder	145
sono probe	10	remove	55	gauze	320
specimen bag	145	retract	4330	glisson	275
stapler	510	suture	15	Hem-o-lok	5
suction	3715			hemostatic agents	20
				hepatoduodenal ligament	295
				hepatogastric ligament	80
				inflow stapler line	435
				intrahepatic	185

	vein	
	left coronary ligament	475
	left hepatic vein	235
	left triangular ligament	710
	liver	2200
	liver cyst	45
	liver parenchyma	4345
	liver surface	405
	needle	5
	null target	2320
	omentum	375
	outflow stapler line	25
	round ligament	1365
	specimen	345
	specimen bag	15
	stomach	25
	suture	20
	vein	5

Counts are aggregated over the 195 distinct action-triplet classes in the annotation, totaling 16,950 triplet-frame occurrences. Each distinct triplet is counted at most once per annotated frame. A component can therefore be counted more than once in a frame when it occurs in different triplets; these are not unique component-frame counts.

Supplementary Table 3. Distribution of triplet labels in the LLS48 dataset

Name	Count	Name	Count	Name	Count	Name	Count
bipolar, coagulate, liver parenchyma	490	grasper, retract, diaphragm	20	right angle, dissect, round ligament	5	suction, aspirate, gauze	45
bipolar, dissect, liver parenchyma	20	grasper, retract, falciform ligament	15	right angle, retract, glisson	10	suction, aspirate, hepatoduodenal ligament	10
bipolar, grasp, gauze	30	grasper, retract, gallbladder	5	right angle, retract, intrahepatic vein	5	suction, aspirate, hepatogastric ligament	5
bipolar, grasp, round ligament	5	grasper, retract, gauze	5	right angle, retract, left hepatic vein	15	suction, aspirate, left coronary ligament	5
bipolar, retract, hepatogastric ligament	10	grasper, retract, hepatoduodenal ligament	70	scissor, cut, G2 and G3	10	suction, aspirate, left hepatic vein	15
bipolar, retract, liver	25	grasper, retract, hepatogastric ligament	15	scissor, cut, diaphragm vein	5	suction, aspirate, left triangular ligament	10
bipolar, retract, omentum	15	grasper, retract, inflow stapler line	20	scissor, cut, glisson	55	suction, aspirate, liver cyst	5
bulldog applicator, remove,	55	grasper, retract, left coronary	15	scissor, cut, inflow stapler line	30	suction, aspirate, liver parenchyma	70

bulldog		ligament					
bulldog, clamp, aberrant left hepatic artery	5	grasper, retract, left hepatic vein	5	scissor, cut, intrahepatic vein	15	suction, aspirate, liver surface	5
bulldog, clamp, hepatoduodenal ligament	105	grasper, retract, left triangular ligament	55	scissor, cut, left hepatic vein	5	suction, aspirate, omentum	5
clipper, clip, G2 and G3	20	grasper, retract, liver	1590	scissor, cut, left triangular ligament	10	suction, dissect, left coronary ligament	10
clipper, clip, diaphragm vein	5	grasper, retract, liver cyst	5	scissor, cut, outflow stapler line	10	suction, dissect, left triangular ligament	5
clipper, clip, glisson	90	grasper, retract, liver parenchyma	25	scissor, dissect, G2 and G3	5	suction, dissect, liver cyst	10
clipper, clip, inflow stapler line	35	grasper, retract, omentum	95	scissor, dissect, liver parenchyma	10	suction, irrigate, left triangular ligament	20
clipper, clip, intrahepatic vein	90	grasper, retract, round ligament	20	Hem-o-lok clip, clip, glisson	25	suction, irrigate, liver surface	170
clipper, clip, left coronary ligament	5	grasper, retract, specimen	90	Hem-o-lok clip, clip, intrahepatic vein	5	suction, irrigate, omentum	5
clipper, clip, left hepatic	10	grasper, retract,	15	Sonicision, cut, glisson	10	suction, place, gauze	15

vein		stomach					
clipper, clip, left triangular ligament	25	Hem-o-lok clip, clip, inflow stapler line	5	Sonicision, cut, intrahepatic vein	5	suction, retract, duodenum	5
clipper, clip, outflow stapler line	10	Hem-o-lok clip, clip, left hepatic vein	5	Sonicision, cut, left triangular ligament	20	suction, retract, falciform ligament	5
clipper, clip, round ligament	5	hemostatic agents, place, left coronary ligament	10	Sonicision, dissect, G2 and G3	5	suction, retract, gallbladder	5
clipper, clip, vein	5	hemostatic agents, place, left triangular ligament	10	Sonicision, dissect, adhesion	70	suction, retract, glisson	5
grasper, dissect, left coronary ligament	5	hemostatic agents, place, liver parenchyma	110	Sonicision, dissect, falciform ligament	80	suction, retract, hepatoduodenal ligament	40
grasper, dissect, left triangular ligament	5	hemostatic agents, place, liver surface	40	Sonicision, dissect, glisson	30	suction, retract, hepatogastric ligament	5
grasper, grasp, adhesion	60	hook, coagulate, falciform ligament	5	Sonicision, dissect, hepatoduodenal ligament	15	suction, retract, intrahepatic vein	5
grasper, grasp, bulldog	30	hook, coagulate, left triangular ligament	5	Sonicision, dissect, hepatogastric ligament	5	suction, retract, left hepatic vein	10

grasper, grasp, clip	20	hook, coagulate, liver parenchyma	35	Sonicision, dissect, inflow stapler line	5	suction, retract, left triangular ligament	10
grasper, grasp, diaphragm vein	15	hook, coagulate, liver surface	130	Sonicision, dissect, intrahepatic vein	40	suction, retract, liver parenchyma	1855
grasper, grasp, drain tube	165	hook, coagulate, omentum	10	Sonicision, dissect, left coronary ligament	5	suction, retract, omentum	25
grasper, grasp, duodenum	15	hook, coagulate, round ligament	20	Sonicision, dissect, left triangular ligament	85	suction, retract, round ligament	30
grasper, grasp, falciform ligament	205	hook, dissect, adhesion	235	Sonicision, dissect, liver	15	suction, retract, specimen	5
grasper, grasp, gallbladder	125	hook, dissect, falciform ligament	15	Sonicision, dissect, liver parenchyma	1710	anti-adhesive agents, place, null target	70
grasper, grasp, gauze	215	hook, dissect, hepatoduodenal ligament	30	Sonicision, dissect, liver surface	60	bipolar, null verb, null target	110
grasper, grasp, Hem-o-lok	5	hook, dissect, hepatogastric ligament	20	Sonicision, dissect, omentum	15	bulldog applicator, null verb, null target	15
grasper, grasp, hemostatic	10	hook, dissect, left coronary ligament	410	Sonicision, dissect, round ligament	115	bulldog, null verb, null target	15

agents							
grasper, grasp, hepatoduodenal ligament	25	hook, dissect, left triangular ligament	370	Sonicision, grasp, gauze	10	clipper, null verb, null target	50
grasper, grasp, hepatogastric ligament	20	hook, dissect, liver cyst	10	Sonicision, grasp, intrahepatic vein	5	grasper, null verb, null target	745
grasper, grasp, inflow stapler line	330	hook, dissect, liver parenchyma	5	Sonicision, retract, inflow stapler line	5	Hem-o-lok clip, null verb, null target	5
grasper, grasp, left coronary ligament	10	hook, dissect, omentum	10	Sonicision, retract, liver	50	hemostatic agents, null verb, null target	5
grasper, grasp, left triangular ligament	80	hook, dissect, round ligament	60	Sonicision, retract, liver parenchyma	15	hook, null verb, null target	305
grasper, grasp, liver	430	hook, retract, bulldog	5	Sonicision, retract, specimen	5	needle holder, null verb, null target	5
grasper, grasp, liver cyst	15	hook, retract, gallbladder	5	sonoprobe, examine, liver	10	right angle, null verb, null target	45
grasper, grasp, omentum	195	hook, retract, round ligament	5	specimen bag, pack, specimen	85	scissor, null verb, null target	70
grasper, grasp, outflow	5	hook, retract, liver	80	stapler, divide, G2 and G3	230	Sonicision, null verb, null target	360

stapler line							
grasper, grasp, round ligament	1100	needle holder, grasp, needle	5	stapler, divide, left hepatic vein	165	specimen bag, null verb, null target	60
grasper, grasp, specimen	155	needle holder, suture, glisson	15	suction, aspirate, G2 and G3	5	stapler, null verb, null target	115
grasper, grasp, specimen bag	15	right angle, dissect, G2 and G3	20	suction, aspirate, adhesion	5	suction, null verb, null target	345
grasper, grasp, stomach	10	right angle, dissect, glisson	35	suction, aspirate, blood	885	scissor, retract, inflow stapler line	5
grasper, grasp, suture	20	right angle, dissect, intrahepatic vein	15	suction, aspirate, fluid	55	scissor, retract, specimen	5
grasper, place, hemostatic agents	10	right angle, dissect, left hepatic vein	5	suction, aspirate, gallbladder	5		

Counts of all 195 instrument-verb-target combinations in the annotation, including explicit null labels. The total is 16,950 triplet-frame occurrences. Each distinct triplet is counted once per frame in which it is present; repeated instances of the same triplet within a frame are not counted again. Different triplets in the same frame contribute separately.

Supplementary Table 4. Comparative performance of action triplet recognition models using the LLS48 dataset

Dataset	Method	mAP_I	mAP_V	mAP_T	mAP_IV	mAP_IT	mAP_IVT
LLS48	RDV	48.6 ± 6.9	46.8 ± 7.9	36.6 ± 5.4	30.7 ± 3.5	29.5 ± 4.2	27.7 ± 4.4
	SelfD-B	73.3 ± 3.9	68.7 ± 3.1	54.1 ± 2.3	50.3 ± 2.0	50.3 ± 1.8	48.0 ± 2.7
	TERL-B	76.7 ± 3.8	68.9 ± 1.6	56.1 ± 4.0	51.4 ± 3.5	50.1 ± 2.0	46.5 ± 3.2
	CurConMix-B	67.5 ± 2.3	64.4 ± 2.9	52.8 ± 3.4	46.9 ± 2.9	47.1 ± 2.4	44.7 ± 2.6

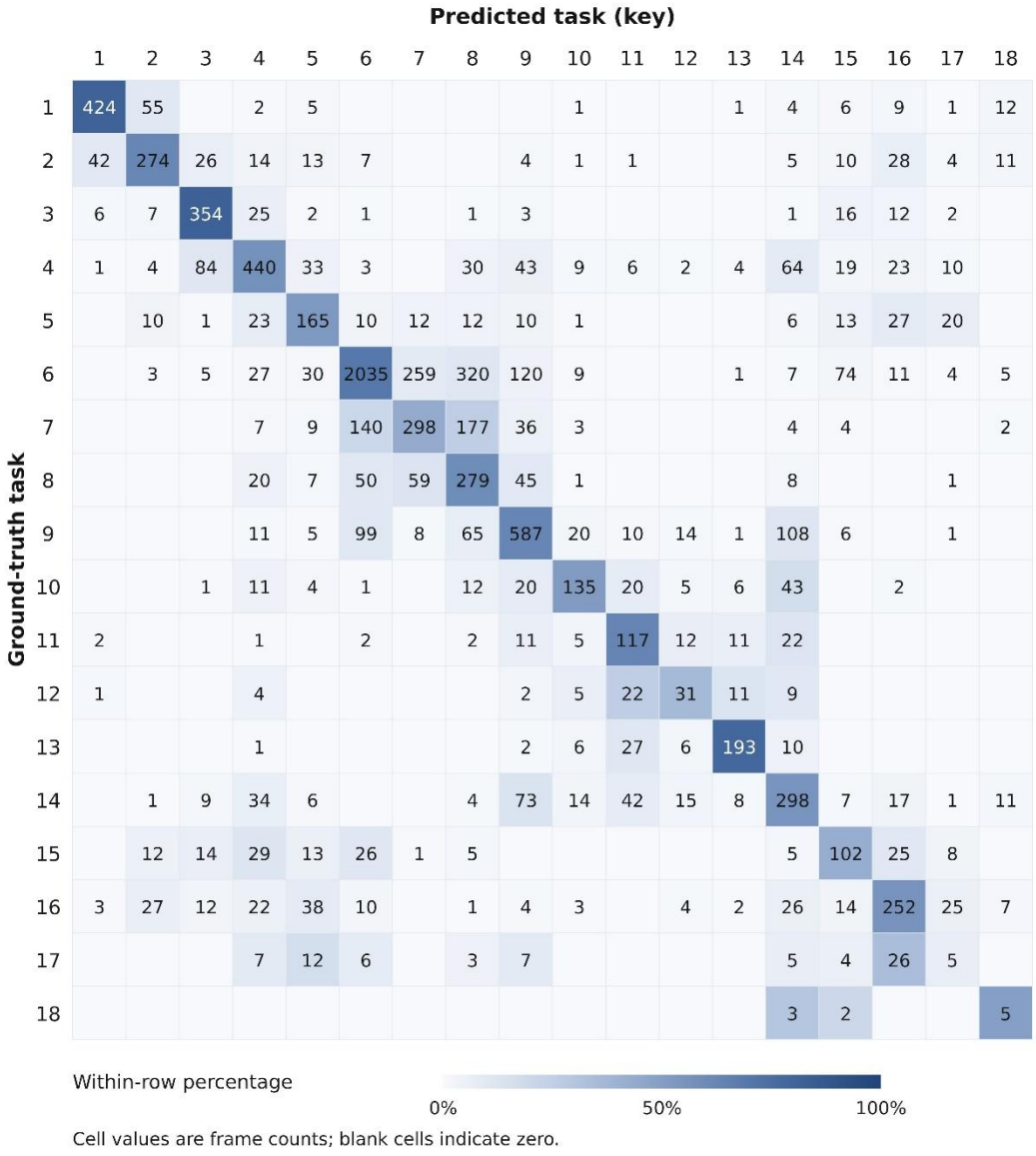
Results are reported as mean ± standard deviation across five test folds. mAP_I, mAP_V, mAP_T, mAP_IV, mAP_IT, and mAP_IVT denote mean average precision for instruments, verbs, targets, instrument–verb pairs, instrument–target pairs, and full triplets, respectively. CurConMix-B results are from the additional analysis. RDV, SelfD-B, and TERL-B were not retrained, and their previously obtained results are retained for descriptive reference. These results should not be interpreted as a comparison under identical experimental conditions. In the retained SelfD-B and TERL-B experiments, checkpoints were selected according to their highest test-fold performance, whereas revised CurConMix-B checkpoints were selected using validation AP before test-fold evaluation. The suffix "-B" denotes a Swin Transformer–Base backbone. RDV: Rendezvous; SelfD: self-distillation for surgical action recognition; TERL: tail-enhanced representation learning; CurConMix: curriculum contrastive learning with feature mixup.

Supplementary Table 5. Frequency-stratified action-triplet performance in the additional CurConMix analysis

Annotated frame frequency	Non-null classes	mAP_IVT (%) Mean ± SD
< 50	135	31.1 ± 4.5
≥ 50	44	59.9 ± 3.8

Frequency is the number of annotated frames containing each distinct triplet across all 9,560 frames [Supplementary Table 3]. Class counts refer to non-null classes in the full dataset. Within each test fold, AP was computed separately for each class in each procedure, then averaged across procedures containing positive examples of that class. Group mAP_IVT was the unweighted mean of these class-specific AP values. Classes without positive examples in the test fold were omitted, so evaluable class counts varied by fold. The 16 null-containing classes were excluded from averaging; frames containing null annotations were retained. Values are mean ± sample SD across five equally weighted test folds.

Supplementary Figure 1. Task-level out-of-fold confusion matrix



Cell values are frame counts; blank cells indicate zero.

Key	Task	Key	Task
1	Trocar placement	10	Package of the specimen
2	Dissection of the falciform ligament	11	Hemostatic agents placement
3	Dissection of the left coronary ligament	12	Anti-adhesive agents placement
4	Dissection of the left triangular ligament	13	Drainage tube placement
5	Pringle maneuver	14	Hemostasis of the perihepatic tissue
6	Parenchymal transection	15	Demarcation of left lateral section
7	Inflow control: division of G2 and G3	16	Adhesiolysis
8	Outflow control: division of left hepatic vein	17	Dissection of the hepatogastric ligament
9	Hemostasis of the transected liver surface	18	Liver cyst aspiration

Confusion matrix pooled across five test folds, with each of the 9,560 frames counted once. Rows indicate ground truth and columns indicate predictions. Cell values are counts, with blank cells representing zero. Colors show within-row percentages. Numbered keys identify the evaluation classes, not the manuscript task codes.