A VISUO-HAPTIC FEEDBACK SURGICAL SIMULATOR FOR TWIN-TO-TWIN TRANSFUSION SYNDROME

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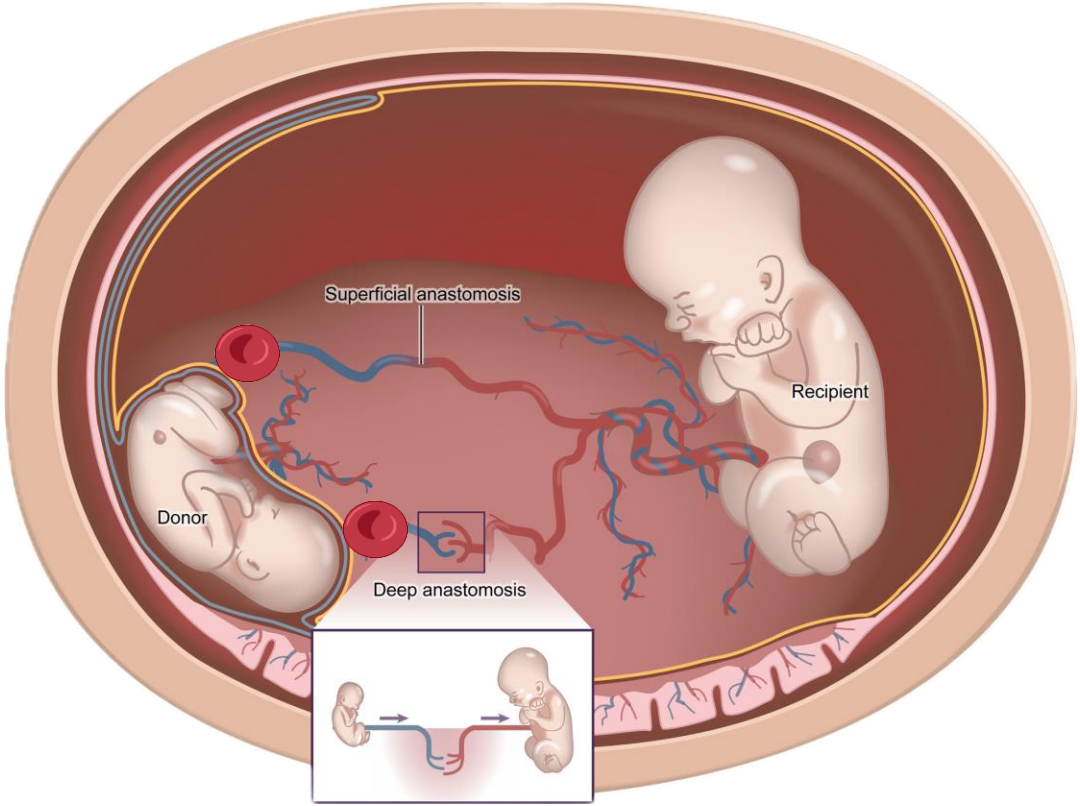
What is Twin-to-Twin Transfusion Syndrome (TTTS)?

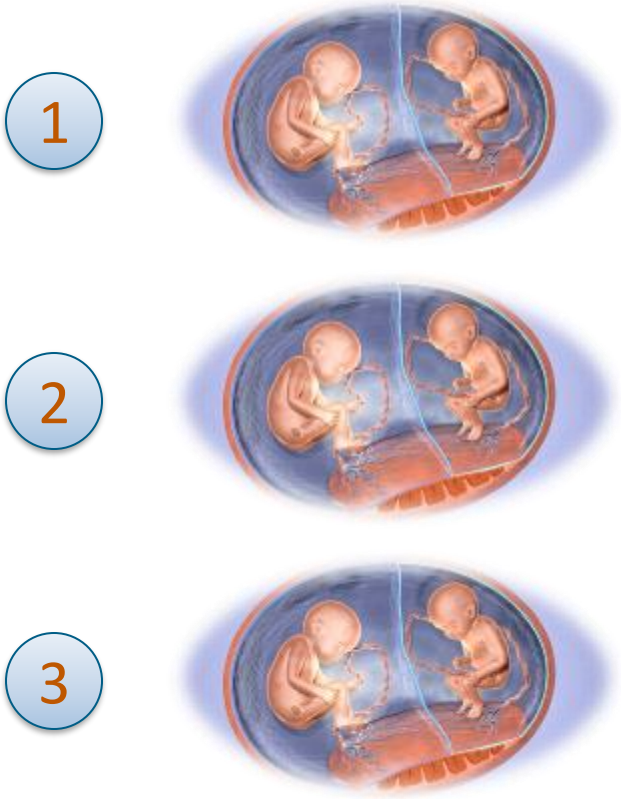
- Approximately 10-15% of monochorionic twin pregnancies
- Life-threatening pregnancy complication where there is unequal distribution of blood between the twins
- The recipient twin develops excessively, and the donor is at high risk of cardiac failure
- Left untreated, can lead to the death of one or both twins
- Rare condition, incredibly difficult procedure, and hard to train



Fetoscopic Laser Photocoagulation (FLP)

The goal is to identify anastomoses and ablate vessels to decouple the twins' vascular system

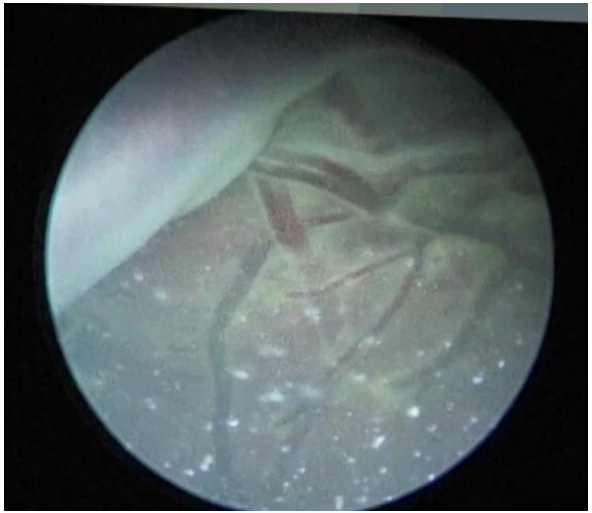
1. Final all anastomosis on the surface of the placenta
2. Ablate each anastomosis site
3. "Solomon method" – create a laser path connecting each ablation site



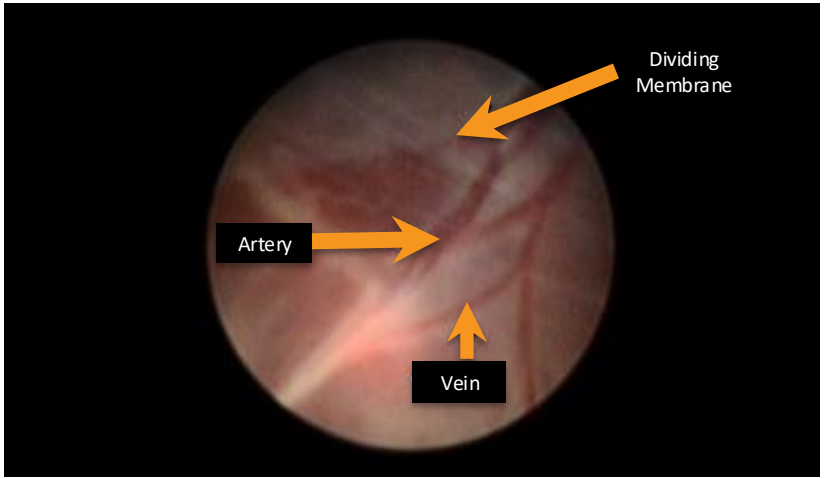
Improving Proprioception

Where are the surgeons in the workspace relative to the identified anastomoses?

Real Fetoscopic Procedure



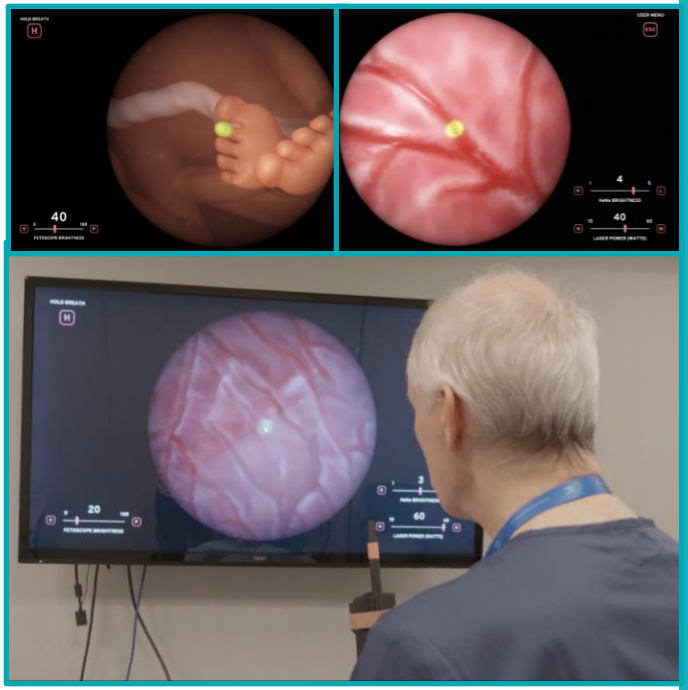
Placenta Anatomical Features



- Challenging to maintain an accurate sense of position in relation to identified anastomoses
- Difficult to remember vein and artery patterns

Type of TTTS Simulators

Virtual



ADVANTAGES

- Simulates the baby and placenta
- Custom fetoscope interface attached to an abdomen model
- Fetoscope settings (brightness, laser power, etc.)
- UI/UX

DISADVANTAGES

- Absence of camera noise, unrealistic textures, laser effect lacks differentiation between vessels and tissue
- Placental vessels are flat
- No haptic or visual feedback

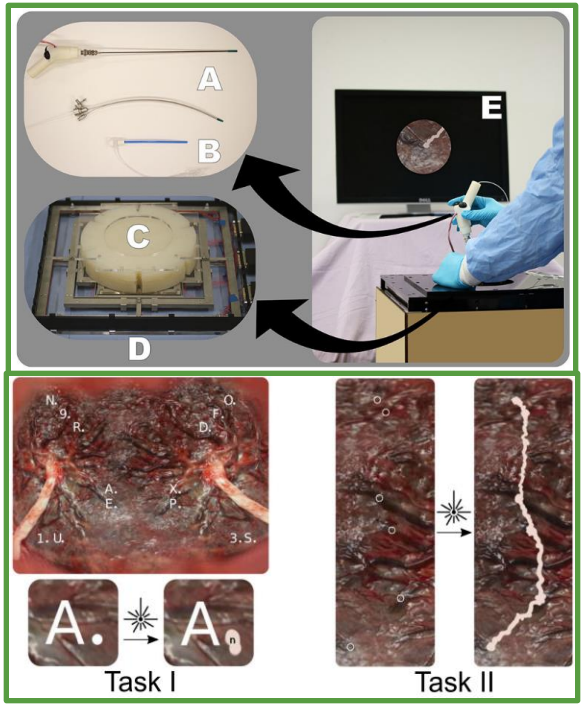
Type of TTTS Simulators

Virtual

ADVANTAGES

- Feels realistic and functional
- Can render placental image for anterior and posterior locations
- Able to add visual indicators to the placenta
- EM tracker at tip for motion analysis

Mixed-Reality



Real Environment

DISADVANTAGES

- Does not render essential elements: twins, fluid, particles, laser effects, etc.
- Placenta is a planar rendering
- No haptic feedback

Type of TTTS Simulators

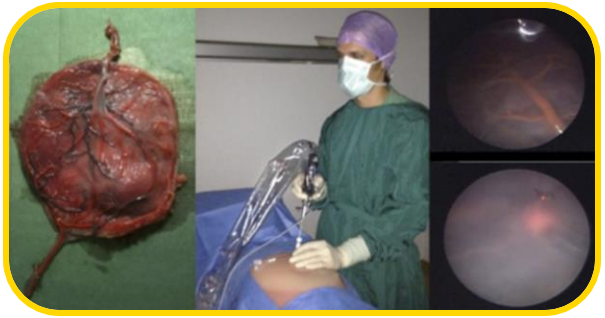
ADVANTAGES

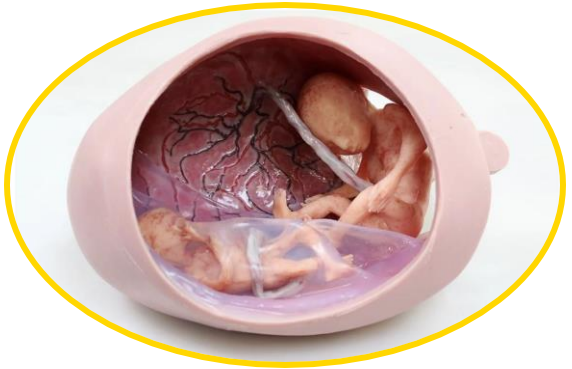
- High fidelity
- Placental vasculature injected with dye to differentiate between veins and arteries

DISADVANTAGES

- Utility is post-delivery, limited placenta availability
- Does not simulate floating twins and amniotic particles
- Very expensive

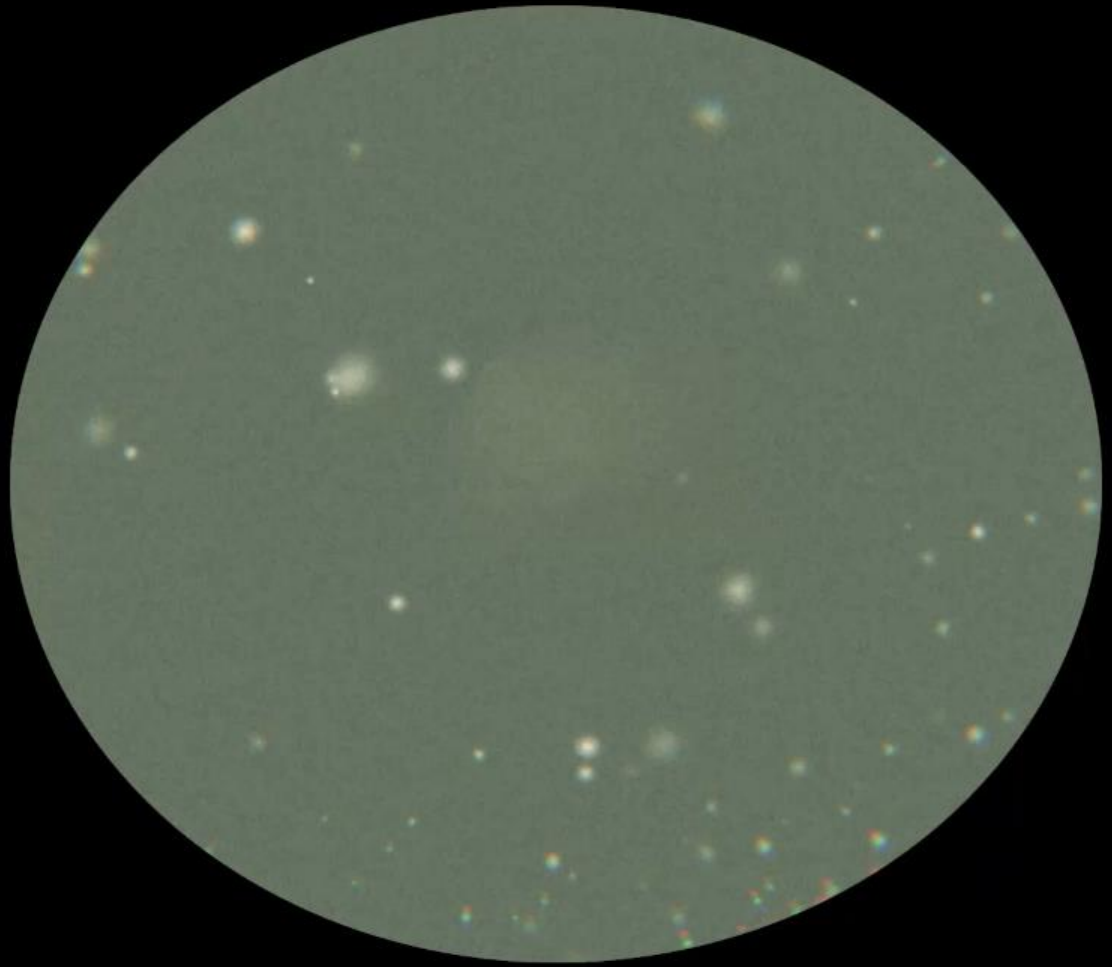
Real Environment





Contributions of This Work

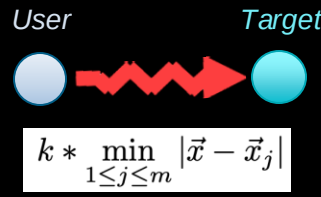
1. The development of a hyper-realistic simulator with all essential elements of TTTS that fetal surgeons will use
2. The improvement of surgical education with visuo-haptic feedback and assistance
3. Proof of concept of assistance features for real surgery



No Assistance

Visual Guidance

Haptic Guidance



Mini-Map Guidance

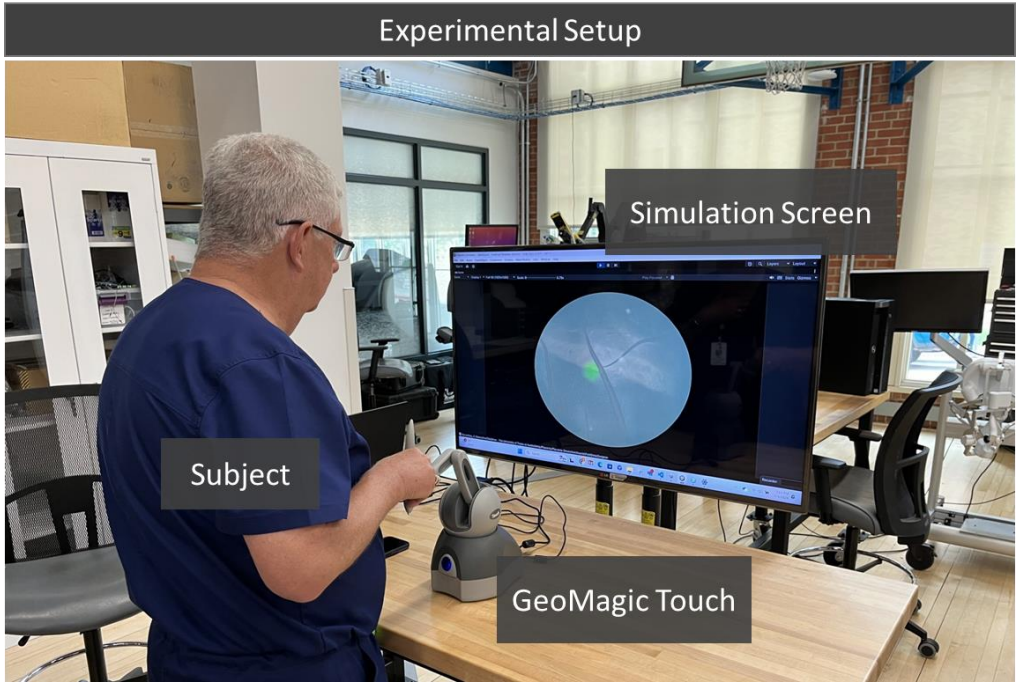
Combined Guidance

HoloLens Guidance


HoloLens Trainer Demo

Experimental Setup

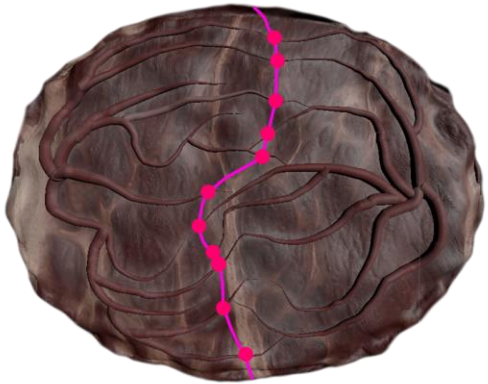
- **Participants:** 30 novices, 1 expert surgeon
  - 5 novices for each assistance case
- **Age (years old)**
  - **Expert:** 68
  - **No Assistance:** 23 ± 5
  - **Haptic Guidance:** 32 ± 17
  - **Visual Guidance:** 32 ± 17
  - **Mini-Map Guidance:** 26 ± 4
  - **Combined Guidance:** 24 ± 4
  - **HoloLens Guidance:** 24 ± 4
- Anastomosis waypoints and trajectory of laser ablation task are collected for analysis



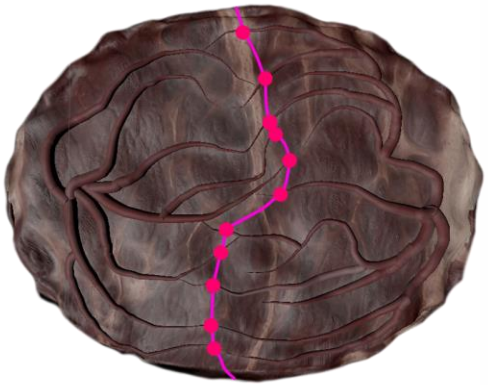
Experimental Task

Participants repeated these tasks 2 times: first trial (no assistance) and second trial (assistance)

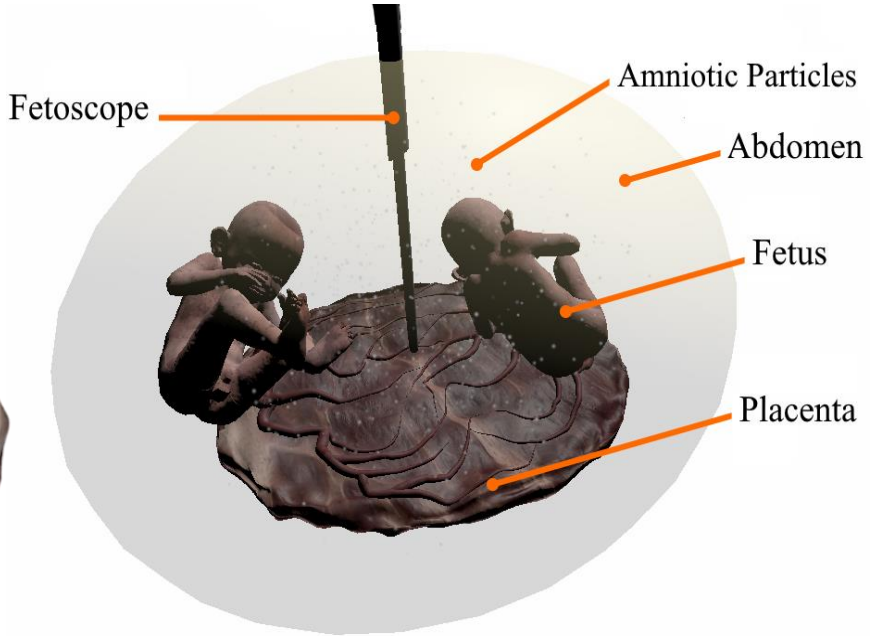
1. Identify anastomosis sites
2. Laser ablation of anastomosis sites
3. Create a laser path



(a) Optimal Placenta Path



(b) Reversed Placenta Path



Experimental Design

Metrics

1. Waypoints Placed

$$\sum_{i=1}^{k}\sum_{j=1}^{n}|\vec{x}_i - \vec{x}_j|^2 \qquad \text{(Eq. 1)}$$

$$(x_i - x_{i+1})/x_i < 0.2 \qquad \text{(Eq. 2)}$$

2. Laser Path Deviation

$$\frac{1}{n}\sum_{i=1}^{n}\min_{1\le j\le m}|\vec{x}_i - \vec{x}_j| \qquad \text{(Eq. 3)}$$

3. Velocity, Acceleration, Jerk

$$v_{\text{avg}} = \frac{1}{n}\sum_{i=1}^{n-1}\frac{|\vec{x}_{i+1} - \vec{x}_i|}{\Delta t_i} \qquad \text{(Eq. 4)}$$

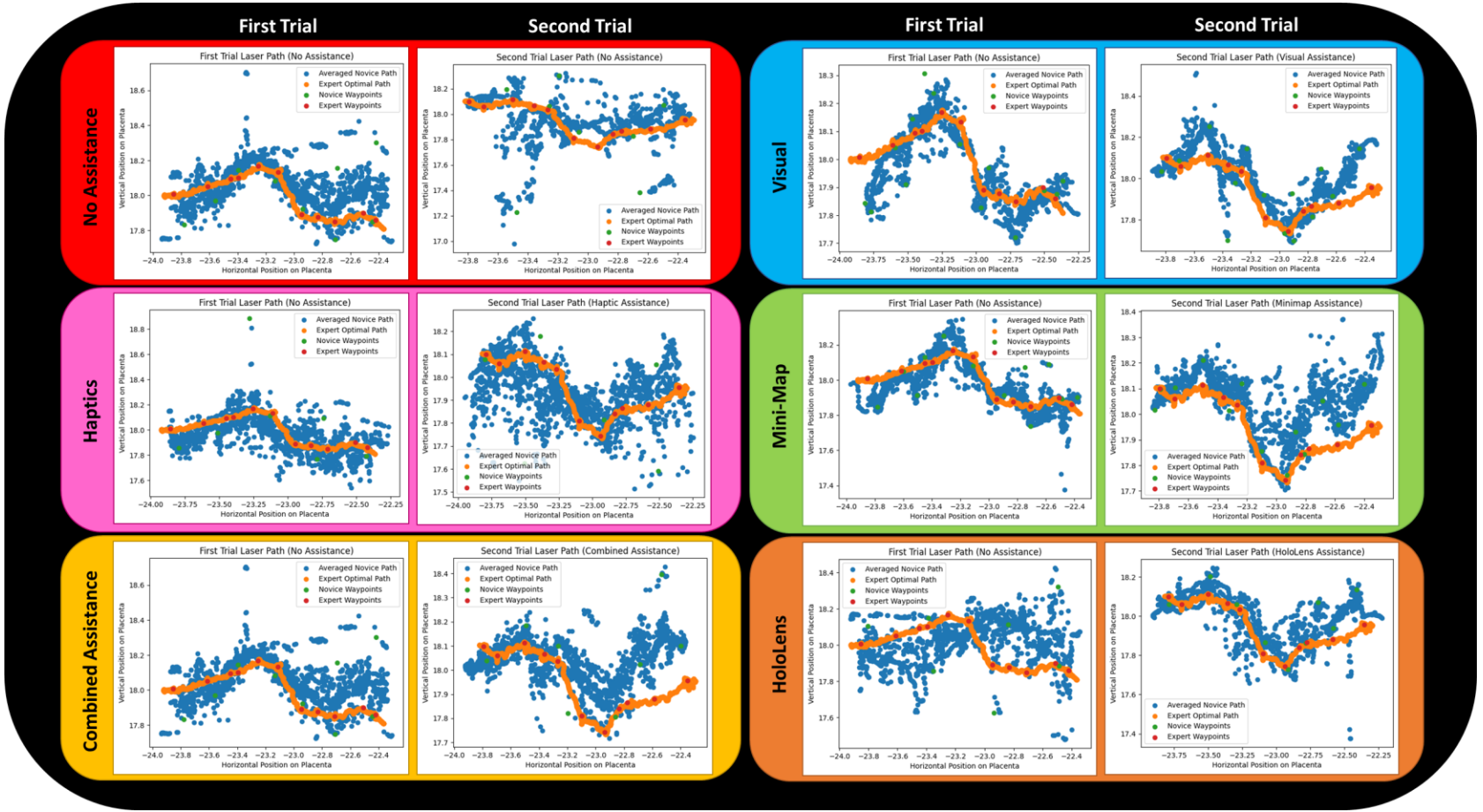
4. Efficiency

$$\frac{1}{\text{Task Completion Time}} \qquad \text{(Eq. 5)}$$

5. Waypoint and Laser Error

Same computation as Eq. 3 except comparing using the novices' waypoints to the expert's waypoints and the novices' laser ablation path to the expert's path.

Results

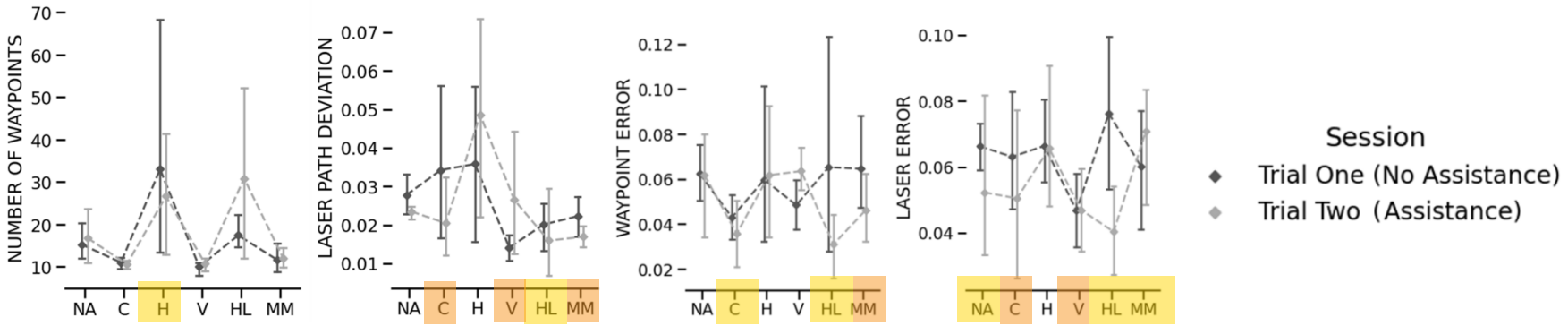

First Trial
Second Trial
First Trial
Second Trial
No Assistance
First Trial Laser Path (No Assistance)
Second Trial Laser Path (No Assistance)
Visual
First Trial Laser Path (No Assistance)
Second Trial Laser Path (Visual Assistance)
Haptics
First Trial Laser Path (No Assistance)
Second Trial Laser Path (Haptic Assistance)
Mini-Map
First Trial Laser Path (No Assistance)
Second Trial Laser Path (Minimap Assistance)
Combined Assistance
First Trial Laser Path (No Assistance)
Second Trial Laser Path (Combined Assistance)
HoloLens
First Trial Laser Path (No Assistance)
Second Trial Laser Path (HoloLens Assistance)
Averaged Novice Path
Expert Optimal Path
Novice Waypoints
Expert Waypoints
Vertical Position on Placenta
Horizontal Position on Placenta

Result – Difference Between Groups

- ***Kruskall-Wallis* test** does not show a significant difference between groups
- However, individual p-value compared between specific groups show statistical significance using ***post-hoc Dunn test***
  - Number of Waypoints Placed
  - Laser Path Deviation
  - Waypoint Error
  - Laser Error

Metrics	Session		Guidance Cases	
	p	post-hoc comparisons	p	post-hoc comparisons
Waypoints Placed	0.926	(Trial One < Trial Two)	0.133	(C < V < MM < NA) < H < (HL)
Laser Path Deviation	0.345	(Trial Two < Trial One)	0.202	HL < (MM < C < V) < NA < H
Waypoint Error	0.449	(Trial Two < Trial One)	0.100	HL < C < (MM < H = NA) < V
Laser Error	0.092	(Trial Two < Trial One)	0.184	HL < (V < C) < NA < (H) < MM

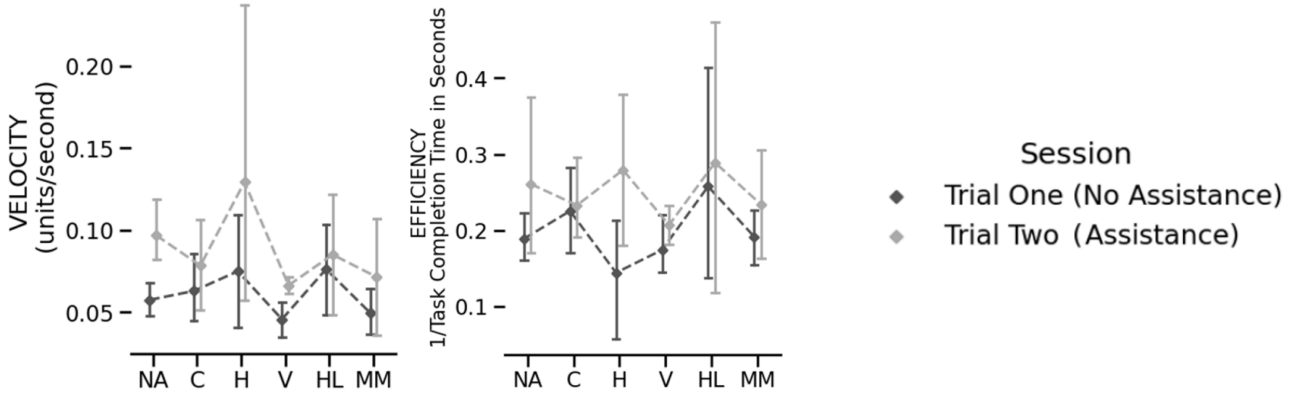
*Asterisk * represents significant differences between groups $p < 0.05$. Round bracket denotes no significance between the pairs of group levels.*



Result – Task Efficiency and Velocity

- Efficiency and Velocity: Significant differences between trial one and trial two; task is becoming easier to do

	Session		Guidance Cases	
Metrics	p	post-hoc comparisons	p	post-hoc comparisons
Velocity	0.021*	Trial One < Trial Two	0.758	(V < MM < C < HL < NA < H)
Efficiency	0.038*	Trial One < Trial Two	0.701	(V < C < MM < NA < H < HL)



User Feedback

		E	N	V	MM	HL	H	C
NASA TLX	Q1: How mentally demanding was the task?	65	60 (30)	86 (21)	74 (22)	58 (10)	70 (6)	70 (20)
	Q2: How physically demanding was the task?	20	59 (39)	21 (29)	60 (26)	30 (18)	33 (19)	31 (22)
	Q3: How hurried or rushed was the pace of the task?	10	28 (26)	23 (25)	35 (16)	33 (19)	37 (18)	17 (8)
	Q4: How successful were you in accomplishing what you were asked to do?	60	62 (20)	56 (33)	44 (18)	37 (13)	65 (13)	43 (22)
	Q5: How hard did you have to work to accomplish your level of performance?	45	64 (21)	83 (21)	72 (13)	52 (15)	64 (19)	72 (10)
	Q6: How insecure, discouraged, irritated, stressed, and annoyed were you?	25	51 (35)	60 (31)	51 (35)	33 (24)	58 (21)	41 (39)
	Q7: The simulator looks realistic	80	76 (17)	80 (16)	85 (10)	75 (10)	76 (17)	84 (17)
	Q8: The simulator feels realistic	60	80 (20)	88 (11)	84 (9)	85 (10)	84 (17)	76 (22)
	Q9: The content of the simulation is relevant to the surgical procedure	60	92 (11)	100 (0)	85 (19)	85 (19)	80 (14)	96 (9)
	Q10: The simulation was fun to complete	100	76 (33)	84 (17)	64 (17)	95 (10)	76 (22)	68 (30)
	Q11: I was anxious during the task	100	56 (41)	60 (20)	48 (23)	55 (34)	52 (27)	84 (17)
	Q12: The task was difficult to complete	30	80 (24)	76 (22)	84 (9)	75 (10)	80 (14)	68 (18)
Pre-Exp Survey	Q13: Age	68	23 (5)	32 (17)	26 (4)	24 (4)	32 (17)	24 (4)
	Q14: Experience with human/machine interactive devices	1	2.8 (1.1)	1.8 (1.3)	2.4 (0.9)	2.8 (1.1)	2.2 (1.1)	3.2 (0.9)

Data is shown as mean (standard deviation). Q1-6 are NASA TLX questions. For Q1-4,6: 0 is very low and 100 is very high. For Q5: 0 is perfect and 100 is failure. For Q7-10,12: 0 is strongly disagree and 100 is strongly agree. For Q11: 100 is not anxious at all while 0 is very anxious. For Q14: 0 is none and 4 extensive. E=Surgeon. Assistance cases: N=None, V=Visual, MM=Minimap, HL=HoloLens, H=Haptic, C=Combined.

Expert Surgeon Feedback

TABLE II: Post-Experiment Survey: Surgeon-Specific Questions

Q1:	The simulator resembles real-life surgery	4
Q2:	The simulator can differentiate between different performance levels (e.g. novice vs expert)	4
Q3:	The simulator can accurately assess the skill level of the user	4
Q4:	This simulator is better than others or expected	4
Q5:	This simulator gives results consistent with other tests for the same skill	4
Q6:	The performance in the simulator would translate to a similar performance in a real-life procedure	3
Q7:	A surgeon who performs well in the simulation will perform well in a real surgery	3
Q8:	Another evaluator would assess a surgeon's performance on the simulator similar to yours	4
Q9:	If you were to repeat the test at a different time you would achieve a similar result	5
Q10:	This simulator is good for learning	4
Q11:	I would recommend this simulator to a peer	5
Q12:	Confirm position of placenta, fetuses, and cord insertions	3
Q13:	Identification of intertwin dividing membrane	3
Q14:	Mapping of placental surface and vascular equator	4
Q15:	Use of selective laser techniques (only coagulation of anastomoses)	4
Q16:	Use of Solomon technique	4
Q17:	Identify and record number and type of anastomosis sites coagulated	5

1-11 are rated strongly agree or strongly disagree, 5 and 0 respectively. 12-17 are rated as how accurate, from perfect to not at all, 5 and 0 respectively.

Limitations and Future Work

- Lack of situational haptics for user interface
- Overall improve laser depth perception
- Combining a physical model with the virtual simulation
- Mimic the energy loss when the laser is not angled at approximately 0°
- Intrauterine bleeding onto the placenta
- A viscous field between points that directs you back to the path that connects the identified anastomoses

Conclusion

- In this work we introduce a novel hyper-realistic TTTS simulator
- Through a human subject study, our simulator could improve performance of laser ablation path accuracy
- Significant difference between certain assistance cases cases
- Significant difference between task efficiency and laser ablation velocity from trial one to trial two
- The results of our simulator could improve surgical training and inform the development of novel robotic systems for TTTS

Thank you!

Any Questions?