The Role of Haptic Force Feedback in Reducing Surgical Force: Optimization of Force Application in Robotic Cholecystectomies

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INTUITIVE

Does **force feedback** have a positive impact on force application during surgery?

The purpose of this study is to evaluate the potential of haptic force feedback (FFB) technology during RC to reduce excessive force application.

Introduction Robotic cholecystectomy (RC) is the minimally invasive process of surgically extracting a diseased gallbladder.

- Despite the advantages of robotic surgery, a perceived limitation is lack of haptic feedback, as inadequate sensation input may result in an unintentional force application on tissue that can increase the risk of tissue injury or inadequate suturing, resulting in prolonged operative time and increased patient morbidity [1].
- Clearance of the hepatocystic triangle, exposure of the lower third of the cystic plate, cystic artery and cystic duct are essential steps to achieving the critical view of safety, which is the single most important intervention to mitigate against bile duct injury during RC [2]. The surgical steps Dissection of Triangle of Calot and Dissection of Gallbladder off Liver Bed, and the phase Dissection from a standardized temporal segmentation framework are examined in this study to understand the effects of force feedback on these imperative steps and phases [3].

Methodology

Surgeries conducted using DaVinci Surgical System and accessories

- Accessories include cannulas, sterile drapes, seals, and tool instruments with force sensors at the instrument tips.
- Sensors measure forces applied in the X, Y, and Z directions and transmit forces back to hand controllers at the surgeon's console [4]
- Feedback is relayed to surgeon's hand controls and scaled to the following sensitivity settings: Off, Low, Medium, High [4]

Segmentation and Annotation of surgeries completed

- A standardized temporal annotation was used to segment cases.
- The framework has clear definitions of the start and stop parameters for annotating relevant tasks and phases to minimize subjectivity [3].
- In addition to human annotations, ML models that were previously trained on ground truth human annotations have been utilized to segment dissection phase.
- See Fig 1 for parameter details

Data analysis is conducted

- Data preprocessing and statistical analysis were performed using Python (3.9.7). Data extraction and preprocessing were conducted using SQL.
- Force data was partitioned according to standardized step and phase segmentation. Forces less than $0.5\ N$ were omitted from the analysis, since $0.5\ N$ has been reported to represent the minimum detectable force encountered during endoscopic procedures [5]. Force measurements for each phase and task were summarized per case using median force across different sensitivity settings.
- Cases with median force value above $6.5\ N$ were excluded as $6.5\ N$ is the system threshold above which force is not quantified.
- Cases with multiple sensitivity settings were excluded to ensure statistical independence and prevent bias from double-counting outcomes across sensitivity groups.

Extended Surgical Phase and Definition

Extended Phase	Definition
Dissection	Surgical activities to gain access and/or prepare target anatomy for subsequent transection, reconstruction and/or extraction. Target anatomy is separated or mobilized to gain access to subsequent structures without full division into two distinct structures or distinct functional compartments

Recommended Segments from RC Annotation

Ontology	Name	Surgical Objective	Start Parameter	Stop Parameter
Step	Dissection of Triangle of Calot	Dissection of structures within Triangle of Calot to achieve the critical view of safety.	First dissecting tool interaction with gallbladder infundibulum with intent to dissect Triangle of Calot	Last dissecting tool interaction with Triangle of Calot after the critical view of safety has been achieved.
Step	Dissection of Gallbladder off Liver Bed	Gallbladder is dissected off with the liver bed with intent to free the gallbladder.	First dissecting tool interaction with gallbladder with intent to dissect the gallbladder off the liver bed.	Last dissecting tool interaction with gallbladder resulting after the gallbladder has been freed from the liver bed.

Fig 1. Relevant step and extended phase segmentation are defined by Mlambo et al. For each step and phase, the table includes the ontology at a granular level, surgical objective, start parameter, and stop parameter or definition used for segmentation and annotation purposes. Extended phases are the least granular tier of temporal segmentation, and surgical steps are the second hierarchical tier and are more granular than extended phases. In RC, Dissection of Triangle of Calot and Dissection of Gallbladder off Liver Bed are nested within Dissection phase [3].

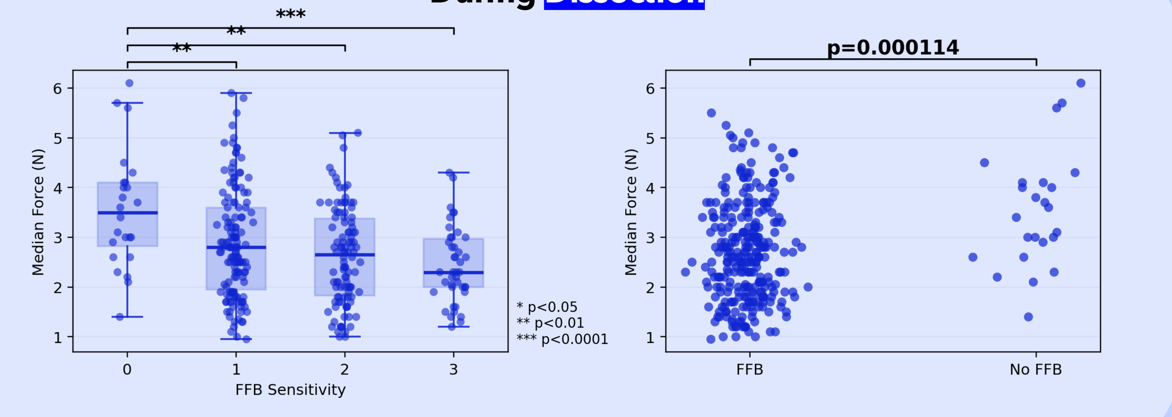
Nested Ontology Step and Phase Framework for RC

Fig 2 The diagram visually represents the segmentation of RC workflow, with Dissection of Triangle of Calot and Dissection of Gallbladder off Liver Bed nested within Dissection phase. The schematic is indicative of an observed variation in time progression during RC.

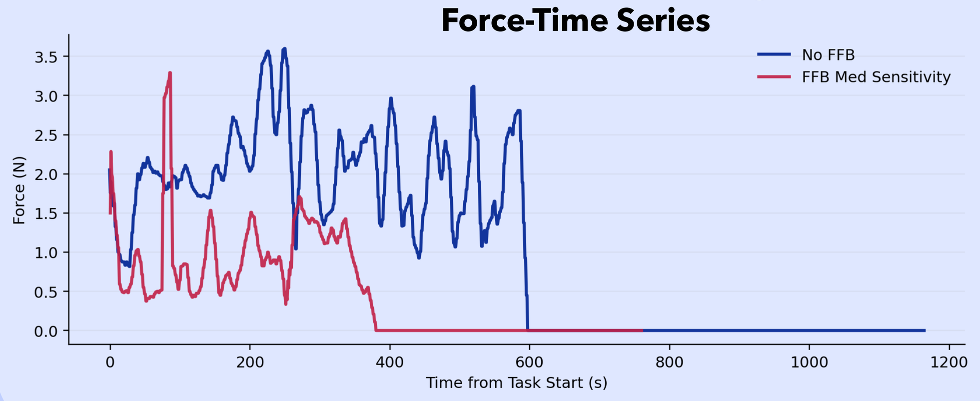
Results

Haptic force feedback usage **reduces** median force exertion during **dissection** in cholecystectomies

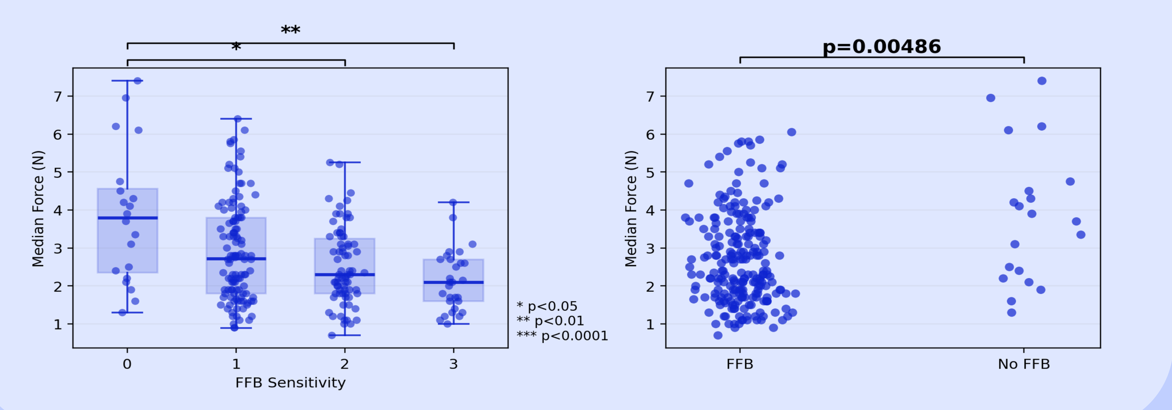
Case-Level Median Force Across FFB Sensitivity During Dissection



Dissection of Calot's Triangle Force-Time Series



Case-Level Median Force Across FFB Sensitivity During Dissection of Gallbladder off Liver Bed



Dissection of Gallbladder off Liver Bed Force-Time Series

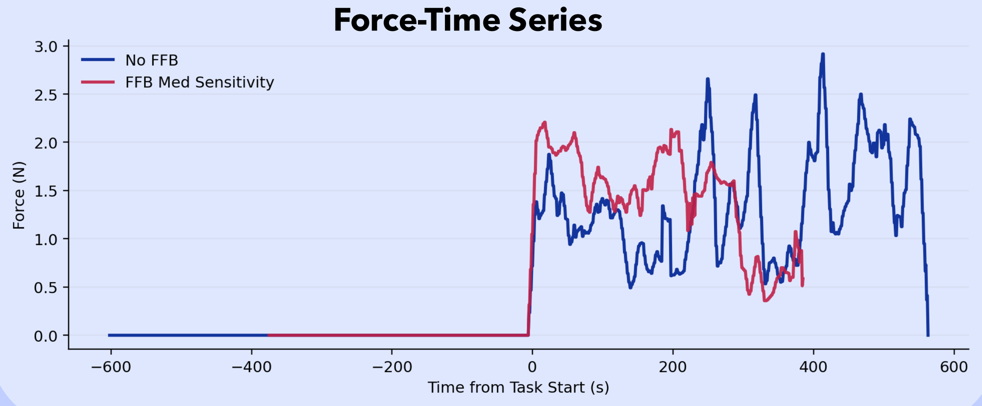


Fig 3 Force applied during each surgical task was summarized at the case level using the median force, with each case providing one observation per sensitivity setting. Cases with multiple sensitivity settings were excluded to ensure statistical independence, and outliers were identified and filtered using an IQR-based method. Cases with a median force above $6.5\ N$ were excluded, as $6.5\ N$ is the system threshold above which force values are not quantifiable. Box-and-whisker plots display the distribution of these case-level median forces across FFB sensitivity settings. The center line indicates the median, and box edges denote interquartile range (IQR).

Results indicate that median force generally declined as FFB sensitivity increased, supporting the hypothesis that FFB usage reduces median force exertion. Statistical group comparisons were performed during the Kruskal-Wallis test followed by pairwise Mann-Whitney U tests with Bonferroni correction. Statistically significant results are indicated with * (see figure key for details). Comparisons between FFB and no FFB (Baseline) are also illustrated on the right plot, with both Dissection and Dissection of Gallbladder off Liver Bed showing statistically significant differences between groups by Mann-Whitney U test.

Fig 4. Force over time with x-axis being seconds from task start is shown for two representative cases: No FFB (Baseline) and Med sensitivity. Baseline demonstrates consistently higher and more variable force, while Med sensitivity exhibits lower overall force with occasional, more controlled spikes. Cases were matched for similar workflow, procedure duration, and Parkland Grading Scale to control for these variables.

Sample Sizes per Sensitivity Setting

Segment	Sensitivity 0 (Off)	Sensitivity 1 (Low)	Sensitivity 2 (Med)	Sensitivity 3 (High)
Dissection Phase	26	144	106	42
Dissection of Gallbladder off Liver Bed	20	119	77	29

Table 1 Summarizes the sample sizes for each FFB sensitivity setting (Off, Low, Med, High), representing the number of cases in each group for Dissection phase and Gallbladder off Liver Bed step.

Kruskal-Wallis Test Results

Segment	H Statistic	p-value
Dissection	20.86	< 0.001
Dissection of Gallbladder off Liver Bed	16.51	< 0.001

Table 2 Presents Kruskal–Wallis H test results comparing median force values across all FFB sensitivity levels for each segment. Statistically significant p -values indicate detectable group differences in applied force, supporting further pairwise comparisons.

Mann–Whitney U Test Results No FFB vs FFB

Segment	U Statistic	p-value
Dissection	2063.0	0.000114
Dissection of gallbladder off liver bed	1394.5	0.00486

Table 3 Compares force applied in baseline cases against cases with any force feedback (FFB On), using Mann–Whitney U tests for each segment. The tests resulted in statistically significant p -values ($p < 0.05$).

Mann–Whitney U, Bonferroni-corrected Results Dissection Phase

Comparison	U Statistic	Raw p	Bonf. p	Significant?
Off vs Low	2579.5	0.0022	0.0207	p < 0.05
Off vs Med	2068.5	7.8×10^{-5}	0.0002	p < 0.001
Off vs High	881.0	2.38×10^{-5}	7.14×10^{-5}	p < 0.0001

Mann–Whitney U, Bonferroni-corrected Results Dissection of Gallbladder off Liver Bed Step

Comparison	U Statistic	Raw p	Bonf. p	Significant?
Off vs Low	1552.0	0.03	0.09	No
Off vs Med	1090.5	0.0043	0.0129	p < 0.05
Off vs High	463.0	0.000446	0.00134	p < 0.01

Table 4 and **Table 5** Report results of pairwise Mann–Whitney U tests comparing baseline to other sensitivity settings (Low, Med, High) for Dissection phase and Gallbladder off Liver Bed step, with p -values corrected for multiple comparisons. Statistically significant results identify sensitivity levels where force application was reduced compared to baseline.

Medians of Force per Sensitivity Group

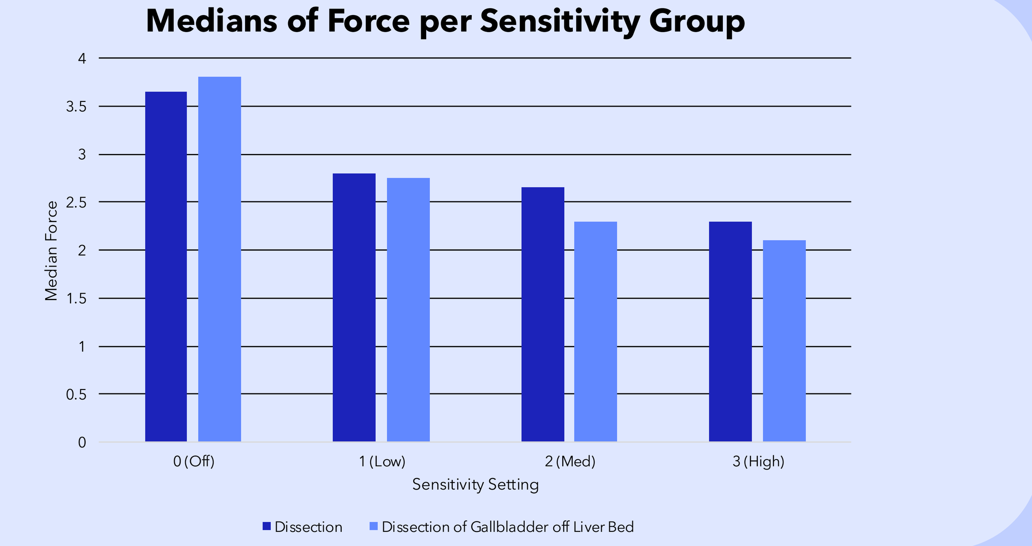


Fig 5 The median force (N) recorded for each FFB sensitivity group in Dissection phase and Gallbladder off Liver Bed step is shown. Results demonstrate a consistent reduction in median applied force as sensitivity setting increases, which is also depicted in Fig 3.

FFB Distribution of Forces

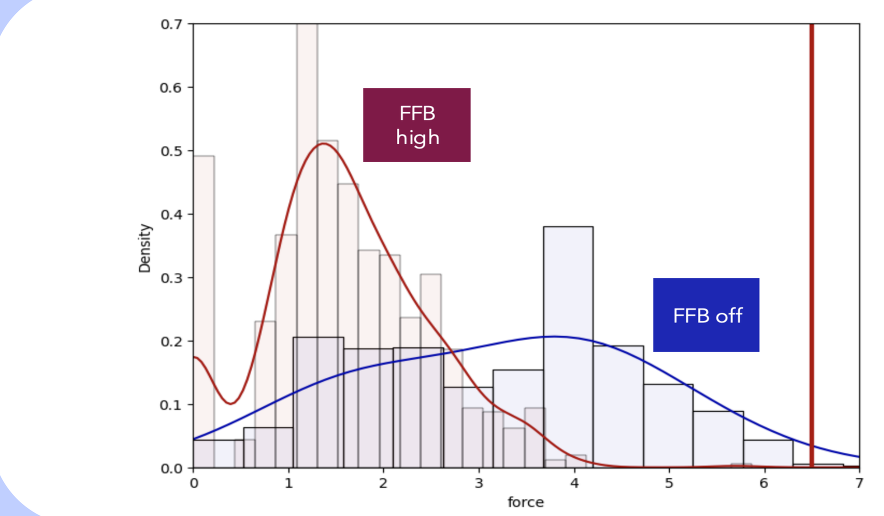


Fig 6 In this FFB Force Distribution Plot, high FFB yields a tighter, reduced distribution of force application with respect to baseline. High FFB reduces the range and overall distribution of force usage, indicating greater consistency and control during surgical dissection.

Conclusion

Results Haptic FFB usage reduced median force exertion during both the Dissection phase and the Dissection of Gallbladder off Liver Bed in robotic surgery. Analysis revealed a consistent decrease in case-level median force as FFB sensitivity increased. Median force during dissection dropped from $3.65\ N$ (Off) to $2.80\ N$ (Low), $2.65\ N$ (Med), and $2.30\ N$ (High). For gallbladder removal, median force decreased from $3.80\ N$ (Off) to $2.75\ N$ (Low), $2.30\ N$ (Med), and $2.10\ N$ (High).

The Kruskal–Wallis test showed statistically significant differences in force distributions across FFB sensitivity settings for both tasks (Dissection: $H = 20.86$, $p = 0.00011$; Gallbladder: $H = 16.51$, $p = 0.00089$). Pairwise Mann–Whitney U tests with Bonferroni correction confirmed that all sensitivity settings in the Dissection phase and Med and High sensitivities for Gallbladder off Liver Bed produced significantly lower force with respect to baseline.

Overall, increased FFB sensitivity was associated with lower force application, supporting the impact of haptic feedback settings on surgeon force behavior during key procedural segments. Detailed breakdowns, sample sizes, and statistical results are presented in Tables 1–6 and Fig 3-5.

Conclusion Our analysis demonstrates that haptic FFB usage reduces median force exertion during Dissection phase and Dissection of Gallbladder off Liver Bed step of RC. A consistent pattern across both clinical segments is that Med and High sensitivity settings produce the most meaningful reductions in force, whereas Low sensitivity produces a smaller separation from the absence of FFB baseline sensitivity. Previous work on the impact of FFB in robotic surgery has focused on simulated tasks or *ex-vivo* models, and they demonstrate a reduction of applied force under FFB [4]. This investigation extends this line of evidence into clinical RC, which exhibit the added complexities of real operative context and variations in gallbladder anatomy. While this study does not directly link force reduction to decreased patient complications, minimizing excessive force is directionally consistent with safer surgical practice and minimizing tissue trauma. Future work relating force application to patient outcomes or tissue damage would aid in further enhancing our understanding of the clinical significance of force application and its potential impact in surgical care.

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