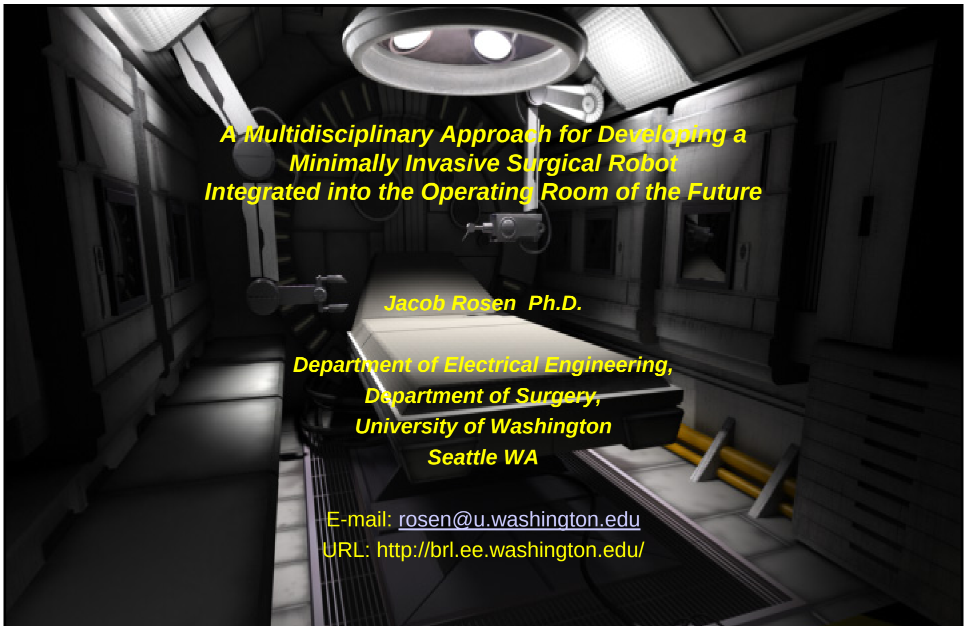

A Multidisciplinary Approach for Developing a Minimally Invasive Surgical Robot Integrated into the Operating Room of the Future

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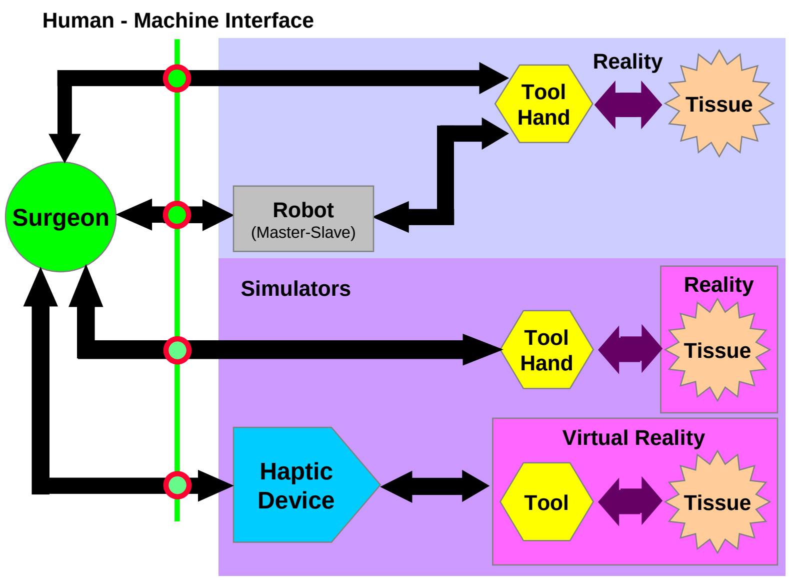
Medical Procedure – The Big Picture



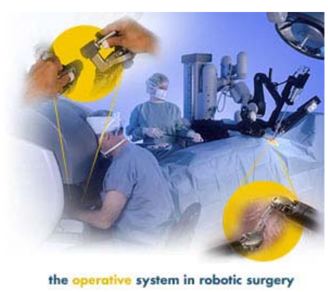
Part 1: The Operating Room of the Future

DARPA - Defense Advanced Research Projects


OWI 35269 D

Commercial Surgical Robotic Systems

- Intuitive Surgical: da Vinci
- Computer Motion: Zeus



www.intuitivesurgical.com

www.computermotion.com

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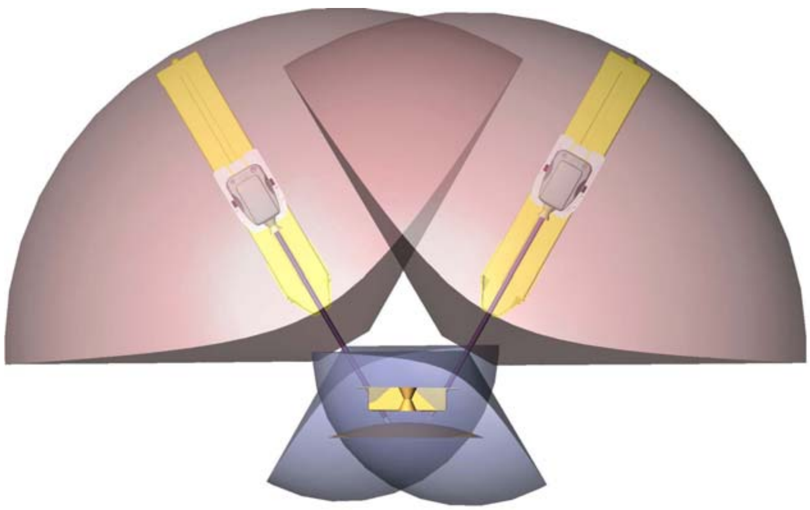

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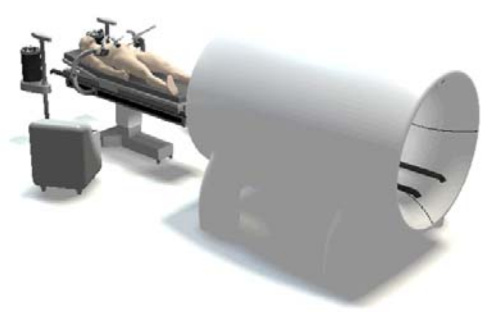
OR of the Future - Vision

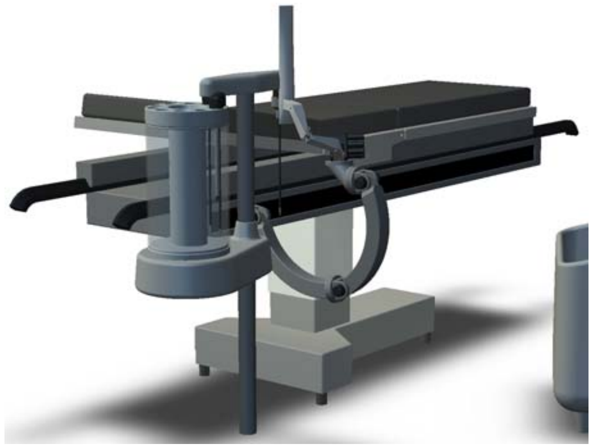
Integration of an intelligent surgical robotic system into the unmanned and automated operating room.

1. Full Body Scan
2. Simulation
3. Surgical Robotic Arm Extended Mobility
4. Surgeon Teleoperation Workstation
5. Tool Changer (Scrub Nurse)
6. Equipment Dispenser (Circulation Nurse)
7. High-Level Control and Monitoring Intelligence Layer
8. Inventory Management Software

OR – Overview (Movie Clip)



OR – Tool Changer



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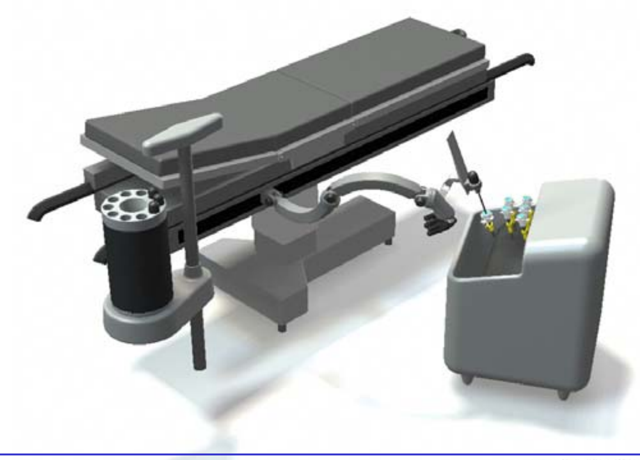
OR – Equipment Dispenser



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Trauma Pod Video Clip

www.traumapod.org

Part 2: Surgical Robot – Optimization & Design

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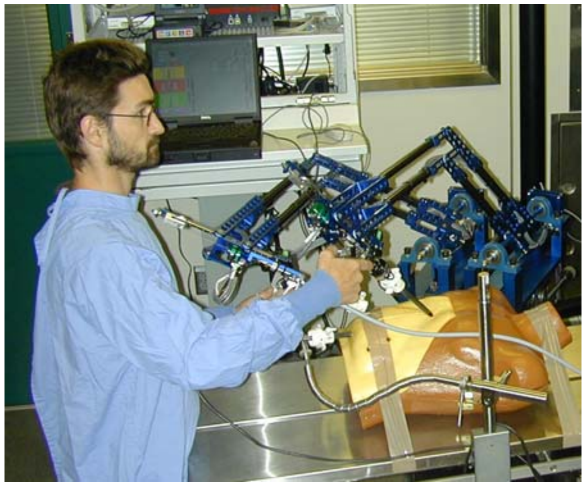
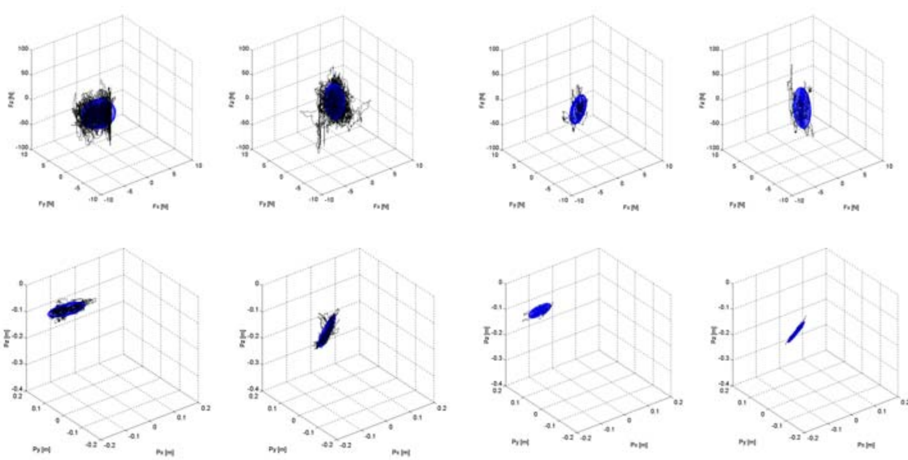
The Blue Dragon



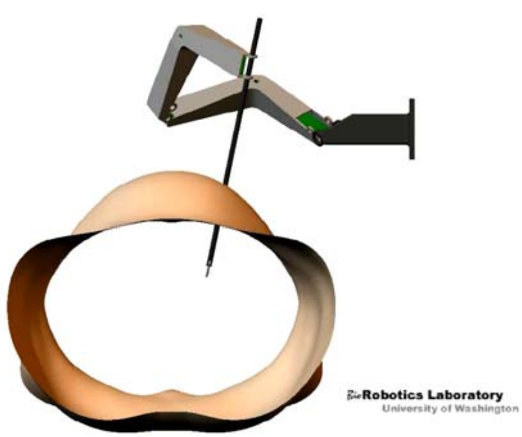
BlueDRAGON - Data



Engineering Specifications - BlueDRAGON

Device				DRAGON	UC Berkeley	UC Berkeley	UC Berkeley	DeVinchi	Zeus
Generation				R1 - E (95%)		1	2		
Referance					Measured	Traget	Obtained		
Base	Overall Geomtery	Shaft Diameter	[m]			0.01 - 0.015	0.01 - 0.015	0.01	0.005
	Position / Oriantataion	Delta Theta x	[Deg]	53.8047				+/-60	
		Delta Theta y	[Deg]	36.3807				+/-80	
		Delta Theta z	[Deg]	148.0986	90	180-270	720	+/-180	
		R	[m]	0.1027				0.2	
		Grasping Jaw s	[Deg]	24.0819				200	
		Grasping Jaw s	[m]	*	0.006	0.002-0.003	0.008 min		
		Delta X	[m]	0.1026					
		Delta Y	[m]	0.0815					
		Delta Z	[m]	0.0877					
	Velocity (Angular Linear)	Wx	[Rad/sec]	0.432					
		Wy	[Rad/sec]	0.486					
		Wz	[Rad/sec]	1.053			9.4 min		
		VR	[m/sec]	0.072					
		Wg	[Rad/sec]	0.0468					
	Force	Fx	[N]	14.7299					
		Fy	[N]	13.1981					
		Fz	[N]	184.3919					
		Fg	[N]	41.6085	15	5 min	40 min		
	Torque	Tx	[Nm]	2.3941					
		Ty	[Nm]	1.6011					
		Tz	[Nm]	0.0464	0.088	0.022			

Kinematic Analysis –
Playback Simulation using Measured Data



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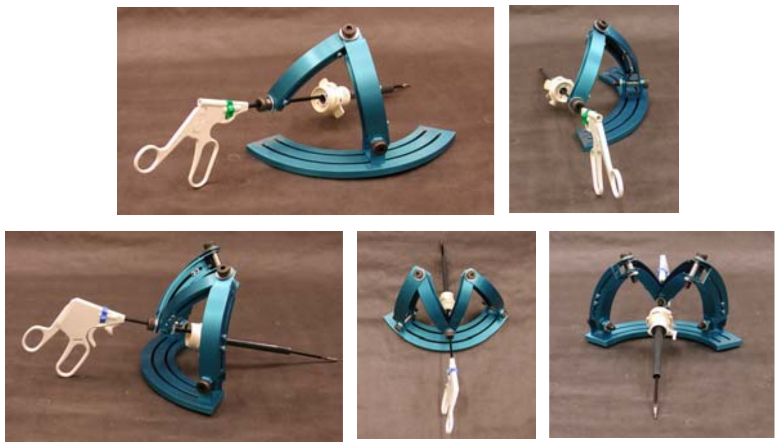
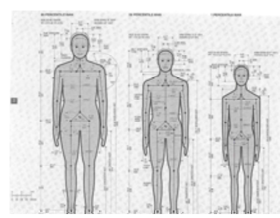
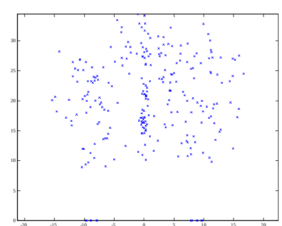
Spherical Mechanisms – Serial / Parallel



Port Locations Analysis



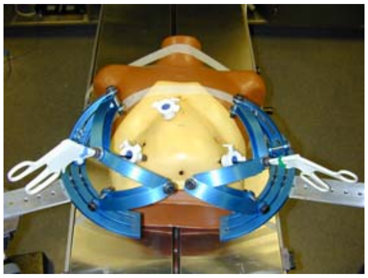


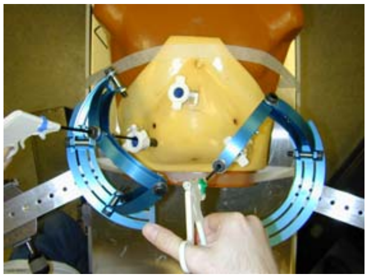
- Aortal Access
- Gastrectomy
- Left and Right Adrenalectomy
- Cholesystectomy
- Nissen Fundoplication
- Liver Access
- Left Nephrectomy
- Pelvic Access
- Colon
- Small Bowel Resection

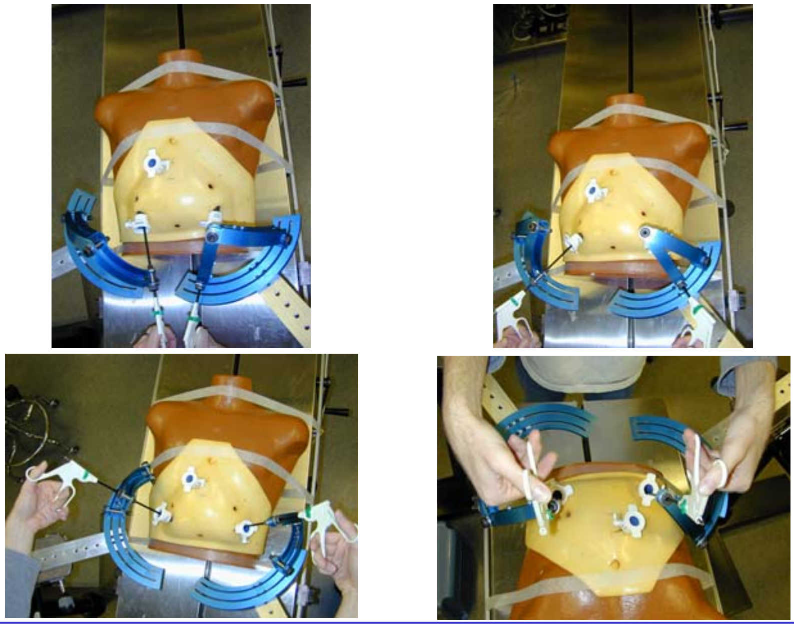
Experiment No. 1

- System:Mockup C – Plastic Human Torso
- Aim: Detect self collisions using different mockup configuration

Config. No.	Left Robot		Right Robot		Base Angle
	Type	Link Angle	Type	Link Angle	
A	Parallel	90	Parallel	90	90
B	Parallel	60	Parallel	60	60
C	Parallel	60	Serial	60	60
D	Serial	60	Serial	60	*







Experiment No. 2

- System:Mockup C – Pig
- Aim: Detect self collisions and functionality in real OR setup using an animal model (Pig)
- Configuration: Left & Right System – Serial configuration with arm lengths of 60 Deg.
- Surgical Task: Suturing, Running the bowel

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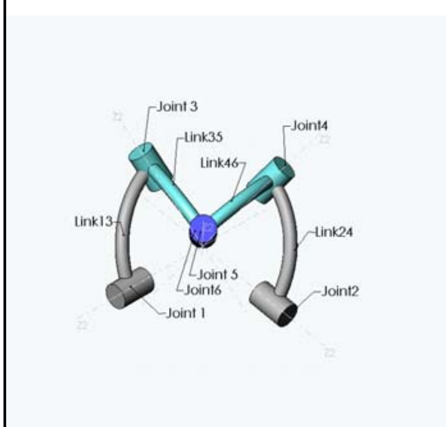
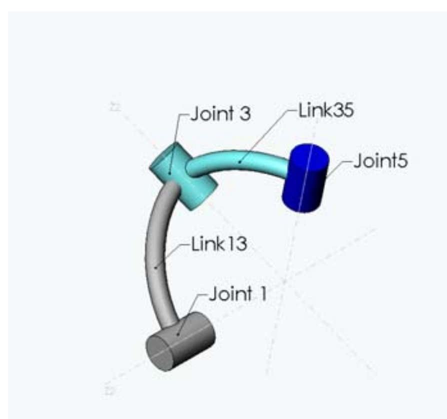
Spherical Mechanisms
Parallel and Serial





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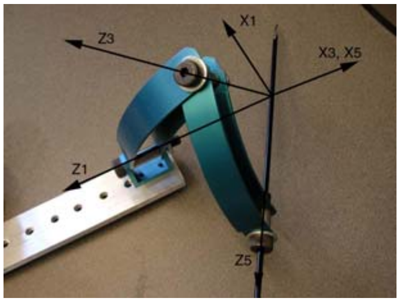
Mechanism Kinematic Optimization



i-1	i	i+1	α_{i-1}	θ_i
0’	1	3	0	θ_1
1	3	5	$-\alpha_{13}$	θ_3
3	5	-	α_{35}	$\theta_5 = 0$

Mechanism Kinematic Optimization – Direct Kinematics

$$ {}^{0'}_{5}R = {}^{0'}_{1}R * {}^{1}_{3}R * {}^{3}_{5}R $$

$$ {}^{0'}u = \begin{bmatrix} {}^{0'}u_x \\ {}^{0'}u_y \\ {}^{0'}u_z \end{bmatrix} = {}^{0'}_{5}R \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} c\theta_1 s\theta_3 s\alpha_{35} + s\theta_1 c\theta_3 c\alpha_{13} - s\theta_1 s\alpha_{13} c\alpha_{35} \\ s\theta_1 s\theta_3 s\alpha_{35} - c\theta_1 c\theta_3 c\alpha_{13} - c\theta_1 s\alpha_{13} c\alpha_{35} \\ c\theta_3 s\alpha_{13} s\alpha_{35} + c\alpha_{13} c\alpha_{35} \end{bmatrix} $$

Mechanism Kinematic Optimization – Inverse Kinematics

- Two solutions
  - elbow up/down

$$c\theta_3 = \frac{{}^{0'}u_z - c\alpha_{13}\,c\alpha_{35}}{s\alpha_{13}\,s\alpha_{35}}$$

$$\theta_{3a}, \theta_{3b} = a\tan 2\left(\pm\sqrt{1-c^2\theta_3}, c\theta_3\right)$$

$$c\theta_1 = \frac{{}^{0'}u_x\, s\theta_3\, s\alpha_{35} - {}^{0'}u_y\,(c\theta_3\, c\alpha_{13}\, s\alpha_{35} - s\alpha_{13}\, c\alpha_{35})}{(s\theta_3\, s\alpha_{35})^2 + (c\theta_3\, c\alpha_{13}\, s\alpha_{35} - s\alpha_{13}\, c\alpha_{35})^2}$$

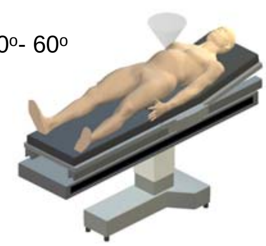
$$s\theta_1 = \frac{{}^{0'}u_y\, s\theta_3\, s\alpha_{35} + {}^{0'}u_x\,(c\theta_3\, c\alpha_{13}\, s\alpha_{35} - s\alpha_{13}\, c\alpha_{35})}{(s\theta_3\, s\alpha_{35})^2 + (c\theta_3\, c\alpha_{13}\, s\alpha_{35} - s\alpha_{13}\, c\alpha_{35})^2}$$

$$\theta_1 = atan2(s\theta_1, c\theta_1)$$

Mechanism Kinematic Optimization

- Dexterous Work Space (DWS)
  - High dexterity region defined by a right circular cone with a vertex angel of 60º
  - Contains 95% of the tool motions based on *in-vivo* measurements.
- Extended Dexterous Work Space (EDWS)
  - The workspace required to reach the entire abdominal cavity with MIS instruments and defined by a cone with an elliptical cross section created by two orthogonal vertex angels of 60º and 90º.

60º- 60º



60º- 90º

Mechanism Kinematic Optimization

- Jacobian Matrix

$$\{\omega\} = [J]\{\dot{\theta}\} \qquad \begin{bmatrix} {}^5\omega_{5x} \\ {}^5\omega_{5y} \end{bmatrix} = \left[J_{5\,truncated}\right]_{2x2} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_3 \end{bmatrix}$$

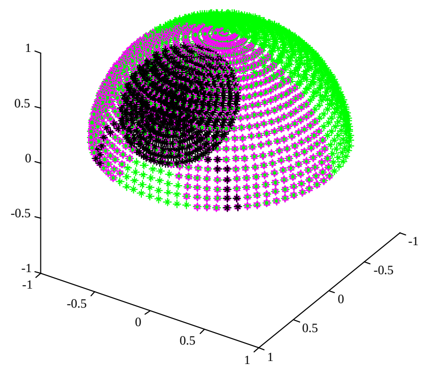
$$\{\dot{\theta}\} = [J]^{-1}\{\omega\}$$

- Mechanism Manipulability - Mechanism isotropy as the performance metric

$$ISO(\theta_1, \theta_3) = \frac{\lambda_{\min}}{\lambda_{\max}} \qquad ISO \in \langle 0,1 \rangle$$

- Pose dependant (different score for different poses)

Mechanism Kinematic Optimization (Serial)



Mechanism Kinematic Optimization

- Scoring Criteria

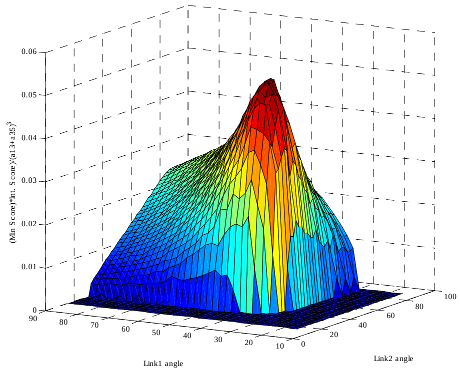
$$S_{sum} = \underset{K}{MAX}\left\{\sum_{k^p_{\sigma,\zeta}} ISO(\theta_1,\theta_3) * A(\sigma,\zeta)\right\}$$

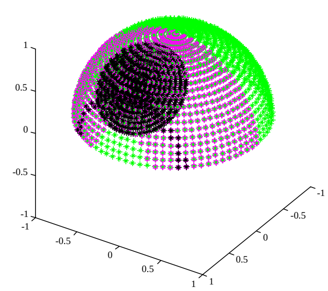
$$S_{\min} = \underset{K}{MAX}\left\{\underset{k^p_{\sigma,\zeta}}{MIN}\left(ISO(\theta_1,\theta_3)\right)\right\}$$

$$\phi(\alpha_{13},\alpha_{35}) = \frac{S_{\text{sum}} \cdot S_{\min}}{(\alpha_{13}+\alpha_{35})^3} \qquad max\ \phi\ (\alpha_{13},\alpha_{35},\theta_1,\theta_3) \begin{cases} 16^o < \alpha_{13} < 90^o \\ 16^o < \alpha_{35} < 90^o \\ \theta_1 \in DWS \\ \theta_3 \in DWS \end{cases}$$

Mechanism Kinematic Optimization (Serial)

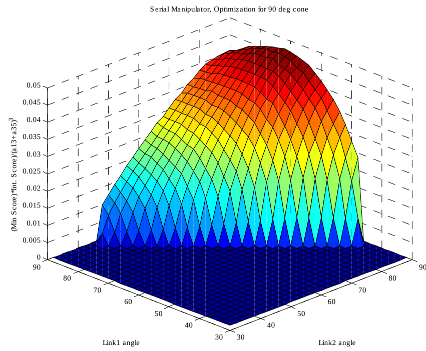
DWS (60º cone) – Best Design: α_{13}=52º and α_{35}=40º

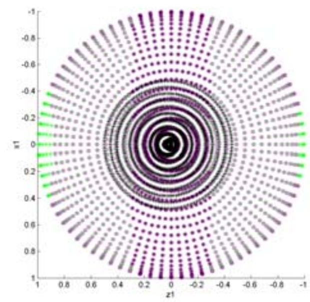




Mechanism Kinematic Optimization (Serial)

Superset of EDWS (90º cone): Best Design α_{13}=90º and α_{35}=72º





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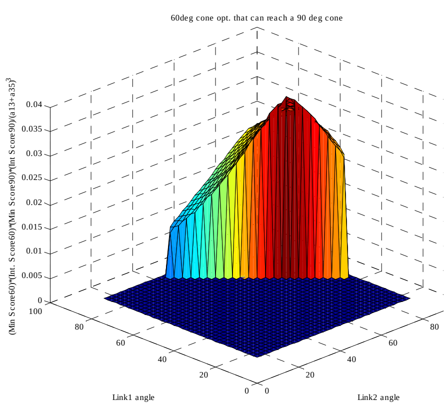
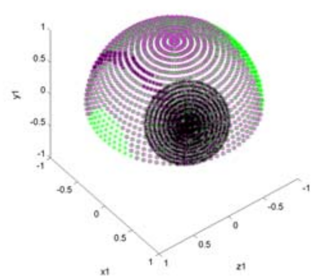
Mechanism Kinematic Optimization (Serial)

Optimized on DWS (60º cone) constrained to meet 90º cone: Best Design α_{13}=74º and α_{35}=60º





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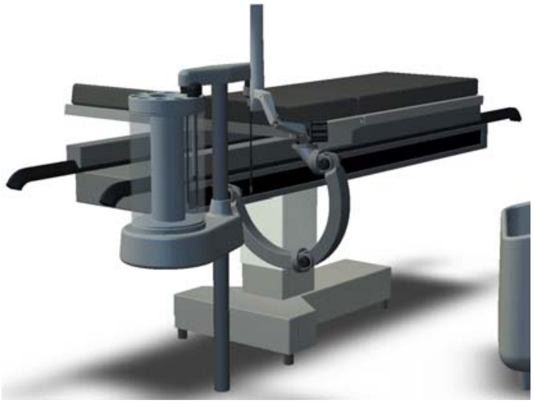
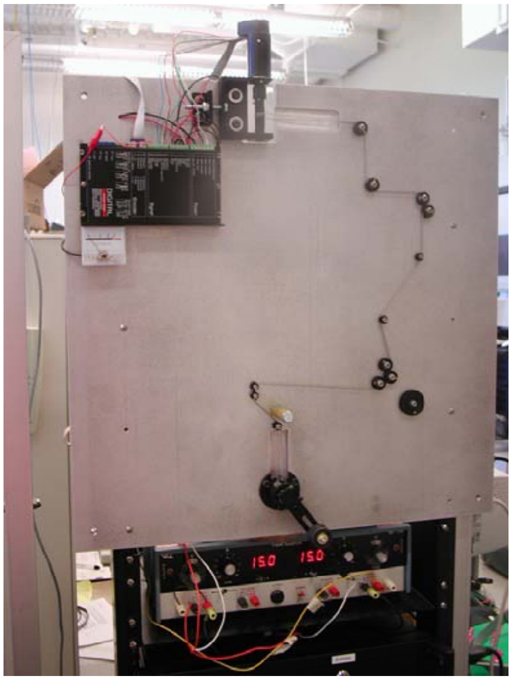
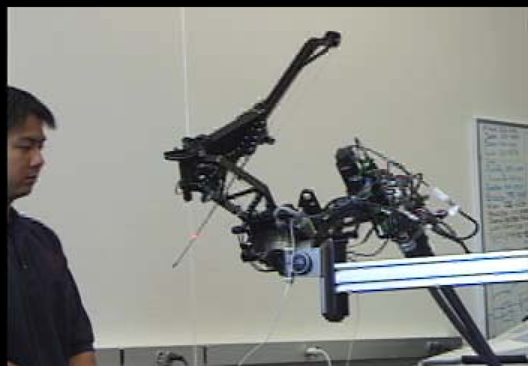
OR – Tool Changer



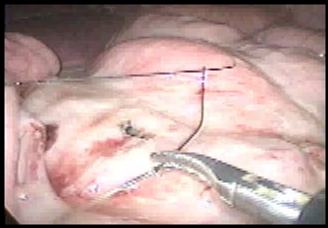
Pulley Board

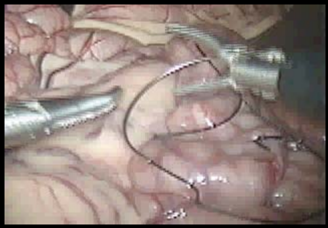




Objective Assessment of Surgical Skills – Markov Model

Evaluation of Surgical Skill

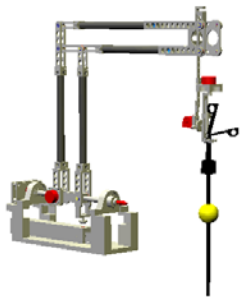




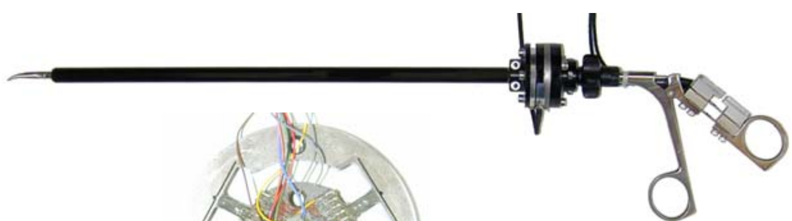
Surgery - The Hidden Language Elements

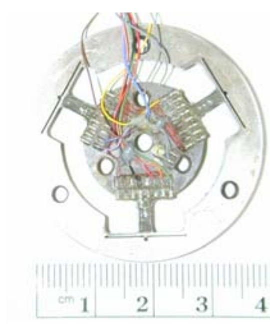
Human Language	Surgical Language	Markov Model
Book	Operation	Multiple Models
Chapter	Step of the Operation	Single Model
Words	Tool/Tissue Interaction	State
Pronunciation	Force / Torque	Observation

Blue DRAGON



Instrumented Endoscopic Grasper





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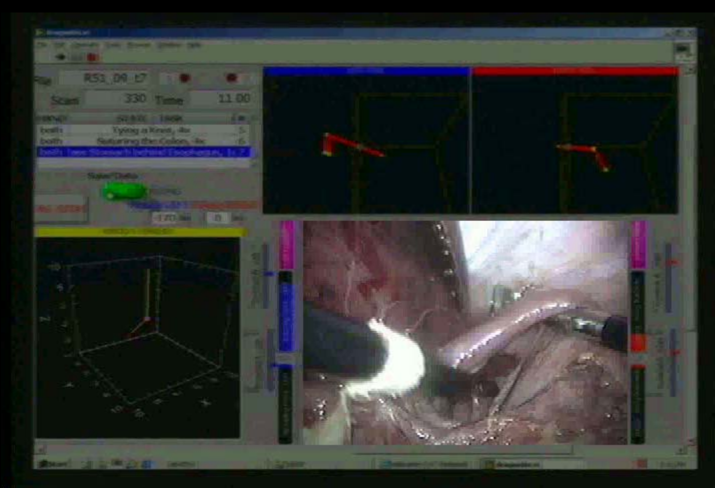
Blue DRAGON

Blue DRAGON - Graphical User Interface



Experimental Protocol

- **Surgical Tasks:**

- Task 1: Running the bowel, 10x3" (right to left)
- Task 2: Running the bowel, 10x3" (left to right)
- Task 3: Dissecting Mesenteric Vessels, 4x
- Task 4: Passing a Suture, 5x
- Task 5: Tying a Knot, 4x
- Task 6: Suturing the Bowel and Tying a Knot
- Task 7: Passing Stomach Fundus behind the Esophagus, 1x

- **Subjects:** 5x (R1, R2, R3, R4, R5, E) - 30 Subjects

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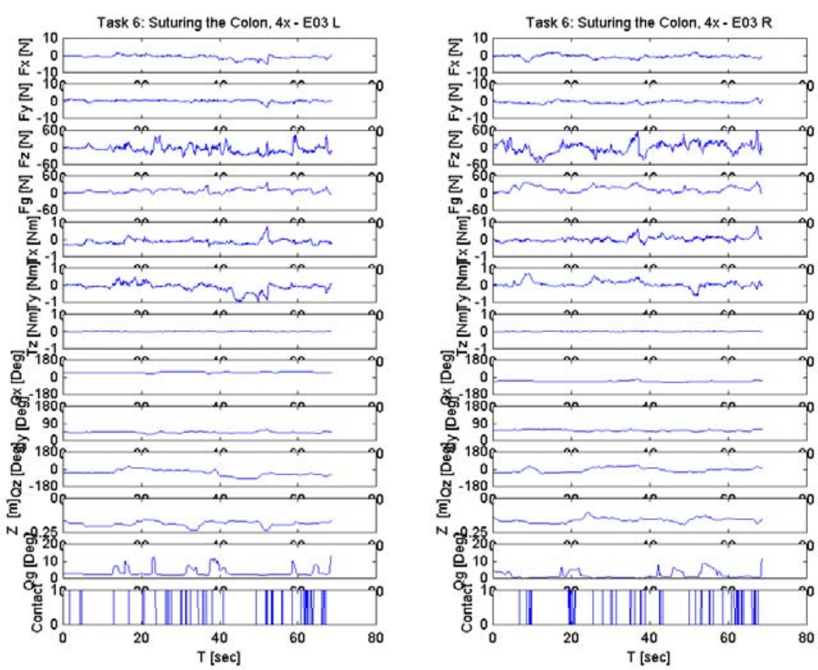
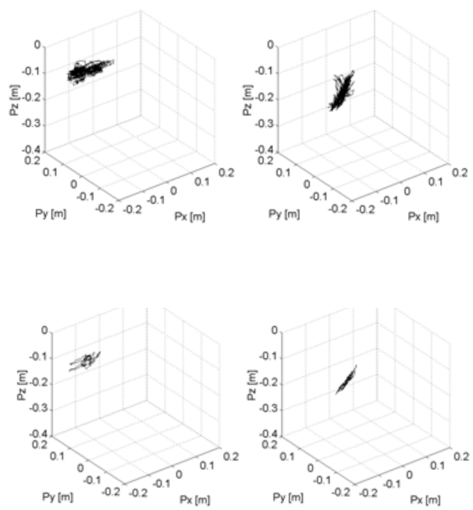


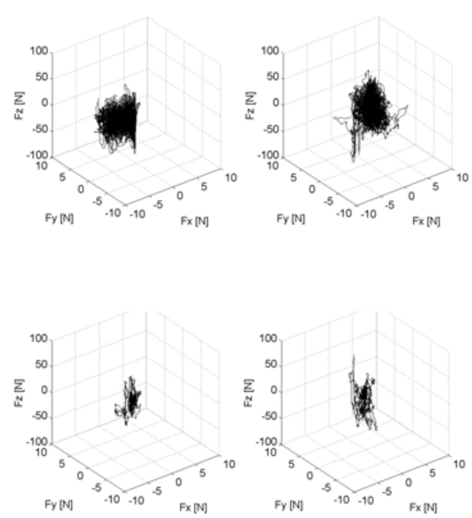
Position (Path) - Raw Data



Novice

Expert

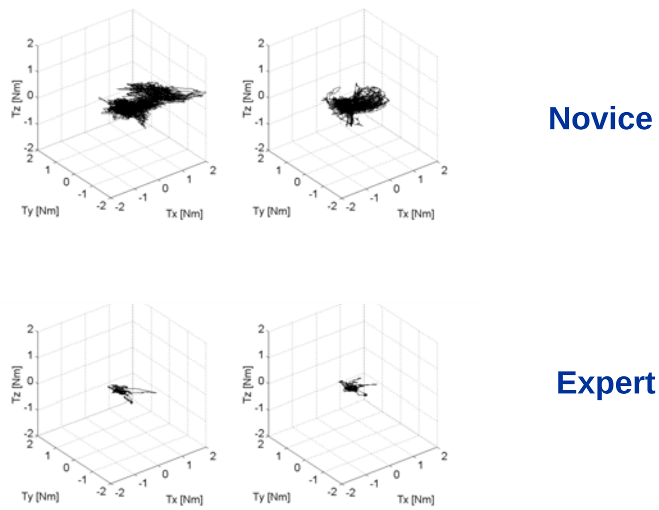
Forces - Raw Data



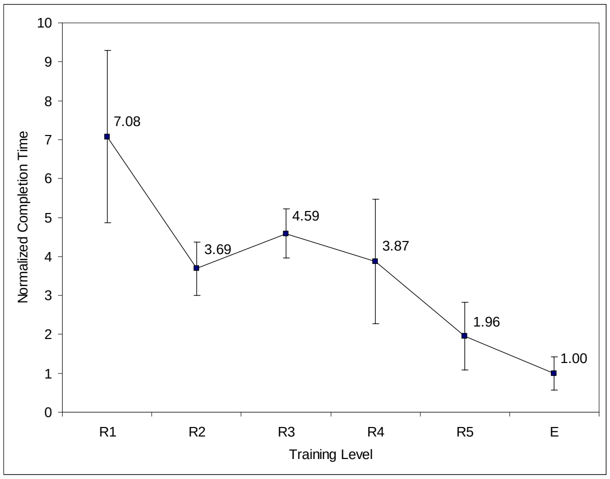
Novice

Expert

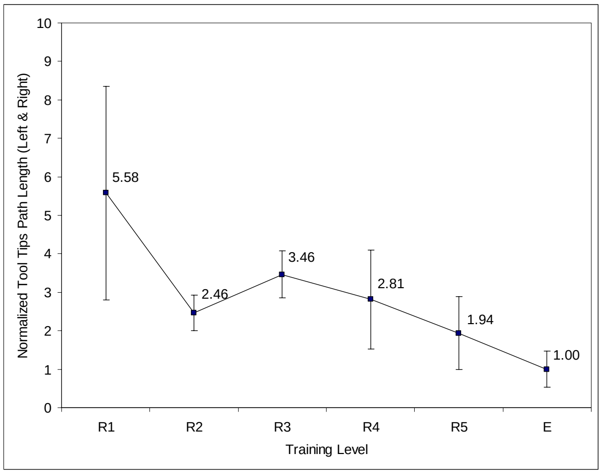
Torques - Raw Data



Normalized Completion Time
Learning Curve of Surgical Residents



Normalized Trajectory Length
Learning Curve of Surgical Residents

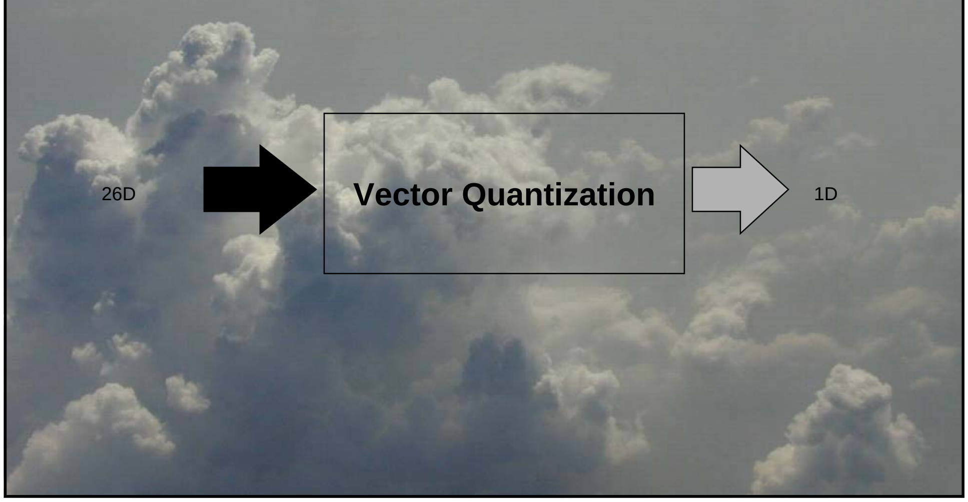


Endoscopic Tool – 5 DOF

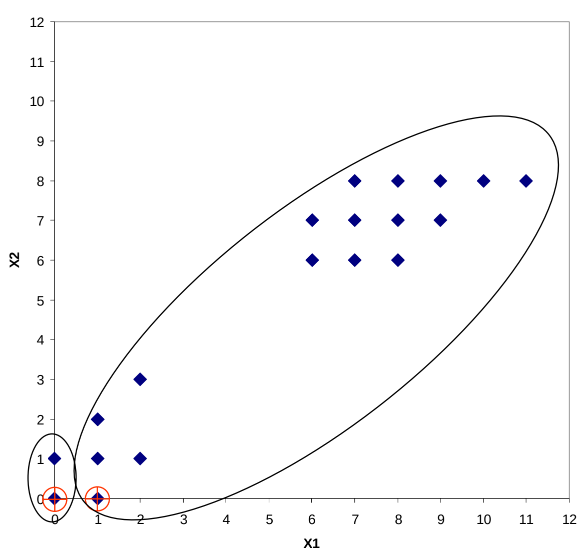
Tool/Tissue-Object Interactions - Taxonomy

Type	No.	State Name	State Acronym	Tissue Contact	Position / Orientation $\dot\theta_x$	$\dot\theta_y$	$\dot\theta_z$	$\dot L_z$	$\dot\theta_g$	Force / Torque F_x	F_y	F_z	T_x	T_y	T_z	F_g
I	1	Idle	ID	-	$\pm\varepsilon_{\dot\theta_x}$	$\pm\varepsilon_{\dot\theta_y}$	$\pm\varepsilon_{\dot\theta_z}$	$\pm\varepsilon_{\dot L_z}$	$\pm\varepsilon_{\dot\theta_g}$	$\pm\varepsilon_{F_x}$	$\pm\varepsilon_{F_y}$	$\pm\varepsilon_{F_z}$	$\pm\varepsilon_{T_x}$	$\pm\varepsilon_{T_y}$	$\pm\varepsilon_{T_z}$	$\pm\varepsilon_{F_g}$
	2	Closing Handle (Grasping / Cutting)	CL	•	$\pm\varepsilon_{\dot\theta_x}$	$\pm\varepsilon_{\dot\theta_y}$	$\pm\varepsilon_{\dot\theta_z}$	$\pm\varepsilon_{\dot L_z}$	$\dot\theta_g < \varepsilon_{\dot\theta_g}$	$\pm\varepsilon_{F_x}$	$\pm\varepsilon_{F_y}$	$\pm\varepsilon_{F_z}$	$\pm\varepsilon_{T_x}$	$\pm\varepsilon_{T_y}$	$\pm\varepsilon_{T_z}$	$F_g > \varepsilon_{F_g}$
	3	Opening Handle (Spreading)	OP	•	$\pm\varepsilon_{\dot\theta_x}$	$\pm\varepsilon_{\dot\theta_y}$	$\pm\varepsilon_{\dot\theta_z}$	$\pm\varepsilon_{\dot L_z}$	$\dot\theta_g > \varepsilon_{\dot\theta_g}$	$\pm\varepsilon_{F_x}$	$\pm\varepsilon_{F_y}$	$\pm\varepsilon_{F_z}$	$\pm\varepsilon_{T_x}$	$\pm\varepsilon_{T_y}$	$\pm\varepsilon_{T_z}$	$F_g < -\varepsilon_{F_g}$
	4	Pushing	PS	•	$\pm\varepsilon_{\dot\theta_x}$	$\pm\varepsilon_{\dot\theta_y}$	$\pm\varepsilon_{\dot\theta_z}$	$\dot L_z < -\varepsilon_{\dot L_z}$	$\pm\varepsilon_{\dot\theta_g}$	$\pm\varepsilon_{F_x}$	$\pm\varepsilon_{F_y}$	$F_z > \varepsilon_{F_z}$	$\pm\varepsilon_{T_x}$	$\pm\varepsilon_{T_y}$	$\pm\varepsilon_{T_z}$	$\pm\varepsilon_{F_g}$
	5	Rotating (Sweeping)	RT	•	$\dot\theta_x > \lvert\varepsilon_{\dot\theta_x}\rvert$	$\dot\theta_y > \lvert\varepsilon_{\dot\theta_y}\rvert$	$\pm\varepsilon_{\dot\theta_z}$	$\pm\varepsilon_{\dot L_z}$	$\pm\varepsilon_{\dot\theta_g}$	$F_x > \lvert\varepsilon_{F_x}\rvert$	$F_y > \lvert\varepsilon_{F_y}\rvert$	$\pm\varepsilon_{F_z}$	$T_x > \lvert\varepsilon_{T_x}\rvert$	$T_y > \lvert\varepsilon_{T_y}\rvert$	$\pm\varepsilon_{T_z}$	$\pm\varepsilon_{F_g}$
II	6	Closing - Pulling	CL -PL	•	$\pm\varepsilon_{\dot\theta_x}$	$\pm\varepsilon_{\dot\theta_y}$	$\pm\varepsilon_{\dot\theta_z}$	$\dot L_z > \varepsilon_{\dot L_z}$	$\dot\theta_g < \varepsilon_{\dot\theta_g}$	$\pm\varepsilon_{F_x}$	$\pm\varepsilon_{F_y}$	$F_z < -\varepsilon_{F_z}$	$\pm\varepsilon_{T_x}$	$\pm\varepsilon_{T_y}$	$\pm\varepsilon_{T_z}$	$F_g > \varepsilon_{F_g}$
	7	Closing - Pushing	CL -PS	•	$\pm\varepsilon_{\dot\theta_x}$	$\pm\varepsilon_{\dot\theta_y}$	$\pm\varepsilon_{\dot\theta_z}$	$\dot L_z < -\varepsilon_{\dot L_z}$	$\dot\theta_g < \varepsilon_{\dot\theta_g}$	$\pm\varepsilon_{F_x}$	$\pm\varepsilon_{F_y}$	$F_z > \varepsilon_{F_z}$	$\pm\varepsilon_{T_x}$	$\pm\varepsilon_{T_y}$	$\pm\varepsilon_{T_z}$	$F_g > \varepsilon_{F_g}$
	8	Closing - Rotating	CL-RT	•	$\dot\theta_x > \lvert\varepsilon_{\dot\theta_x}\rvert$	$\dot\theta_y > \lvert\varepsilon_{\dot\theta_y}\rvert$	$\pm\varepsilon_{\dot\theta_z}$	$\pm\varepsilon_{\dot L_z}$	$\dot\theta_g < \varepsilon_{\dot\theta_g}$	$F_x > \lvert\varepsilon_{F_x}\rvert$	$F_y > \lvert\varepsilon_{F_y}\rvert$	$\pm\varepsilon_{F_z}$	$\pm\varepsilon_{T_x}$	$\pm\varepsilon_{T_y}$	$\pm\varepsilon_{T_z}$	$F_g > \varepsilon_{F_g}$
	9	Pushing - Opening	PS-OP	•	$\pm\varepsilon_{\dot\theta_x}$	$\pm\varepsilon_{\dot\theta_y}$	$\pm\varepsilon_{\dot\theta_z}$	$\dot L_z < -\varepsilon_{\dot L_z}$	$\dot\theta_g > \varepsilon_{\dot\theta_g}$	$\pm\varepsilon_{F_x}$	$\pm\varepsilon_{F_y}$	$F_z < -\varepsilon_{F_z}$	$\pm\varepsilon_{T_x}$	$\pm\varepsilon_{T_y}$	$\pm\varepsilon_{T_z}$	$F_g < -\varepsilon_{F_g}$
	10	Pushing - Rotating	PS-RT	•	$\dot\theta_x > \lvert\varepsilon_{\dot\theta_x}\rvert$	$\dot\theta_y > \lvert\varepsilon_{\dot\theta_y}\rvert$	$\pm\varepsilon_{\dot\theta_z}$	$\dot L_z < -\varepsilon_{\dot L_z}$	$\pm\varepsilon_{\dot\theta_g}$	$F_x > \lvert\varepsilon_{F_x}\rvert$	$F_y > \lvert\varepsilon_{F_y}\rvert$	$F_z > \varepsilon_{F_z}$	$\pm\varepsilon_{T_x}$	$\pm\varepsilon_{T_y}$	$\pm\varepsilon_{T_z}$	$\pm\varepsilon_{F_g}$
	11	Rotating - Opening	RT-OP	•	$\dot\theta_x > \lvert\varepsilon_{\dot\theta_x}\rvert$	$\dot\theta_y > \lvert\varepsilon_{\dot\theta_y}\rvert$	$\pm\varepsilon_{\dot\theta_z}$	$\pm\varepsilon_{\dot L_z}$	$\dot\theta_g > \varepsilon_{\dot\theta_g}$	$F_x > \lvert\varepsilon_{F_x}\rvert$	$F_y > \lvert\varepsilon_{F_y}\rvert$	$\pm\varepsilon_{F_z}$	$T_x > \lvert\varepsilon_{T_x}\rvert$	$T_y > \lvert\varepsilon_{T_y}\rvert$	$\pm\varepsilon_{T_z}$	$F_g < -\varepsilon_{F_g}$
III	12	Closing - Pulling - Rotating	CL-PL-RT	•	$\dot\theta_x > \lvert\varepsilon_{\dot\theta_x}\rvert$	$\dot\theta_y > \lvert\varepsilon_{\dot\theta_y}\rvert$	$\pm\varepsilon_{\dot\theta_z}$	$\dot L_z > \varepsilon_{\dot L_z}$	$\dot\theta_g < \varepsilon_{\dot\theta_g}$	$F_x > \lvert\varepsilon_{F_x}\rvert$	$F_y > \lvert\varepsilon_{F_y}\rvert$	$F_z < -\varepsilon_{F_z}$			$\pm\varepsilon_{T_z}$	$F_g > \varepsilon_{F_g}$
	13	Closing -Pushing - Rotating	CL-PS-RT	•	$\dot\theta_x > \lvert\varepsilon_{\dot\theta_x}\rvert$	$\dot\theta_y > \lvert\varepsilon_{\dot\theta_y}\rvert$	$\pm\varepsilon_{\dot\theta_z}$	$\dot L_z < -\varepsilon_{\dot L_z}$	$\dot\theta_g < \varepsilon_{\dot\theta_g}$	$F_x > \lvert\varepsilon_{F_x}\rvert$	$F_y > \lvert\varepsilon_{F_y}\rvert$	$F_z > \varepsilon_{F_z}$	$T_x > \lvert\varepsilon_{T_x}\rvert$	$T_y > \lvert\varepsilon_{T_y}\rvert$	$\pm\varepsilon_{T_z}$	$F_g > \varepsilon_{F_g}$
	14	Pushing - Rotating - Opening	PS-RT-OP	•	$\dot\theta_x > \lvert\varepsilon_{\dot\theta_x}\rvert$	$\dot\theta_y > \lvert\varepsilon_{\dot\theta_y}\rvert$	$\pm\varepsilon_{\dot\theta_z}$	$\dot L_z < -\varepsilon_{\dot L_z}$	$\dot\theta_g > \varepsilon_{\dot\theta_g}$	$F_x > \lvert\varepsilon_{F_x}\rvert$	$F_y > \lvert\varepsilon_{F_y}\rvert$	$F_z > \varepsilon_{F_z}$	$\pm\varepsilon_{T_x}$	$\pm\varepsilon_{T_y}$	$\pm\varepsilon_{T_z}$	$F_g < -\varepsilon_{F_g}$
II	15	Closing Handle - Spinning	CL-SP	•	$\pm\varepsilon_{\dot\theta_x}$	$\pm\varepsilon_{\dot\theta_y}$	$\lvert\dot L_z\rvert > \varepsilon_{\dot\theta_z}$	$\pm\varepsilon_{\dot L_z}$	$\dot\theta_g < \varepsilon_{\dot\theta_g}$	$\pm\varepsilon_{F_x}$	$\pm\varepsilon_{F_y}$	$\pm\varepsilon_{F_z}$	$\pm\varepsilon_{T_x}$	$\pm\varepsilon_{T_y}$	$T_z > \lvert\varepsilon_{T_z}\rvert$	$F_g > \varepsilon_{F_g}$

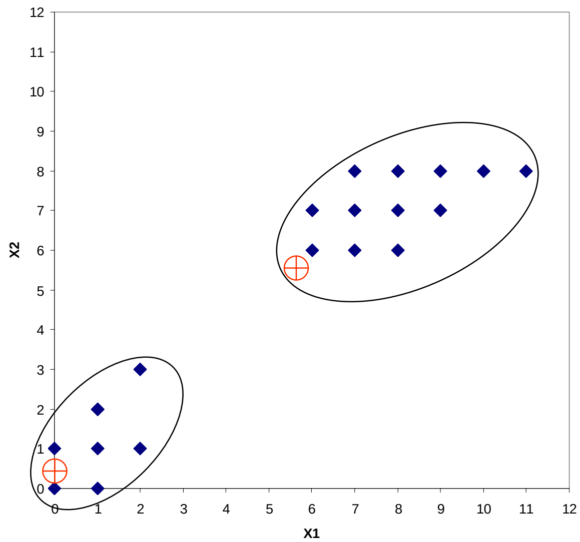
Data Reduction



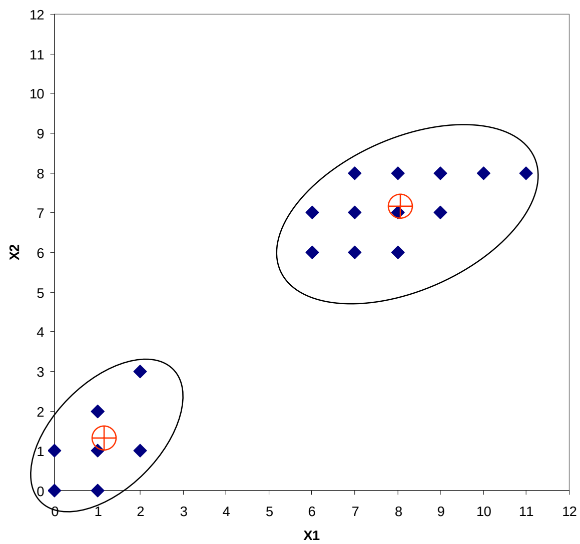
Vector Quantization (VQ) - Step 1



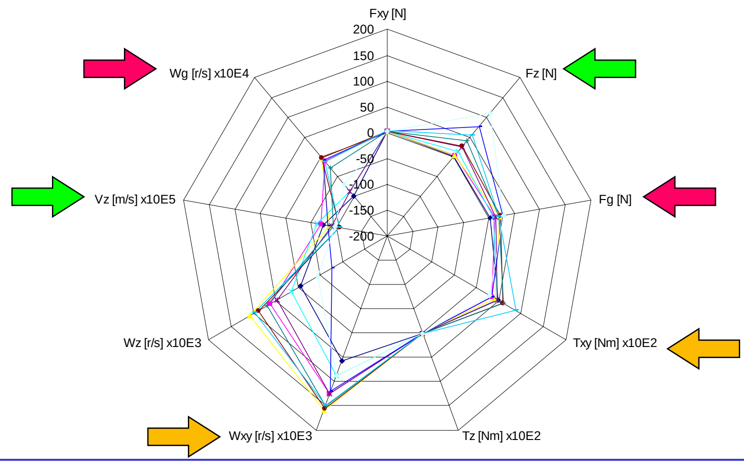
Vector Quantization (VQ) - Step 2



Vector Quantization (VQ) - Step 3



F/T Clusters (GR-PS-SW)



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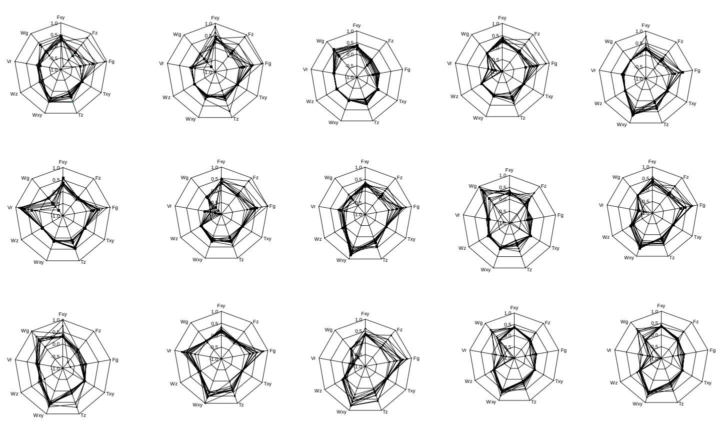
Clusters (150)



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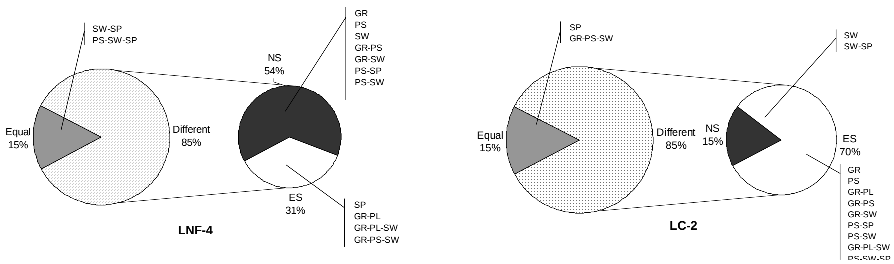
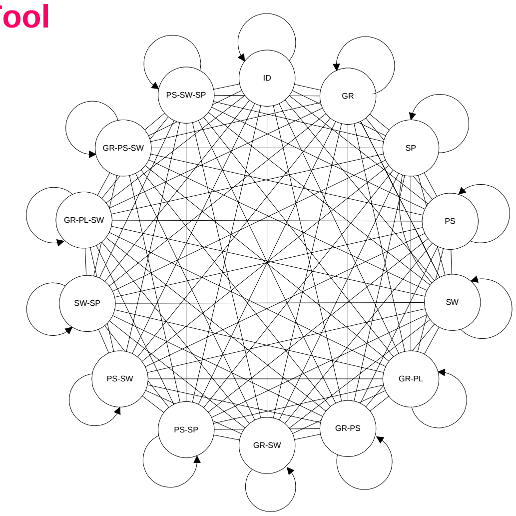
Distributions of Clusters

Tissue Manipulation

Tissue Dissection



Generalized Markov Model of MIS Surgery - One Tool



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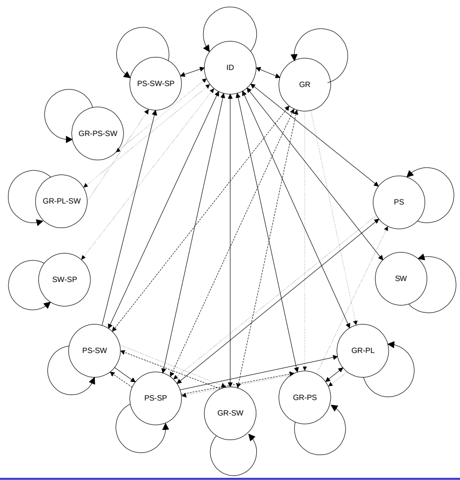
Laparoscopic Cholecystectomy Exposure of Cystic Duct



Surgeon ———

Non - Surgeon - - - - - -

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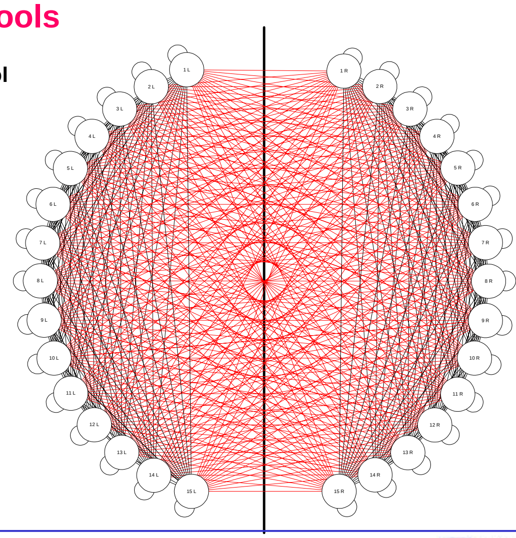
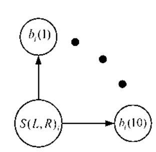
Generalized Markov Model of MIS Surgery - Two Tools

Left Tool

Right Tool





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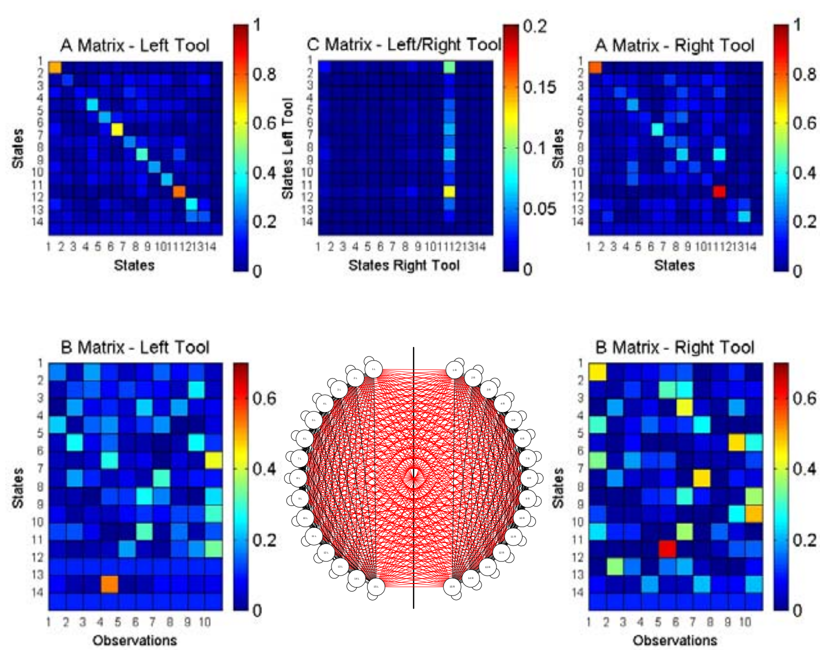
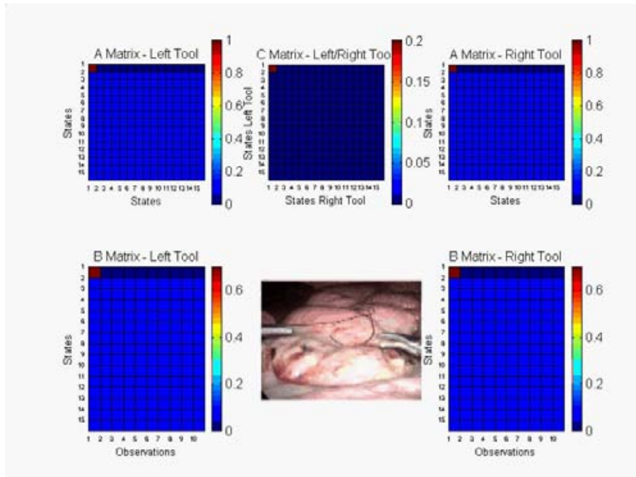
Markov Model

- The Model components $\lambda_L = (A_L, B_L, \pi_L) \quad \lambda_R = (A_R, B_R, \pi_R)$
- Initial state distribution vector $\pi_i = P[q_1 = s_i]$
- State transition matrix $A = \{a_{ij}\} \quad a_{ij} = P[q_{t+1} = s_j \mid q_t = s_i]$
- Observation symbol matrix $B = \{b_j(k)\} \quad b_j(k) = P[v_k \text{ at } t \mid q_t = s_j]$
- Cooperation matrix $C = \{c_{lr}\} \quad c_{lr} = P[q_{Lt} = s_l \cap q_{Rt} = s_r]$

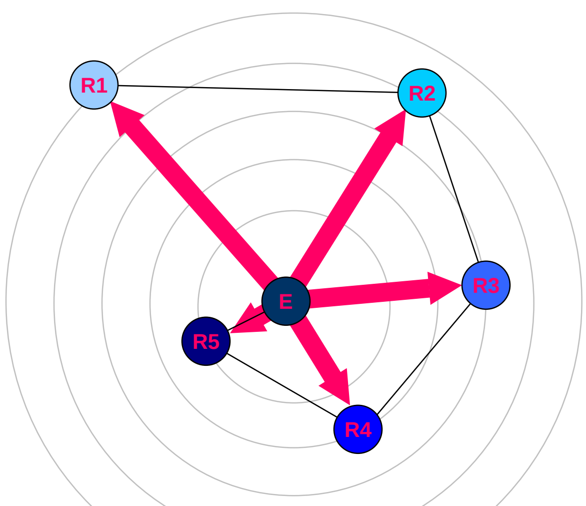
$$P(Q,O \mid \lambda_L, \lambda_R, C) = \pi_{q_L} \pi_{q_R} \prod_{t=0}^{T} a_{L q_t q_{t+1}} b_{L q_t}(o_t) a_{R q_t q_{t+1}} b_{R q_t}(o_t) c_{q_{Lt} q_{Rt}}$$

$$Log(P(Q,O \mid \lambda_L, \lambda_R, C)) = Log(\pi_{q_L}) + Log(\pi_{q_R}) + \sum_{t=1}^{T} Log(a_{L q_t q_{t+1}}) + Log(b_{L q_t}(o_t)) + Log(a_{R q_t q_{t+1}}) + Log(b_{R q_t}(o_t)) + Log(c_{q_{Lt} q_{Rt}})$$

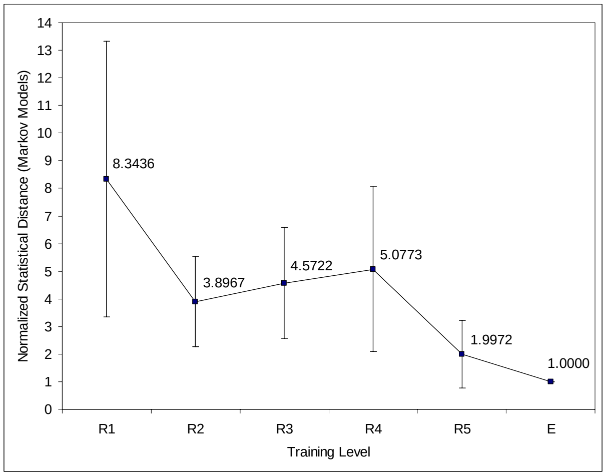




Learning Curve - Markov Model Statistical Distance



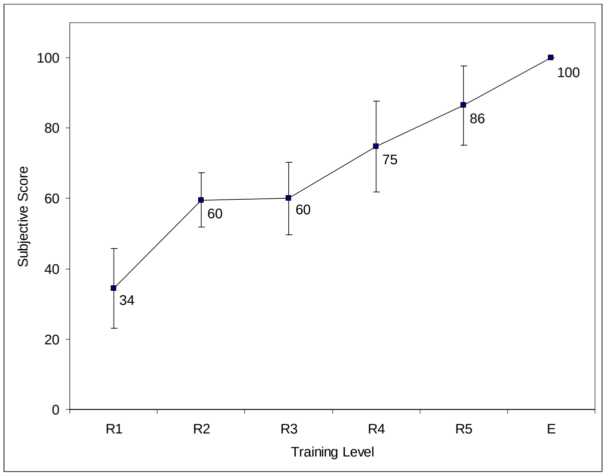
Normalized Statistical Distance
Learning Curve of Surgical Residents



Subjective Score (Video Analysis) - Criteria
Suturing the Bowel and Tying a Knot

- Overall performance [1-5]
- Economy of movement [1-5]
- Tissue handling [1-5]
- Numbers of errors [No.]
  - Drop needle
  - Drop suture
  - Lose suture loop
  - Break suture
  - Needle injury to adjacent tissue
  - Inability to puncture bowel with needle

Normalized Subjective Score (Video Analysis) Learning Curve of Surgical Residents



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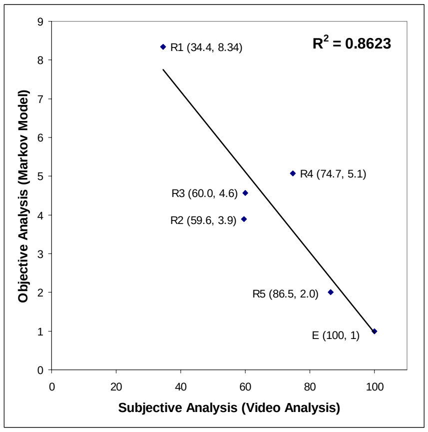
Correlation Between Subjective and Objective Assessment of Surgical Skill



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Objective Assessment of Surgical Skill - Conclusions

- **Analyzing Minimally Invasive Surgery requires a synthesis between visual and haptic information.**
- **Differences between expert and novice surgeons can be defined in terms of:**
  - **Force / Torque / Velocity signatures**
  - **State transitions / combinations**
  - **Time spent in each state**
  - **Trajectory (tool tip) length**
- **Good correlation (R^2=0.86) between objective (Markov Model) and subjective (video analysis scoring) assessment of surgical skill**
- **The objective methodology for surgical skill evaluation is a modality independent. It can be applied to:**
  - **In-vivo surgical conditions**
  - **Telerobotic systems**
  - **VR haptics simulators**

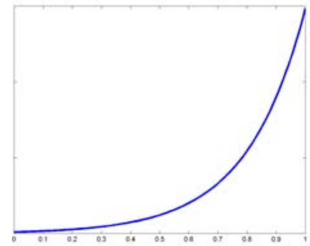
***Part 3: In-Vivo* and *In-Situ* Compressive Properties of Porcine Abdominal Soft Tissues**

Problem Statement

- Accurate tissue models are essential (Simulation)
  - For realistic haptic feedback
  - Need to represent *in-vivo* behavior
  - Current simulators lack *in-vivo* models

- Hypothesis:
  There is a significant difference in mechanical properties *in-vivo* vs. postmortem

Background — Soft Tissues

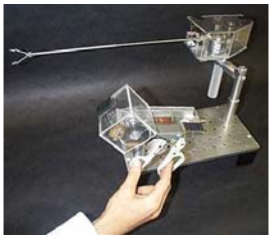


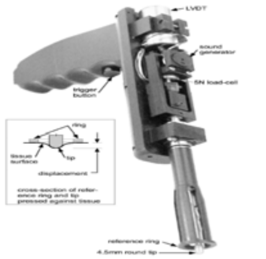
- Highly nonlinear behavior
  - Nonlinear stress-strain
    - not F = k*x
  - Anisotropic
  - Heterogeneous
  - Viscoelastic
    - Rate-dependent stress, creep, relaxation
  - Hysteresis
  - Strain history dependence
    - Preconditioning
  - Behavior depends on many factors
    - Age, gender, pH, tissue health…

Measuring Devices

- Ottensmeyer (2001, 2002)
  - TeMPeST 1-D
  - *in-vivo* compression (indentation)
- Carter *et al.* (2001)
  - *in-vivo* indentation
  - human data
- Rosen *et al.* (1999)

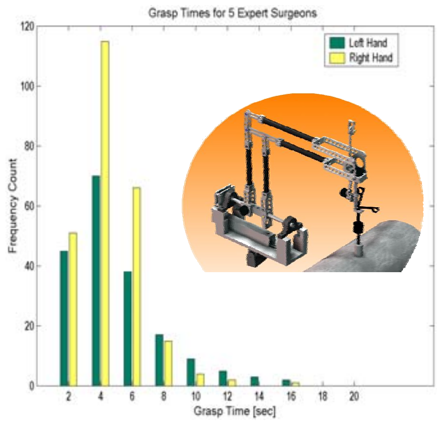

Ottensmeyer (2001)


Rosen et al. (1999)


Carter et al.(2001)

Preliminary Results — Grasping

- Measured grasping force applied during 3 surgical tasks for 5 expert surgeons
  - 97.1% of all grasps (both hands) were held less than 10 sec
  - Maximum force observed was 40 N (rarely)
  - Majority of frequency content was below 3 Hz



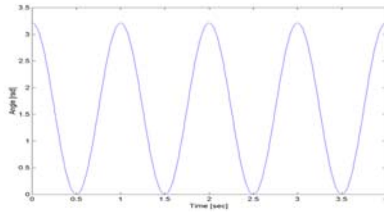
The Motorized Endoscopic Grasper (MEG)

Methodology

- Animal testing
  - pig, female, avg. weight 39.5 kg
  - standard laparoscopic setup (11 mmHg)
  - *in-vivo*: 9 pigs; *in-situ*: 4 pigs;
    - 2 pigs done both *in-vivo* and *in-situ*
  - 7 organs tested
    - gallbladder
    - liver
    - small bowel
    - large bowel
    - spleen
    - stomach
    - urinary bladder

Methodology — Cyclic Loading

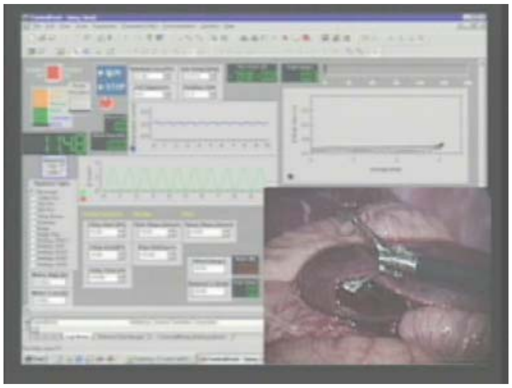
- Haversine and constant velocity
  - 0.25 - 3 Hz



- No preconditioning
  - First squeeze behavior and squeeze history
  - New site for each test

Data Collection

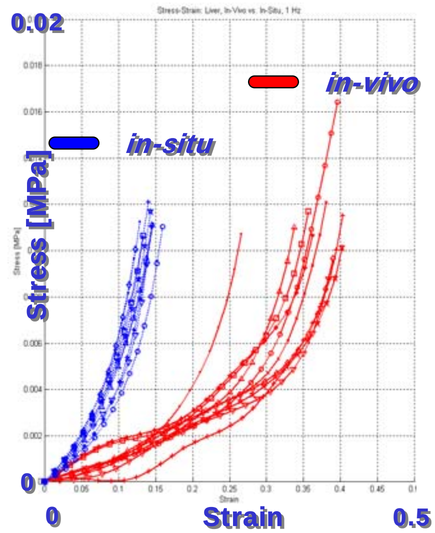
- Data synchronized with video from camera



Results — Cyclic Testing

- 1 Liver
- 1 Hz haversine
- *in-vivo* vs. *in-situ*
- 10 squeezes
- Same organ, different locations

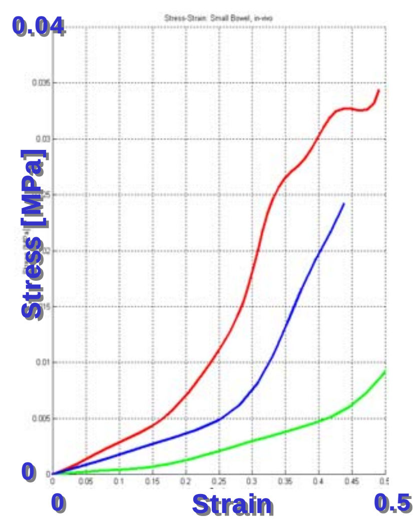
- Remarks:
  - More inter-squeeze variability *in-vivo*
  - Beating heart, ventilator motion, re-perfusion



Results — Cyclic Testing

- 3 small bowels
- *in-vivo*

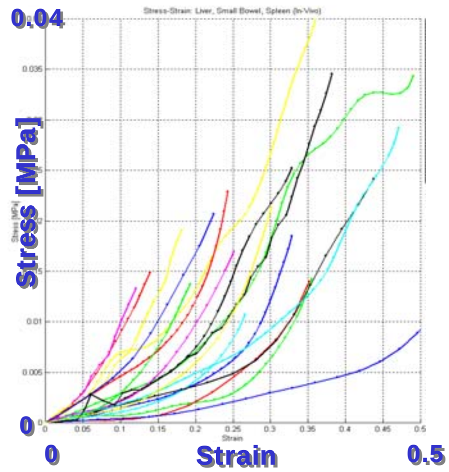
- Remarks:
  - Low initial slope followed by sudden increase
  - Squeezing contents (air, fluid, solid) then walls contacting



Results — Cyclic Testing

- 8 livers
- 8 spleens
- 3 small bowels
- *in-vivo*
- 1 Hz
- 1st squeezes only

- Remarks:
  - Large variability



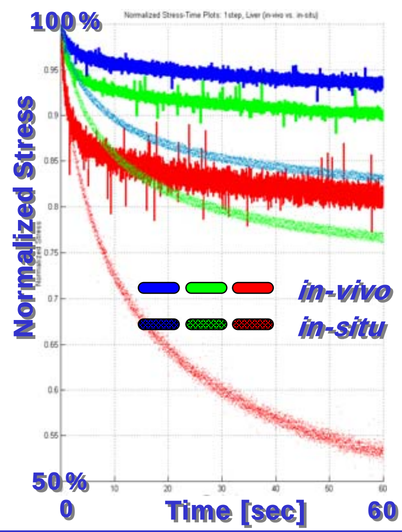
Methodology — Step Loading

- Measure stress relaxation
  - Single steps; held for 60 sec
  - Periodic steps
    - 10 sec hold
    - 2.5, 5, 10, 20, 30 sec off

Results — Stress Relaxation

- 1 Liver
- *in-vivo* vs. *in-situ*
- Single step, 60 sec hold time
- Strains 21% - 41%

- Remarks:
  - Higher percent decay *in-situ*
  - Steady-state not reached in 60 sec, especially *in-situ*



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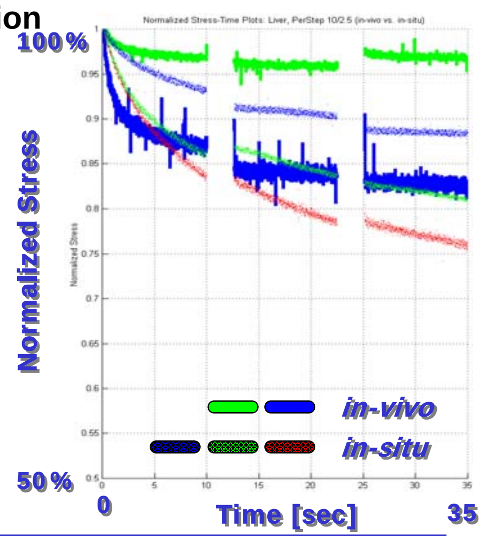
Results — Stress Relaxation

- 1 Liver
- *in-vivo* vs. *in-situ*
- Periodic steps
  - 10 sec on / 2.5 sec off
- Strains 17% - 40%

- Remarks:
  - Higher percent decay *in-situ*
  - Behavior is similar to single step (little recovery between squeezes)



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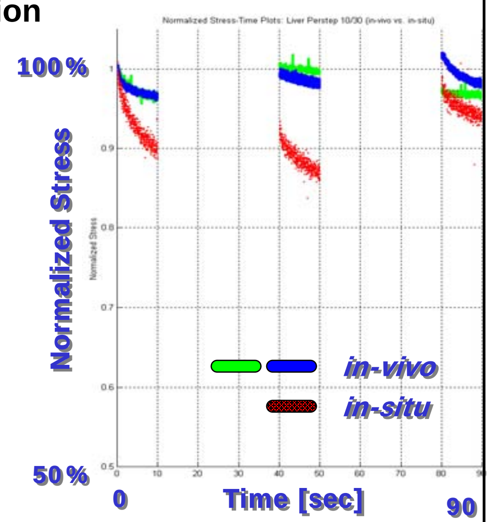
Results — Stress Relaxation

- 1 Liver
- *in-vivo* vs. *in-situ*
- Periodic steps
  - 10 sec on / 30 sec off
- Strains 21% - 51%

- Note:
  - More recovery between squeezes than 10/2.5
  - More recovery *in-vivo*
    - Returns to 100%
    - Some >100%
      - Swelling?
  - Some recovery *in-situ*



Jacob Rosen, SURGICAL ROBOTICS, 2nd Summer European University
MONTPELLIER, FRANCE, September 7-14, 2005

UNIVERSITY OF WASHINGTON

Tissue Damage - In-Vivo

Jacob Rosen, SURGICAL ROBOTICS, 2nd Summer European University
MONTPELLIER, FRANCE, September 7-14, 2005

UNIVERSITY OF WASHINGTON

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Operation @ Home

Appendectomy Kit

Real Surgery Performed Telerobotically by Real Surgeons at Half the Price!

30% Lower Infection Rate Then Hospitals

Wired Magazine - January 2005

Grasper Trauma

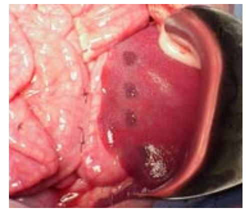
- Obvious injury
  - Bleeding, Perforation (Heijnsdijk, Marucci)
- Little data on damage and consequences due to sub-failure grasper trauma
  - Many potential mechanisms for damage
    - Hypoxia/ischemia
    - Ischemia reperfusion injury
    - Bursting of cells
    - Shearing of cell-to-cell connections
  - Possible consequences
    - Scar tissue formation, pain, adhesions, impaired function

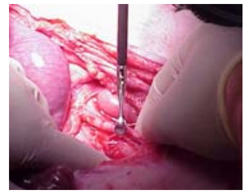
Long term goals

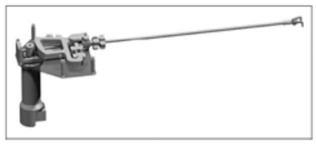
- **Create databases** containing models that correlate stress to tissue damage for a number of organs and develop a better understanding of soft tissue biomechanical properties;
- **Reduce incidence of unintentional tissue injury** and improve safety of MIS devices by incorporating tissue damage data into smart surgical tools to limit potential for excess stress application by a surgeon;
- **Enhance surgical simulator design** to portray more realistic tissue responses during manipulation and provide more detailed evaluations of tissue handling skills.

Animal Experiments

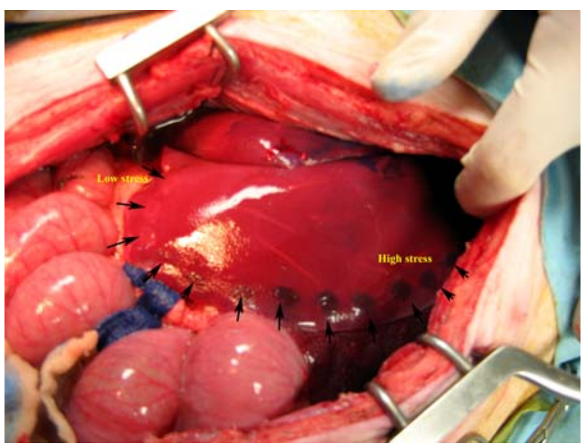
- Animal Experiments using porcine model
- Apply compression stresses in the range of MIS relevant stress magnitudes and durations using a computer-controlled grasper device
- Liver, Ureter, Small bowel
- Allow acute injury to develop
- Harvest compressed tissues and process for histology





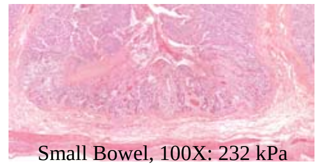


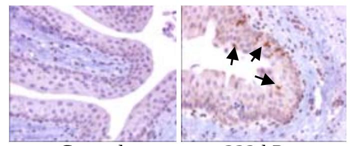
Surface Color Changes



Histology

- Changes in architecture and morphology-H&E
- Measure damage parameters
  - Apoptotic cell area as a measure of cellular death
    - Anti-activated caspase-3 IHC
  - Inflammatory cell counts
    - Leder stain (granulocytes), CD45 (lymphocytes)
  - Coagulation
    - Anti-fibrin antibody IHC
  - Overall cell death
    - H&E eosinophilia


Small Bowel, 100X: 232 kPa


Control 222 kPa
Ureter, 400X

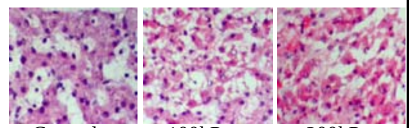
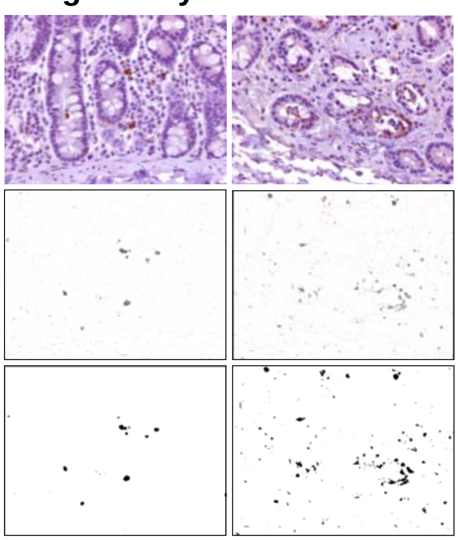

Control 100kPa 200kPa
Liver, 400X

Image Analysis

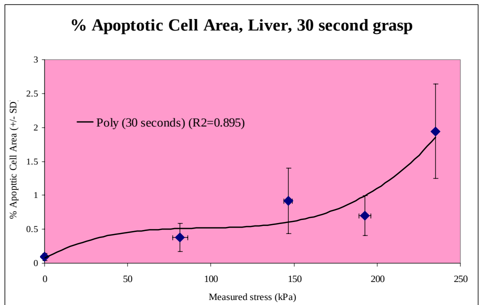

Small bowel, 400X.
Control (0.38%) 285kPa (1.51%)

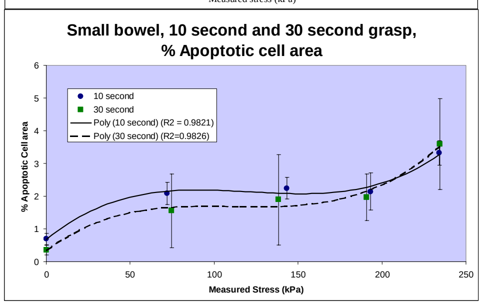
Original Image - apoptotic cells

Background removed, Blue channel

Threshold image

Preliminary Results

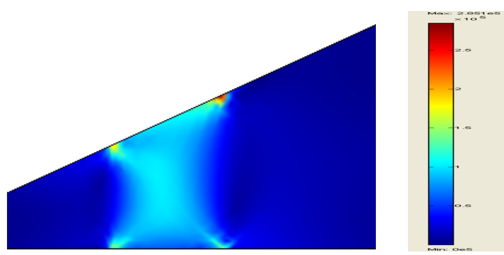




Follow-up with ANOVA and post-hoc analyses

Preliminary results -FEM

FEM analysis of stress distribution throughout a thin plate (5cm x 1cm) with approximate properties of liver (Yu, 2004) and an applied stress in the y-direction of 200kPa (in center of slice). Stress scale on right is from 2.851 E5 Pa (red) to 0 (blue).



Liver (20X), 180 kPa. Crush site is marked by arrows; note increased hemorrhage at sites corresponding to stress concentrations in FEM image above.