

Characterizing Objective Performance Indicators with Force Feedback to Predict Clinical Outcomes in Robot-Assisted Radical Prostatectomy Using a Machine Learning-Enabled Analytics Application

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Abstract

Purpose: Objective performance indicators (OPIs) from robotic platforms can predict postoperative outcomes, yet their interpretability and actionability remain limited. We used a machine-learning analytics application to predict erectile function (EF) and urinary continence (UC) with OPIs reflecting technical behaviors during robotic-assisted radical prostatectomy (RARP).

Materials and Methods: We conducted a retrospective observational study of RARP procedures performed using the da Vinci V platform at a single institution (1.5 years). EF and UC recovery were assessed using validated questionnaires. Step-specific OPIs were calculated from robotic system data and analyzed using regression and classification models with cross-validation. Cases underwent structured postoperative video and metric review.

Results: Outcome analyses included 50 patients for EF and 36 for UC. Predictive performance was stronger for EF ($F1=0.63$) than for UC ($F1=0.35$). Step-level modeling identified clinically relevant operative steps associated with functional recovery: pedicle and posterior plane dissection for EF, and vesicourethral anastomosis, bladder neck, and apical dissection for UC. OPIs within these steps demonstrated interpretable associations with technical behaviors. Improved outcomes were associated with greater instrument motion efficiency ($p<0.05$), reduced energy use ($p=0.01$), and lower peak traction forces ($p=0.04$). Increased passive retraction forces were observed in patients with poorer EF recovery ($p=0.01$). Video review identified relationships between OPIs and observed intraoperative technique.

Conclusions: In this pilot study, we demonstrate that step-specific OPIs are associated with functional recovery after RARP. Video review with clinically contextualized metrics supports technical interpretation and data-driven feedback to improve surgical technique and functional outcomes.

INTRODUCTION

The increasing digitization of robotic surgery has enabled objective, high-resolution measurement of surgeon behavior, creating new opportunities to assess operative performance and predict patient outcomes.^{1,2} Modern robotic platforms capture video, kinematic, and instrument-level data that quantify surgeon-tissue interaction.^{3,4} Prior studies have shown that such intraoperative objective performance indicators (OPIs) can predict postoperative outcomes,⁵ sometimes outperforming prediction with patient factors alone.^{6,7} However, many approaches rely on machine-learning (ML) methods that improve predictive accuracy at the expense of interpretability and actionability, limiting translation of quantitative insights into meaningful changes in surgical technique.⁸

Surgical video provides anatomical context necessary to interpret OPIs and link them to specific technical behaviors.⁹ When informed by outcome data, review of video with OPIs can support actionable feedback by contextualizing how intraoperative behaviors influence recovery.¹ Despite this promise, few

studies have demonstrated a closed-loop framework in which objective data are linked to metrics, contextualized through video, and used to guide feedback and technique modification.^{10–12}

Robot-assisted radical prostatectomy (RARP) is an ideal procedure in which to study the relationship between intraoperative behaviors and functional outcomes.¹³ Recovery of erectile (EF) function and urinary continence (UC) depends on well-defined technical mechanisms, including nerve-adjacent dissection, preservation of neuromuscular and fascial support structures, and precise vesicourethral anastomosis.^{14,15} These characteristics make RARP particularly well-suited for step-based analysis of objective performance indicators (OPIs) that reflect surgical technique.

Standardized tools for evaluating surgical technique have been shown to correlate with outcomes after RARP, including UC associated with tissue retraction quality and EF recovery associated with specific surgical gestures.^{7,16} However, these tools often rely on expert video review, limiting scalability. Hung and colleagues demonstrated that automated performance metrics could independently predict EF and UC after RARP, even after adjustment for patient factors.^{17,18} Despite these advances, most studies have not incorporated direct measures of tissue handling, such as force application, a previously inaccessible dimension of surgical technique that may enhance interpretability.¹⁹

Prior studies have leveraged advanced ML techniques to improve outcome prediction with OPIs,⁵ but few have explored how individual OPIs relate to specific surgical behaviors. Translating objective data into practice change instead requires interpretability and contextualization across patient, surgeon, and operative factors.¹⁷ Analytics workflows have been developed to integrate multimodal robotic data, identify outcome-relevant operative steps, and support structured video review for feedback.¹¹ In this study, we apply an ML-enabled analytics application to predict functional outcomes after RARP with OPIs, including force measured during the procedure, contextualized by surgical step. Intraoperative behaviors were then investigated through video review directed by highly predictive step-level OPIs. Our objective was to identify operative steps in which technical factors reflected by OPIs were associated with recovery of EF and UC.

METHODS

Study Design

We conducted a retrospective observational study of consecutive patients undergoing RARP at a single institution between April 2024 and December 2025 following institutional review board approval (Pro2020-1293) (**Fig. 1**).

Study Population

All RARP procedures performed using the da Vinci 5 (dV5) surgical system (Intuitive Surgical) with force feedback (FFB) instruments during the study period were included.^{4,19} FFB instruments included Maryland or Fenestrated bipolar forceps for non-dominant use and ProGrasp or Cadiere forceps for third-

or fourth-arm passive retraction. Surgeons activated FFB using their preferred sensitivity settings. Patients were included if complete OPIs and baseline clinical data were available. For EF analyses, patients required a baseline SHIM score >0 and follow up to at least 3 months with at least one postoperative SHIM assessment. For continence analyses, patients required a baseline ICIQ score of 0 or daily pad use of 0, and follow up to at least 7 weeks with at least one postoperative incontinence assessment.

Outcome Measures

Patient demographic and clinical variables, including age, body mass index (BMI), prostate volume, comorbidities, prior abdominal surgery, and preoperative prostate-specific antigen (PSA), were obtained from a prospectively maintained prostate cancer database.

Primary endpoints were recovery of EF and UC. EF was assessed using the Sexual Health Inventory for Men (SHIM), administered preoperatively and at standardized postoperative intervals (7 weeks; 3, 6, 9, 12, and 24 months). Patients were stratified by baseline EF as dysfunction (SHIM 1-17) or preserved function (SHIM 18-25). Among patients with preserved baseline function, recovery was defined as the maximal postoperative SHIM score relative to baseline and expressed as a percentage. Recovery was categorized as high ($\geq 67\%$), moderate (34-66%), or low (1-33%). UC was assessed using the International Consultation on Incontinence Questionnaire (ICIQ) at the same postoperative intervals. Continence was defined as an ICIQ score of 0 or daily pad use of 0. Time to continence recovery was categorized as within 6 months, within 12 months, or not achieved within 12 months.

Data Acquisition and OPIs

Robotic surgical data were obtained from the dV5 system and included surgeon experience, synchronized video, instrument kinematics, system events, instrument utilization, and force-related metrics. These data were processed to compute OPIs quantifying intraoperative surgeon behavior, including instrument motion efficiency, console interaction, energy use, and force application. Force measurements reflected absolute applied forces and were independent of surgeon-selected force-sensitivity settings. OPIs were calculated at the case- and step-levels corresponding to predefined operative steps.

Analytics Workflow and Data Processing

Robotic surgery system data, derived OPIs, and outcome data were integrated within a dedicated analytics application. The analytics platform enabled hypothesis-driven exploration through structured workflows supporting segmentation by operative step or target outcome, integration of OPIs, and statistical modeling to identify predictors of clinical outcomes. Automated feature selection, statistical testing, and visualization were supported. Manual model refinement was not performed, by design, to prioritize feasibility, hypothesis generation, and scalability.

Independent variables included patient factors (age, BMI, prior abdominal surgery, prostate size, preoperative PSA, baseline SHIM score, baseline ICIQ score, baseline pad number), surgeon characteristics (procedure-specific volume), and OPIs derived from selected operative segments (**Supplement Table 1**). Preprocessing included removal of variables with excessive missingness and mean imputation of remaining missing values. Univariate associations were associated using Pearson correlation coefficients, with predictors ranked by absolute correlation magnitude.

Predictive Modeling and Statistical Analysis

Segment-specific predictive models were developed using logistic regression for categorical outcomes. Regularization was applied to mitigate overfitting. Model performance was evaluated using 5-fold cross-validation, and F1 score for categorical outcomes. Feature importance was assessed using standardized regression coefficients. Group comparisons were performed using independent-samples t-tests or one-way ANOVA, as appropriate. Statistical significance was defined as a two-sided p-value <0.05. Because this study was exploratory and evaluated many correlated OPIs, formal correction for multiple comparisons was not applied. Reported p-values are intended to identify potentially meaningful associations for future validation.

Case-Based Video Review

To supplement quantitative analyses, representative cases with optimal and poor outcomes were identified using model-derived metrics and outlier analysis. These cases underwent structured postoperative video review (**Supplement Table 2**) with the operating surgeon to qualitatively assess whether variations in OPIs, including force application, energy use, and tissue handling, explained the observed technique and postoperative outcomes, and identified targets for performance improvement.

RESULTS

Patient Demographics

Baseline demographic and clinical characteristics of patients stratified by EF recovery are shown in **Table 1**. Patients with high baseline recovery were younger ($p < 0.001$) and had smaller prostate volumes ($p = 0.010$) compared with those with moderate or low recovery, while BMI, prior abdominal surgery, and baseline PSA were similar across recovery groups. Baseline SHIM scores were similar across groups ($p = 0.508$) along with other characteristics.

	Baseline Erectile Dysfunction (BED)*	High Baseline Recovery (HBR)	Moderate Baseline Recovery (MBR)	Low Baseline Recovery (LBR)
Age (years), median (IQR)	65 (8.5)	56 (10)	62 (6)	66 (4.75)
BMI (kg/m ²), median (IQR)	27.5 (7.25)	29.4 (4.25)	31.4 (4.73)	26 (6.25)
Prior abdominal surgery , N (%)	4 (36.4%)	5 (33.3)	2 (40%)	7 (38.8%)
Prostate size (cc), median (IQR)	49 (26)	34.5 (14.5)	38.2 (10.6)	58.74 (38.73)
Preop PSA , median (IQR)	6.07 (5.08)	5.73 (3.56)	10.15 (5.44)	8.6 (7.91)
Preop SHIM , median (IQR)	0 (1)	22 (8)	20.5 (7.75)	21 (12.25)
*BED used as reference and excluded from analyses.				

Table 1. Patient demographics for recovery of erectile function (EF).

Baseline characteristics stratified by time to continence recovery are presented in **Table 2**. Patients achieving continence within 6 months tended to be younger ($p = 0.136$) and have lower BMI compared with those recovering later or not achieving continence within 1 year ($p = 0.187$), while baseline continence status, prior abdominal surgery, and prostate size were similar across groups. All groups demonstrated excellent baseline continence with median preoperative ICQ scores and pad use of zero.

	UC <6 months	UC 6-12 months	No UC in 1 year
Age (years), median (IQR)	61 (11.25)	66 (11.75)	65 (4.25)
BMI (kg/m ²), median (IQR)	27.1 (4.65)	29.5 (8.83)	30.35 (9.08)
Prior Abdominal Surgery , N (%)	6 (37.5)	4 (40)	2 (20)
Prostate Size (cc), median (IQR)	39.68 (23.25)	56.74 (36.38)	39.25 (32.83)
Preop PSA , median (IQR)	8.29 (5.80)	5.65 (1.46)	6.13 (12.2)
Preop ICIQ , median (IQR)	0 (1.5)	0 (4.5)	0 (0.5)
Preop Pads , median (IQR)	0 (0)	0 (0)	0 (0)

Table 2. Patient demographics for recovery of urinary continence (UC).

Predictive Modeling Performance

Model performance for EF recovery was moderate, with an F1 score of 0.63, whereas performance for continence recovery was less accurate (F1 = 0.35) (**Fig. 2**). Patient-level variables, OPIs, and procedure-specific surgeon experience all contributed to outcome prediction (**Fig. 2, Fig. 3**), with variation in the relative importance of features across procedures.

Step-level modeling revealed that the predictive performance varied across surgical steps (**Fig. 4**). Best performance for EF was exhibited during pedicle dissection (left-side F1 = 0.463, right-side F1 = 0.336) and posterior plane dissection (F1 = 0.438). For UC, best predictive performance was demonstrated during the VUA (F1 = 0.495), bladder neck dissection (anterior F1 = 0.285, posterior F1 = 0.282), and apical dissection (F1 = 0.267) steps.

Erectile Function Outcomes and Recovery

OPIs during pedicle dissection demonstrated multiple associations with EF recovery (**Table 3**). Increased efficiency of instrument motion and console workspace, reflected by reduced hand controller path length and small workspace volume, were associated with improved recovery (**Fig. 5, top**). Specifically, left-hand controller workspace volume was significantly lower in the high-recovery group ($p = 0.016$), and right-hand controller path length was also reduced ($p = 0.024$). Energy utilization metrics also differed between groups, with shorter total energy pedal duration observed in patients with higher recovery ($p = 0.012$). Trends toward improved outcomes were also observed with lower instrument speeds and reduced energy use.

Neurovascular bundle dissection				
Metric	Group	Mean	Std. Dev.	P-value
Step duration	High BR	6.11	4.81	0.256
	Low BR	8.18	4.96	
Left hand controller path length	High BR	8.7	4.8	0.055
	Low BR	12.6	5.9	
Left hand controller workspace volume	High BR	348	254	0.016
	Low BR	761	583	
FFB Maryland bipolar average speed	High BR	0.65	0.10	0.057
	Low BR	0.78	0.13	
Right hand controller path length	High BR	15.7	6.8	0.024
	Low BR	21.7	6.9	
Right hand controller workspace volume	High BR	267	291	0.093
	Low BR	540	547	
Monopolar curved scissors path length	High BR	6.97	3.2	0.084
	Low BR	9.07	3.2	
Monopolar curved scissors smoothness (dimensionless jerk)	High BR	-20.1	1.7	0.051
	Low BR	-21.6	1.5	
Energy pedal count	High BR	8.6	7.6	0.063
	Low BR	21.3	24.6	
Energy pedal total duration	High BR	15.5	11.4	0.012
	Low BR	36.6	28.9	
Energy pedal average duration	High BR	2.1	0.9	0.274

	Low BR	2.8	2.2	
Posterior plane dissection				
Metric				P-value
Step duration	High BR	7.61	6.02	0.314
	Low BR	4.88	3.30	
Total instrument path length	High BR	9.60	5.65	0.745
	Low BR	8.67	4.87	
Total instrument angular path length	High BR	336.9	207.7	0.060
	Low BR	123.9	176.5	
Left hand controller workspace volume	High BR	442	446	0.346
	Low BR	260	208	
Right hand controller workspace volume	High BR	544	535	0.090
	Low BR	167	83	
FFB Maryland bipolar angular path length	High BR	135.0	81.3	0.054
	Low BR	14.7	3.6	
Monopolar curved scissors angular path length	High BR	179.8	110.4	0.053
	Low BR	67.4	83.9	
Monopolar curved scissors average speed	High BR	1.02	0.27	0.040
	Low BR	1.34	0.25	

Table 3. Objective performance indicator domains and trends related to baseline recovery (BR) of erectile function.

During posterior plane dissection, improved EF recovery was associated with lower use of monopolar curved scissors speed ($p = 0.040$), suggesting that more controlled dissection may be beneficial.

Force-based metrics described during pedicle dissection demonstrated trends toward lower applied

forces in patients with improved EF recovery (**Fig. 6, Table 4**), except for average force by the third-arm instrument. Specifically, reduced time above 6.5N was associated with improved EF recovery by the non-dominant ($p = 0.040$) and third-arm ($p = 0.011$) instruments. Overall, greater average force was observed by the third-arm instrument (3.6N) when compared to the non-dominant (2.7N).

Neurovascular bundle dissection				
Metric	Group	Mean	Std. Dev.	P-value
FFB Maryland and fenestrated bipolar (average force)	High BR	2.53	0.65	0.495
	Moderate BR	2.78	0.59	
	Low BR	2.94	0.25	
FFB Maryland and fenestrated bipolar (% time above 6.5N)	High BR	13.2	18.0	0.040
	Moderate BR	25.6	12.9	
	Low BR	47.7	21.3	
FFB Maryland and fenestrated bipolar (max force)	High BR	16.7	10.0	0.103
	Moderate BR	17.5	7.6	
	Low BR	24.2	5.9	
FFB ProGrasp and cadriere forceps (average force)	High BR	3.68	0.55	0.352
	Moderate BR	3.27	0.50	
	Low BR	3.79	0.57	
FFB ProGrasp and cadriere forceps (% time above 6.5N)	High BR	10.6	9.4	0.011
	Moderate BR	11.9	0.8	
	Low BR	61.0	8.9	
FFB ProGrasp and cadriere forceps (max force)	High BR	12.3	4.8	0.203
	Moderate BR	18.0	4.6	
	Low BR	28.3	19.0	

Table 4. Force feedback instrument (non-dominant and third-arm retraction) metrics and trends related to baseline recovery (BR) of erectile function.

Urinary Continence Outcomes and Recovery

During VUA, no statistically significant differences were observed across groups for most objective metrics (**Table 5**). However, trends suggested that reduced left- and right-hand controller workspace volume, as well as lower right-hand controller speed, were associated with improved continence recovery (**Fig. 5, bottom**). Directional patterns were observed for needle driver motion, characterized by trends with increased path length ($p = 0.059$) and reduced angular path length ($p = 0.167$), in patients with improved continence recovery.

Vesicourethral anastomosis				
Metric	Group	Mean	Std. Dev.	P-value
Step duration	<6 months CR	16.8	5.0	0.815
	6-12 months CR	14.9	3.0	
	No CR in 1 year	15.4	10.2	
Large needle driver path length	<6 months CR	18.9	7.5	0.059
	6-12 months CR	12.9	1.0	
	No CR in 1 year	13.3	2.0	
Large needle driver angular path length	<6 months CR	812	505	0.167
	6-12 months CR	1137	156	
	No CR in 1 year	1080	38	
Total instrument angular path length	<6 months CR	1196	685	0.153
	6-12 months CR	1621	214	
	No CR in 1 year	1655	609	
Left hand controller workspace volume	<6 months CR	500	221	0.234
	6-12 months CR	848	609	
	No CR in 1 year	766	552	
Right hand controller workspace volume	<6 months CR	576	270	0.635
	6-12 months CR	794	905	
	No CR in 1 year	773	555	
Right hand controller average speed	<6 months CR	0.038	0.007	0.404
	6-12 months CR	0.043	0.005	
	No CR in 1 year	0.042	0.009	
Posterior bladder neck dissection				
Metric	Group	Mean	Std. Dev.	P-value
Step duration	<6 months CR	6.90	1.44	0.543
	6-12 months CR	8.34	2.47	
	No CR in 1 year	9.36	7.58	
Endoscope path length	<6 months CR	0.66	0.22	<0.001

	6-12 months CR	1.86	0.70	
	No CR in 1 year	0.89	0.44	
Total instrument angular path length	<6 months CR	281	170	0.389
	6-12 months CR	429	140	
	No CR in 1 year	426	364	
Console workspace volume	<6 months CR	2822	1231	0.230
	6-12 months CR	4177	962	
	No CR in 1 year	3467	1760	
Left hand controller average speed	<6 months CR	0.023	0.004	0.015
	6-12 months CR	0.030	0.006	
	No CR in 1 year	0.023	0.004	
Apical dissection				
Metric	Group	Mean	Std. Dev.	P-value
Step duration	<6 months CR	6.28	5.72	0.402
	6-12 months CR	4.78	2.09	
	No CR in 1 year	3.74	1.69	
Left hand controller movement percent	<6 months CR	83.2	5.3	0.014
	6-12 months CR	83.3	3.0	
	No CR in 1 year	89.6	4.6	
Right hand controller movement percent	<6 months CR	97.7	0.9	0.490
	6-12 months CR	98.6	0.9	
	No CR in 1 year	97.6	2.3	
Hand controller clutch rate	<6 months CR	0.34	0.59	0.260
	6-12 months CR	0.72	0.72	
	No CR in 1 year	1.17	1.16	
Monopolar curved scissors path length	<6 months CR	7.3	6.0	0.543
	6-12 months CR	6.1	3.2	
	No CR in 1 year	5.1	2.5	
Posterior plane dissection				

Metric	Group	Mean	Std. Dev.	P-value
Step duration	<6 months CR	5.94	4.50	0.555
	6-12 months CR	3.92	2.21	
	No CR in 1 year			
4.29	4.37			
Endoscope average speed	<6 months CR	1.24	0.67	0.188
	6-12 months CR	0.52	0.33	
	No CR in 1 year	0.71	0.68	
Left hand controller average speed	<6 months CR	0.023	0.004	0.160
	6-12 months CR	0.029	0.005	
	No CR in 1 year	0.026	0.007	
Right hand controller average speed	<6 months CR	0.040	0.012	0.175
	6-12 months CR	0.046	0.008	
	No CR in 1 year	0.055	0.025	
FFB Maryland bipolar path length	<6 months CR	3.09	1.73	0.279
	6-12 months CR	1.88	1.02	
	No CR in 1 year	1.16	0.48	
Energy pedal average duration	<6 months CR	1.59	1.05	0.189
	6-12 months CR	2.07	1.11	
	No CR in 1 year	2.87	1.62	

Table 5. Objective performance indicator domains and trends related to recovery of urinary continence (UC).

Posterior bladder neck dissection demonstrated significant differences in endoscope movement, with shorter endoscope path length in patients achieving early continence ($p < 0.001$). Additionally, lower left-hand controller speed during posterior bladder neck dissection was associated with earlier continence recovery ($p = 0.015$), suggesting more controlled instrument handling. During apical dissection, reduced left-hand controller movement percentage was associated with earlier continence recovery ($p = 0.014$), indicating that more focused instrument use by the dominant hand may facilitate improved outcomes.

Across additional operative segments, trends suggested that increased instrument motion, greater hand controller workspace utilization, and prolonged energy application were associated with delayed

continence recovery.

Case Study-Based Video Review

Video review provided insight into how OPIs reflect underlying technical challenges and surgeon behavior. In the poor-outcome case, the operating surgeon noted substantial tissue induration, inflammation, and difficulty identifying clear dissection planes around the pedicles, necessitating greater traction force and increased monopolar energy use. These challenges were associated with hesitancy, slower dissection, and several deviations from the intended plane due to obscured anatomy. In contrast, the optimal-outcome case demonstrated minimal inflammation and improved visualization, enabling more confident and efficient dissection with limited energy use and reduced traction force (**Fig. 7**).

The surgeon confirmed that the predicted operative steps aligned closely with clinical judgement regarding where functional outcomes are determined. Differences in instrument motion and efficiency were attributed primarily to plane clarity, with inefficiency in the poor-outcome case reflecting technical difficulty rather than deliberate technique. FFB review revealed higher peak forces in the poor-outcome case, particularly during passive retraction, and also identified unrecognized episodes of excessive third-arm force in the optimal-outcome case. Video review exposed technical blind spots not apparent through operative recall and informed actionable technique modifications, including reduced energy use near the pedicles, actively monitoring force applied on tissue, optimizing counter-traction, and favoring sharper capsular dissection to improve plane identification.

DISCUSSION

This study demonstrated the feasibility of using step-level OPIs, including haptic FFB metrics, with patient factors and clinical outcomes to generate ML-enabled predictions of functional recovery after RARP. By leveraging an analytics application to explore multimodal robotic data and video review to interpret findings, we identified step-specific intraoperative behaviors associated with recovery of EF and urinary continence. Predictive performance was stronger for EF than for UC, and highlighted OPIs during key operative steps (pedicle and posterior plane dissection for EF; VUA, bladder neck, and apical dissection for continence) as key drivers of outcome prediction. Across these steps, measures of improved motion efficiency with reduced energy and force were consistently associated with improved recovery, supporting a link between controlled tissue handling and improved functional outcomes.

Erectile Function Recovery

Within the EF cohort, outcomes were most accurately predicted by OPIs during the left pedicle dissection, with the posterior plane dissection and right-sided pedicle dissection metrics reinforcing the importance of the anatomic operative fields related to functional outcomes. Across these steps, patients with high rates of EF recovery demonstrated slower, smoother, and more spatially constrained instrument motion compared with those with low recovery. During NVB, the cohort with better recovery

exhibited substantially smaller hand controller workspace volumes, shorter path lengths, and reduced monopolar scissor speed, suggesting that deliberate, contained dissection near the neurovascular structures may be protective. Energy utilization followed a similar pattern, with markedly reduced electrocautery activation in patients with improved recovery.

Importantly, incorporation of FFB metrics enabled direct quantification of traction forces measured at the pedicles. While average forces were modest, patients with lower rates of recovery experienced greater peak force exposure, particularly during third-arm passive retraction, reflected by increased time above the 6.5N threshold. These findings suggest that avoidance of intermittent high-force peaks, rather than minimizing average force alone, may be critical for neurovascular preservation. Similar signals were observed during posterior plane dissection, where slower scissor speed was associated with improved erectile recovery. Although baseline differences existed between recovery groups, including age and prostate size, these factors were accounted for in multivariable models, isolating the potential independent contribution of OPIs.⁶

Urinary Continence Recovery

In contrast to EF, recovery of continence depended on coordinated performance across multiple operative steps. Outcome prediction during the VUA was most accurate, with OPIs measured during bladder neck and apical dissection also contributing meaningfully, consistent with the multifactorial anatomical basis of continence recovery. Although step-level predictive performance was more modest, the OPIs identified converged on a consistent theme of efficient, constrained, and focused instrument use.

During VUA, higher rates of continence recovery were associated with smaller bilateral workspace volumes and slower controller speeds, indicating more deliberate instrument handling might be important.¹³ Interestingly, the fastest-recovery cohort demonstrated greater needle-driver path length with reduced angular variability, potentially suggesting that intentional, well-oriented needle passes - rather than minimal motion alone - may be important for anastomotic quality. This finding is reflected in Hung's work, which has suggested that wrist articulation during the VUA is important for UC.^{20,21} During posterior bladder neck dissection, early continence recovery was associated with markedly reduced endoscope movement and slower non-dominant hand speed, highlighting the importance of focused camera control. Similarly, reduced non-dominant hand movement during the apical dissection was associated with earlier recovery. In contrast to erectile function, we did not observe strong associations between FFB metrics and continence recovery, which may reflect the distinct technical behaviors required for optimal reconstruction, where precision and alignment may outweigh absolute traction force. These findings suggest that granular instrument-level OPIs and targeted video-based analyses assessing anastomotic quality and tissue approximation might be useful to further elucidate determinants of continence recovery.¹⁷

Relationship to Prior Work and Actionability

Our findings build on prior work by Hung and colleagues demonstrating that objective kinematic metrics and gesture-based analyses predict functional outcomes after RARP.^{13,17} While prior studies have focused primarily on video-derived gestures,² our approach leverages an expanded set of OPIs available on the dV5 platform, including direct force quantification.^{4,19} Both approaches converge on a shared principle: controlled, low-energy, spatially constrained tissue handling is protective of functional recovery. Importantly, our study demonstrates the feasibility of using an analytics application to integrate objective metrics with step-level analysis and structured video review, representing an important step toward closing the loop between data, interpretation, and feedback.

Limitations and Future Directions

This study has several limitations. Its retrospective, single-center design and moderate sample size may limit generalizability and statistical power. Functional outcomes were assessed using validated patient-reported measures, which are subject to variability in patient reporting and follow-up. Given the exploratory objective of identifying actionable OPIs, we used an analytics-driven workflow incorporating feature ranking and visualizations to prioritize evaluation of candidate metrics. Nevertheless, the large number of potential associations examined increases the risk of false-positive findings. Accordingly, statistical comparisons were intended to generate hypotheses rather than establish definitive causal relationships, and findings should be interpreted in that context. Predictive modeling relied on relatively simple, regularized approaches to prioritize interpretability and reduce overfitting; however, alternative modeling methods may identify different predictive relationships. In addition, external validation was not performed, and the robustness of the identified associations across surgeons and institutions remains unknown. Future studies should validate these findings in larger multicenter cohorts, incorporate longer follow-up, evaluate interactions between operative steps, and explore more granular functional outcomes and technical measures.

CONCLUSION

This study explored the ability of OPIs, contextualized by surgical step, to predict functional outcomes after RARP. Increased instrument motion efficiency was associated with improved recovery of EF and UC, while reduced energy use and lower tissue force application were specifically associated with improved EF recovery. Step-level modeling identified clinically relevant operative steps where OPIs were most strongly associated with outcomes. ML-enabled analytics combined with structured video review informs hypothesis generation related to the impact of intraoperative behaviors on clinical outcomes. This research extends prior work by incorporating direct measures of tissue handling and highlighting operative context in which opportunities for feedback and education exist. This approach of leveraging objective surgical data to inform technique refinement has the potential to improve functional recovery after RARP.

Declarations

ETHICS APPROVAL:

This study received ethics approval with its IRB approval on 4/21/2021 (Pro2020-1293).

CONSENT TO PARTICIPATE:

Informed consent was obtained from all individual participants included in this study.

DATA AVAILABILITY:

The datasets generated during and/or analyzed during the current study are not available.

CONTRIBUTIONS:

Project conception by M.S, J.O. and A.Y. Data collection by J.O. Data analysis by A.Y., J.O., and K.B. First draft written by J.O, A.Y, and M.S. Critical revisions by J.O., A.Y., M.S., K.B, and G.P. All authors contributed to and approved of the final draft.

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Conflicts of Interest:

- J.O., N.Y., G.L., and R.M. have no relevant disclosures
- M.A. reports receiving consultation fees from Intuitive Surgical, Inc.
- A.Y., K.B., and G.J. are full-time employees of Intuitive Surgical, Inc.
- M.S. reports receiving consultation fees from Intuitive Surgical, Inc.

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Figures

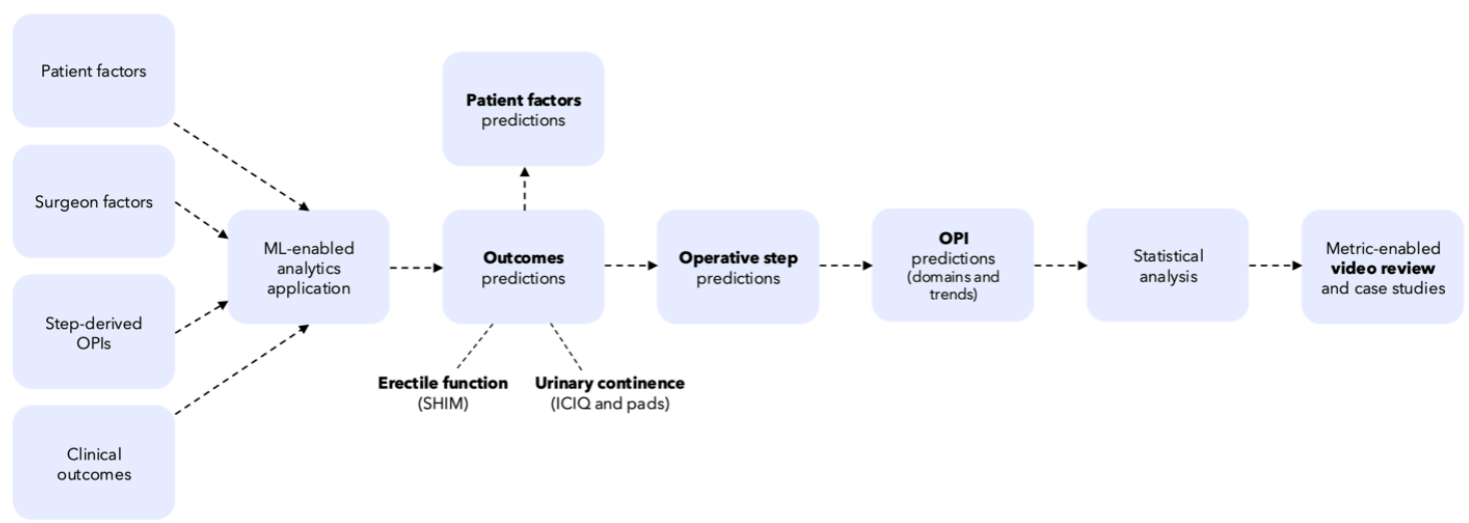


Figure 1

Study workflow.

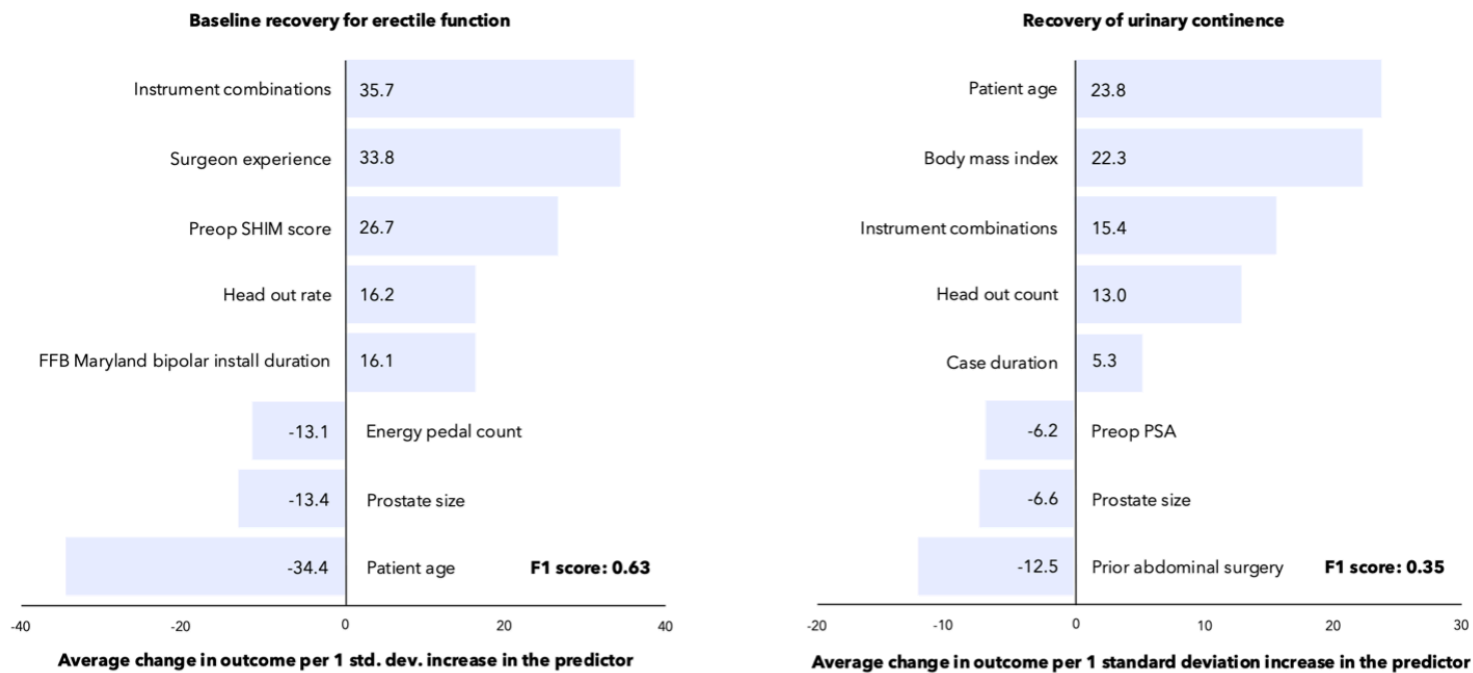


Figure 2

Case-level model performance across patient variables, OPIs, and surgeon experience.

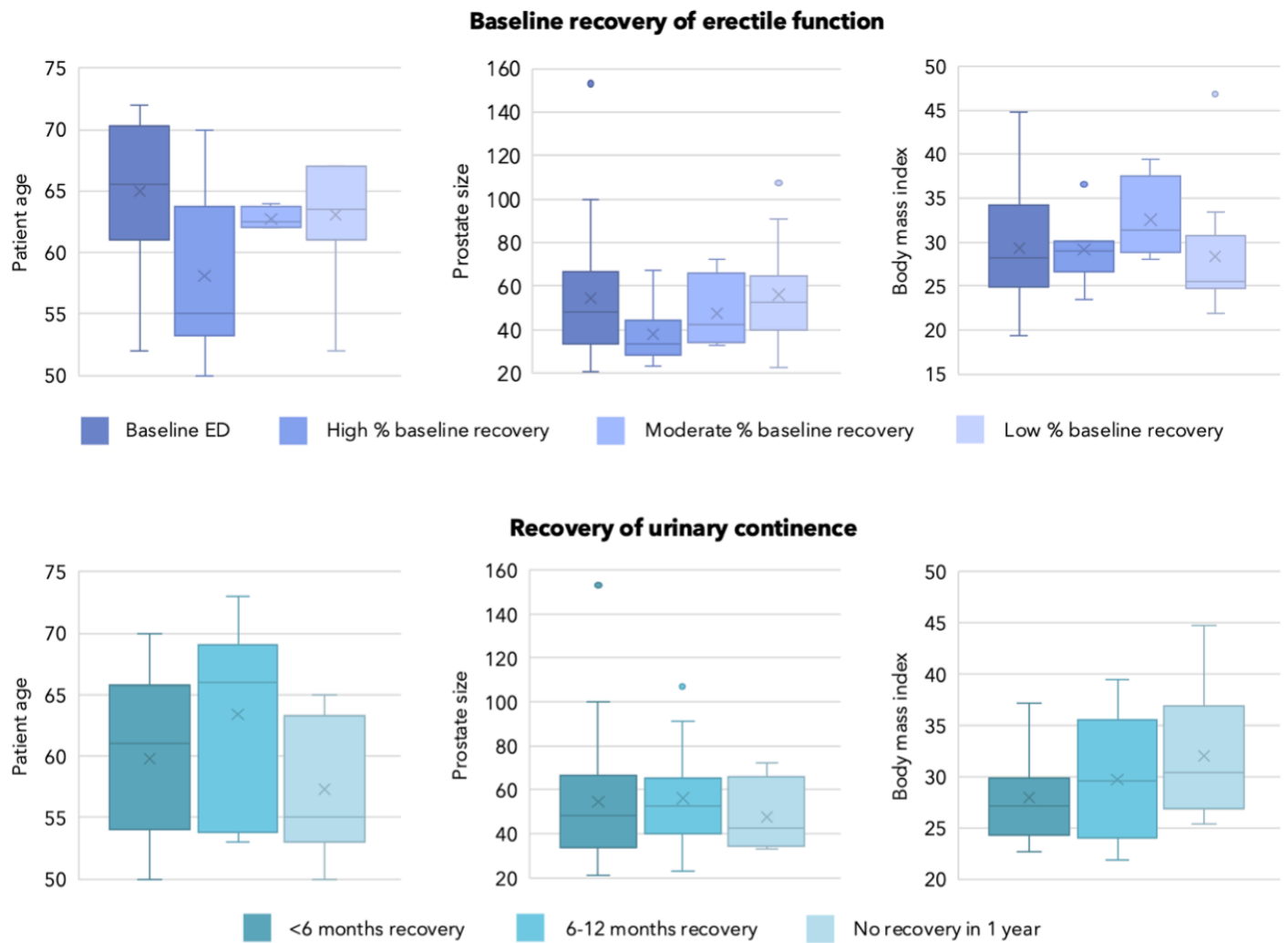


Figure 3

Select case-level patient variable trends analyzed according to EF recovery (top) and return to UC (bottom).

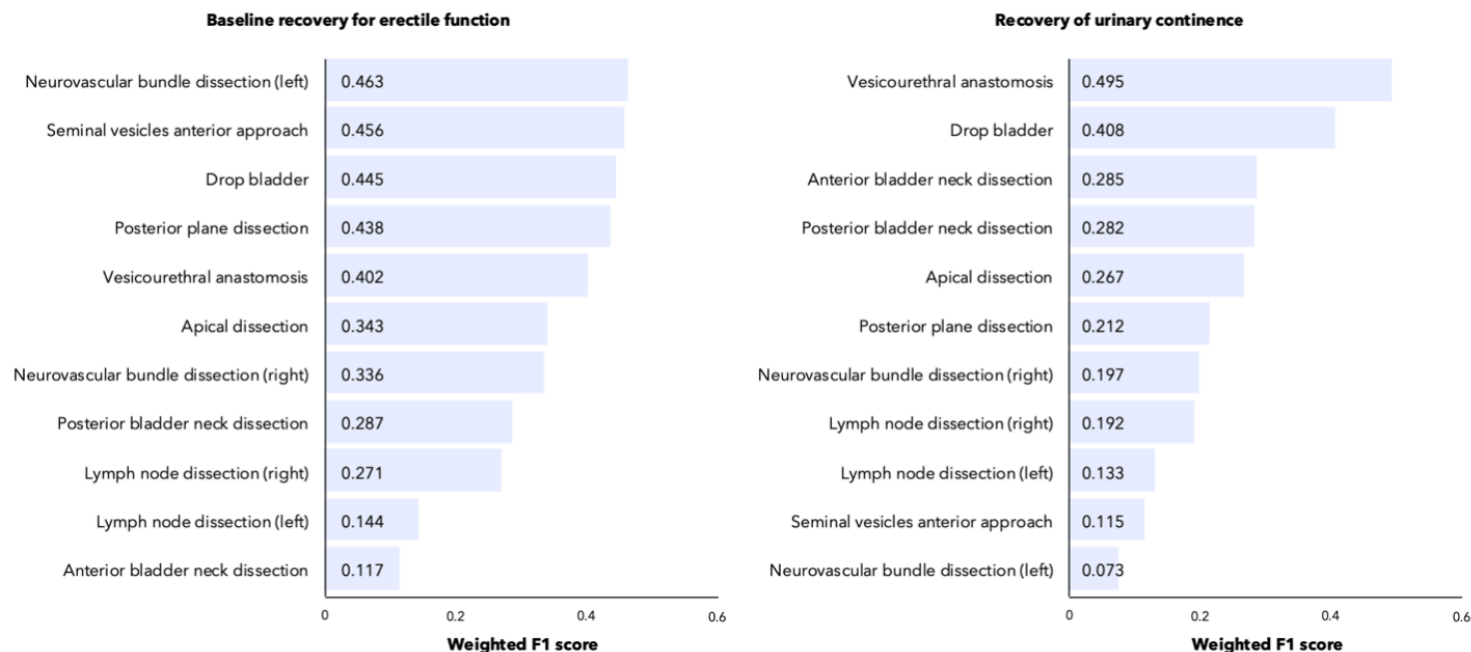


Figure 4

Predictive performance of individual surgical steps for functional outcome recovery.

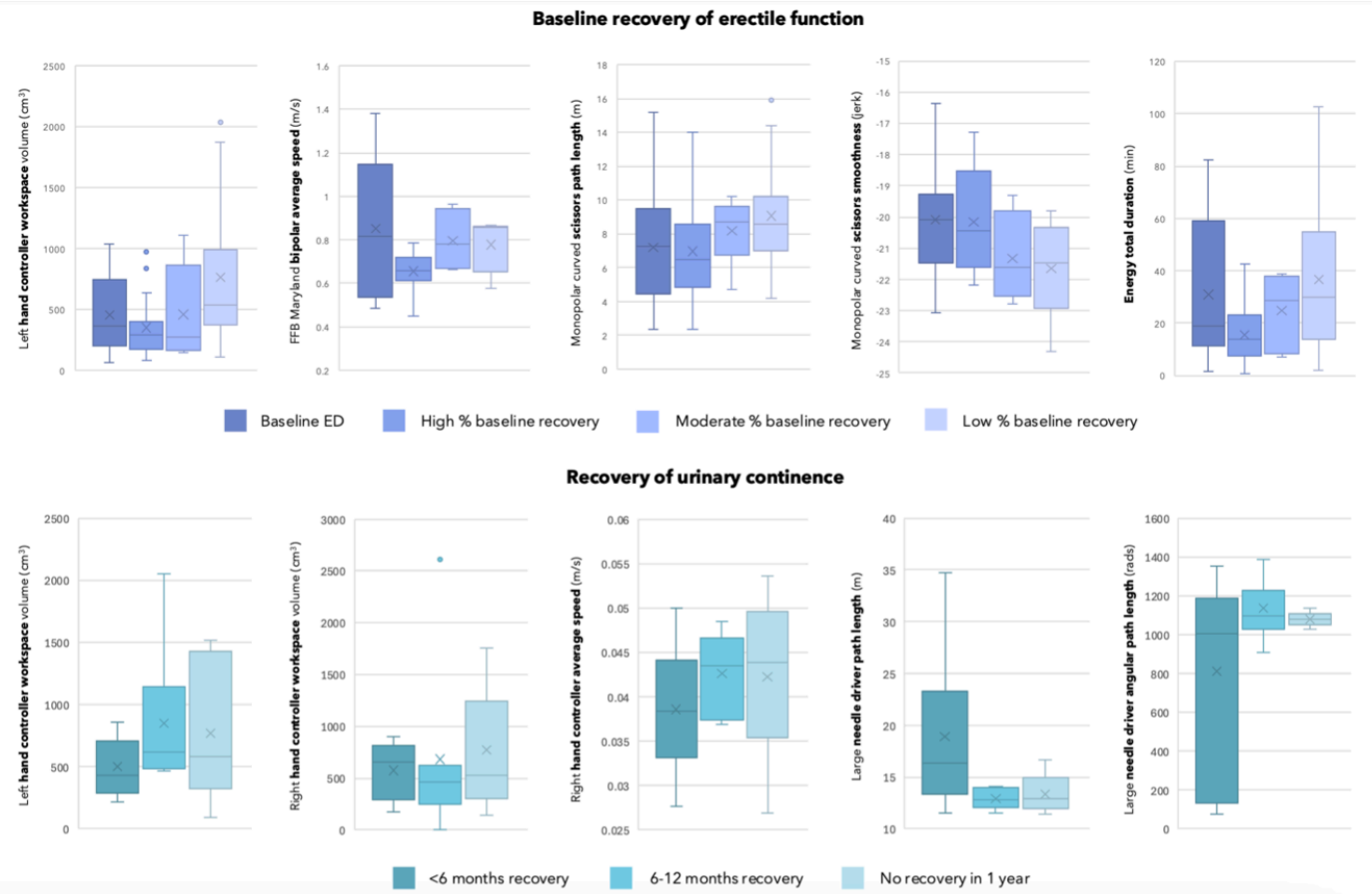


Figure 5

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Select step-level OPI trends analyzed according to EF recovery (top) and return to UC (bottom).

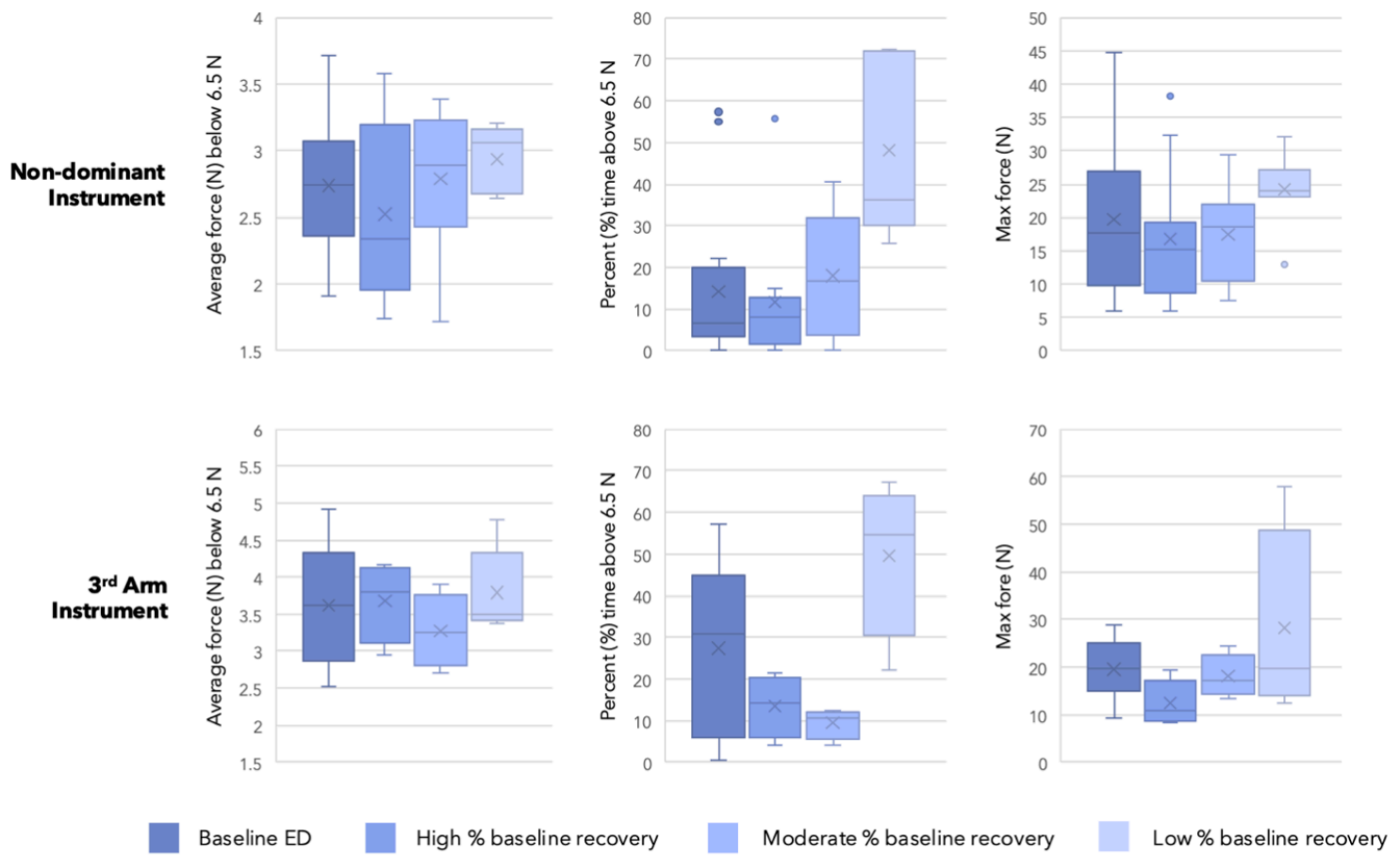
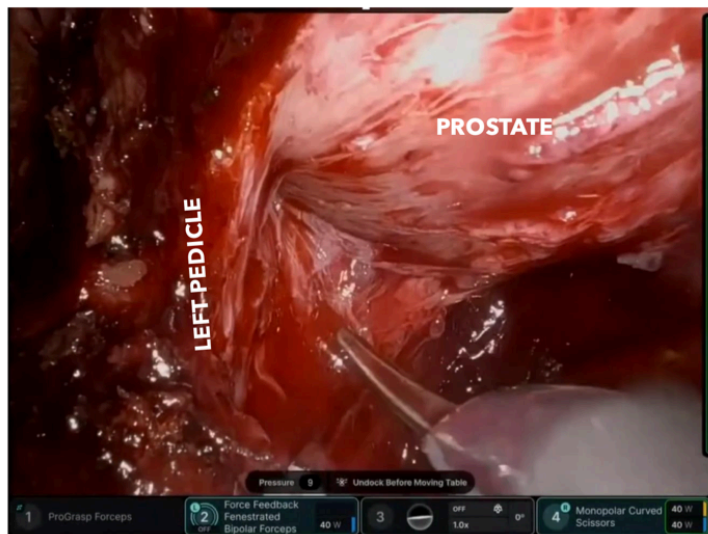


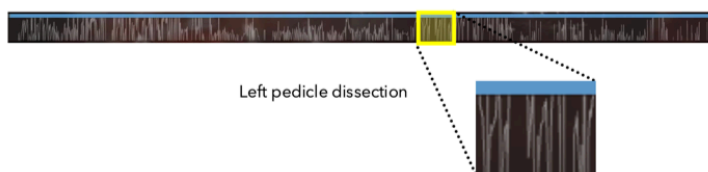
Figure 6

Force-based (non-dominant and 3rd arm instrument) OPI metrics for pedicle dissection analyzed according to EF recovery.

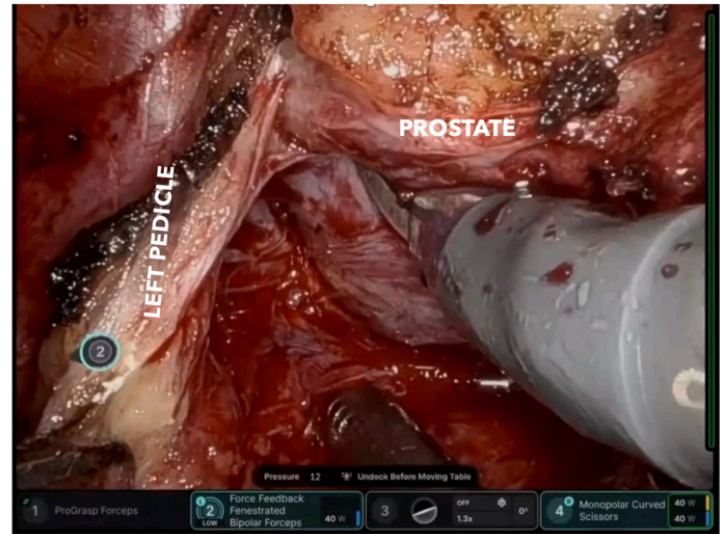
Case Example of Poor Baseline Recovery of Erectile Function



1Hz Force Timeseries Data (Non-dominant Instrument)



Case Example of Optimal Baseline Recovery of Erectile Function



1Hz Force Timeseries Data (Non-dominant Instrument)

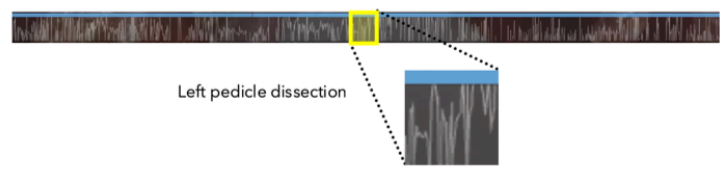


Figure 7

Video review case examples

Supplementary Files

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