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Platform Adaptation During Transition to New Robotic Systems: Learning Curves Across the Da Vinci® X™, Versius®, and Hugo™ RAS Platforms for Robot-Assisted Hysterectomy

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Research Article

Keywords: Learning curve, Risk-adjusted CUSUM, Robotic surgery, Hysterectomy, Modular robotic platforms, Surgical training

Posted Date: November 12th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10989024/v1

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Additional Declarations: No competing interests reported.

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Abstract

Purpose: To characterize adaptation when an experienced robotic surgical team transitioned from the Da Vinci® X™ platform to the Versius® and Hugo™ RAS systems for robot-assisted hysterectomy.

Methods: This secondary analysis of the prospective, single-center COMPAR-HYST study included 144 analyzed procedures (Da Vinci® X™, n = 50; Hugo™ RAS, n = 48; Versius®, n = 46). Draping, docking, hysterectomy, colporrhaphy, and undocking times were evaluated. Platform-specific adaptation was assessed using risk-adjusted cumulative sum curves with segmented regression, and user experience was evaluated prospectively using standardized questionnaires.

Results: Setup-related times differed across platforms, whereas hysterectomy ($p = 0.173$) and colporrhaphy ($p = 0.087$) times did not. Risk-adjusted cumulative sum analyses showed phase-specific patterns. Significant transitions occurred for draping with Hugo™ RAS (15 procedures) and Versius® (38.9), docking with Da Vinci® X™ (4) and Versius® (6.4), hysterectomy with Da Vinci® X™ (32) and Versius® (13), colporrhaphy with all three platforms (5.3, 24.2, and 33.4, respectively), and undocking with all three platforms (29, 15.1, and 7.3, respectively). User-experience ratings broadly paralleled these objective patterns.

Conclusions: Adaptation was not uniform across the components of robot-assisted hysterectomy. Setup-related phases and vaginal cuff closure showed the most evident platform-specific patterns, whereas core console-based performance appeared more transferable. These findings may support phase-specific training when new robotic platforms are introduced.

Trial registration: ClinicalTrials.gov NCT06138197; registered 15/11/2023.

Keywords: Learning curve; Risk-adjusted CUSUM; Robotic surgery; Hysterectomy; Modular robotic platforms; Surgical training

Introduction

The Da Vinci® Surgical System (Intuitive Surgical, Sunnyvale, CA, USA) has long been established as the gold-standard platform for robot-assisted surgery [1, 2]. In gynecology, it remains the most widely used robotic platform [3, 4], and its implementation has contributed substantially to the broader adoption of minimally invasive surgery [5-9]

After decades of market dominance, two new robotic platforms with CE mark approval have become available: the Versius® Robotic Surgery System, produced by CMR Surgical Ltd (Cambridge Medical Robotics Ltd., Cambridge, UK) [10-13], and the Hugo™ RAS system (Medtronic, Dublin, Ireland; Minneapolis, MN, USA) [14, 15]. Compared with the Da Vinci® platform, these systems introduce distinctive features, most notably modular robotic arms and open-console architectures [16].

Although both platforms are increasingly used for robotic hysterectomy, further evidence directly comparing them against each other, and against the Da Vinci® system, is required [17-20]. Specifically, there is a paucity of data regarding the transition of experienced surgical teams to these novel systems. Such insights are crucial for defining appropriate training protocols, standardizing implementation strategies, and ensuring optimal patient safety [21, 22].

To address this knowledge gap, we performed a secondary analysis of the COMPAR-HYST study [20]. This secondary analysis specifically examined the learning process associated with platform transition, an aspect not explored in the primary report. Using detailed procedural timing data, this study investigated learning curves during implementation of the Versius® and Hugo™ systems for the procedure of hysterectomy, benchmarking them against the Da Vinci® X™ platform while also evaluating user experience.

Methods

This is a secondary analysis of the COMPAR-HYST study (Comparison of Outcomes of Multiple Platforms for Assisted Robotic Surgery - Hysterectomy), a single-center, post-marketing investigation conducted between January and December 2024 at the Azienda Ospedaliera Universitaria Integrata (AOUI) Verona, Italy [20]. The protocol was approved by the local ethics board (reference 4217CESC) and was registered on ClinicalTrials.gov under identifier NCT06138197.

The COMPAR-HYST study prospectively compared head-to-head three robotic platforms for the procedure of hysterectomy in terms of perioperative outcomes and costs [20]. The three robotic platforms were the Da Vinci® X™, the Versius®, and the Hugo™ RAS. Apart from the utilized robotic system, all aspects of the surgical technique and perioperative management, including anesthetic protocols and patient positioning, were standardized across study arms in accordance with routine clinical practice. Eligibility criteria followed the original COMPAR-HYST protocol [20]. Briefly, consecutive adult women undergoing elective laparoscopic hysterectomy were enrolled, whereas emergency procedures, nongynecologic indications, previous pelvic radiotherapy, and inability to provide consent were excluded. Enrolled patients were assigned to one of the three robotic platforms in a 1:1:1 ratio based on availability on the day of surgery.

The surgical team of the COMPAR-HYST study had extensive experience in robotic hysterectomy. All console surgeons had performed more than 50 robotic hysterectomies using the Da Vinci® X™ platform before study

initiation, and the entire surgical team completed manufacturer-specific training for the Versius® and Hugo™ systems.

Prospectively collected procedural timing data, previously reported descriptively as part of the perioperative and Time-Driven Activity-Based Costing (TDABC) analysis of the primary COMPAR-HYST study [20], were re-analyzed for the present secondary analysis. The primary objective was to characterize platform adaptation by evaluating learning curves and estimating the principal transition point for each robotic platform across predefined operative phases. The secondary objective was to evaluate user experience using prospectively completed questionnaires independently filled in by the surgeon and scrub nurse after each procedure. User-experience questionnaires were prospectively collected within the COMPAR-HYST study but were not reported in the primary report.

Statistical analysis

Standard descriptive statistics were used as appropriate. Comparisons between the three groups were performed using the Kruskal-Wallis test or a two-tailed Chi-square test, as appropriate. Pairwise comparisons were conducted appropriately, with statistical significance defined using the Bonferroni correction (0.05/3 = 0.0167).

Investigated operative times (min) corresponded to the operative phases of draping, docking, hysterectomy, colporrhaphy, and undocking. Definitions of each interval and the corresponding procedural landmarks are provided in Online Resource 1.

Cases that were converted to other surgical approaches were excluded and procedures were ordered chronologically. Given the right-skewed distribution of operative time variables (min), log-transformation was applied prior to risk-adjusted modeling. Log-transformed operative times were analyzed as continuous outcomes within the same analytical framework described below.

For each time outcome, a multivariable linear regression model fitted to the log-transformed operative time was used with predefined perioperative covariates, including surgeon, uterus weight, indication, age, menopausal status, parity, previous caesarean deliveries, body mass index, ASA class, WHO performance status, Charlson Comorbidity Index, SF-36 score, and uterine manipulator use. Model diagnostics confirmed adequate fit without evidence of relevant multicollinearity or influential observations for all time outcomes.

Learning-curve analyses were conducted separately for each robotic platform. A prespecified two-step outlier management strategy was applied using platform-specific extreme values (>99.9th percentile) and residual diagnostics (absolute standardized residuals >3 and/or residuals beyond Q1 − 2×IQR or Q3 + 2×IQR). Cases meeting these criteria were excluded before sequential case renumbering.

Risk-adjusted CUSUM was chosen to account for differences in case complexity across sequential procedures [23-26]. Risk-adjusted expected log-operative time was estimated using the comprehensive adjustment model described above for each time outcome. Risk-adjusted deviations (observed minus predicted log-operative time) were cumulatively summed to generate RA-CUSUM curves across sequential cases. To detect structural changes consistent with learning-curve transitions, segmented regression was applied to the RA-CUSUM series for each platform and outcome using case order as the running variable. A maximum of one breakpoint per curve was pre-

specified to identify the principal statistical transition in slope. The segmented model was compared with a no-breakpoint model using the Davies test for change in slope. When no statistically significant change in slope was detected, the curve was interpreted as not demonstrating a clear threshold. Estimated breakpoints and segmented fits were graphically overlaid on RA-CUSUM.

Statistical significance was considered with a p-value < 0.05. All statistical analyses were performed with R Statistical Software (v4.1.2; R Core Team 2024).

Results

Of the 150 hysterectomies performed in the COMPAR-HYST study, six were excluded because of conversion. The final analysis included 144 procedures: Da Vinci® X™ (n = 50), Hugo™ RAS (n = 48), and Versius® (n = 46).

Setup-related operative phases differed across robotic platforms (Table 1A). Draping time was shorter with Da Vinci® X™ than with Hugo™ RAS (p = 0.002). Docking time was shorter with Da Vinci® X™ than with both Hugo™ RAS and Versius® (p < 0.001), whereas undocking time was shorter with Hugo™ RAS than with Versius® (p = 0.01). In contrast, hysterectomy (p = 0.173) and colporrhaphy (p = 0.087) times did not differ significantly between platforms (Table 1A).

Table 1A Operative outcomes by robotic platform

Outcome	Total (N = 144)[1]	Da Vinci® X™ (n = 50)[1]	Hugo™ RAS (n = 48)[1]	Versius® (n = 46)[1]	p value[2]
Conversion to another approach	6/150 (4.0%)	0	2 (4.0%)	4 (8.0%)	0.169
Draping, min	10 (6, 14)	9 (5, 11)	10 (10, 15)	10 (7, 13)	0.003
Docking, min	8.5 (5.5, 13)	6 (5, 7)	11 (7, 15.5)	11.5 (8, 15)	< 0.001
Hysterectomy, min	36 (27, 54)	31 (24, 46)	36 (30, 61)	38 (28, 50)	0.173
Colporrhaphy, min	22 (16, 31)	21 (16, 32)	19 (16, 25)	27 (17, 35)	0.087
Undocking, min	2.48 (2, 3.99)	3 (1, 3.78)	2 (1.52, 3)	3.49 (2, 5)	0.009

[1] Median (Interquartile range), n (%)

[2] Kruskal-Wallis rank sum test

Draping time: Hugo™ vs Da Vinci® X = 0.002, Versius® vs Da Vinci® X = 0.209, Versius® vs Hugo™ = 0.245

Docking time: Hugo™ vs Da Vinci® X < 0.001, Versius® vs Da Vinci® X < 0.001, Versius® vs Hugo™ = 1.000

Undocking time: Hugo™ vs Da Vinci® X = 0.675, Versius® vs Da Vinci® X = 0.145, Versius® vs Hugo™ = 0.01

Pairwise comparisons were performed only when the global Kruskal–Wallis test was significant and interpreted using the Bonferroni-adjusted significance threshold (p<0.0167).

Learning Curve Analyses

For draping time (Fig. 1), the Versius® platform accumulated the largest cumulative deviation before reaching a statistically significant transition at 38.9 procedures, after which the curve showed a downward trend. Hugo™ RAS accumulated a smaller deviation and reached a statistically significant transition after 15 procedures, followed by a similar downward trend. In contrast, the Da Vinci® X™ platform showed only limited cumulative deviation throughout the study period, with no statistically significant breakpoint.

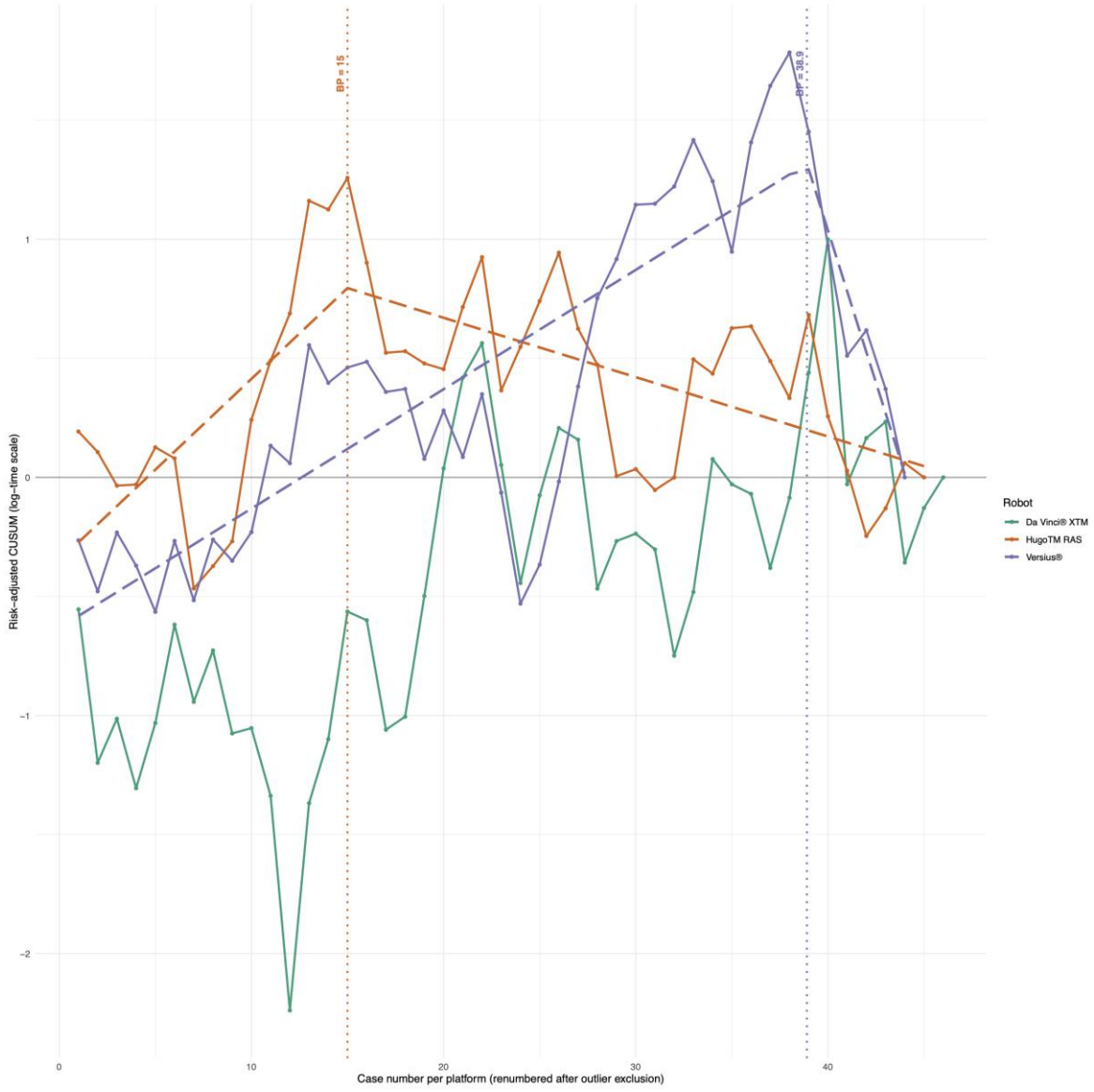


Fig. 1 Risk-adjusted cumulative sum (RA-CUSUM) curves for draping time. Colored curves show observed cumulative deviations, dashed lines show segmented fits, and dotted vertical lines show statistically significant breakpoints for Hugo™ RAS (15 procedures) and Versius® (38.9 procedures); no significant breakpoint was detected for Da Vinci® X™

For docking time (Fig. 2), the Versius® platform initially showed a downward trajectory, followed by a statistically significant transition at 6.4 procedures, after which the curve progressively returned toward the zero line and stabilized. The Hugo™ RAS platform showed moderate cumulative deviation with substantial variability throughout the study period, and no statistically significant transition was identified. In contrast, the Da Vinci® X™ platform showed only limited cumulative deviation before reaching a statistically significant transition at four procedures, followed by a sustained downward trend.

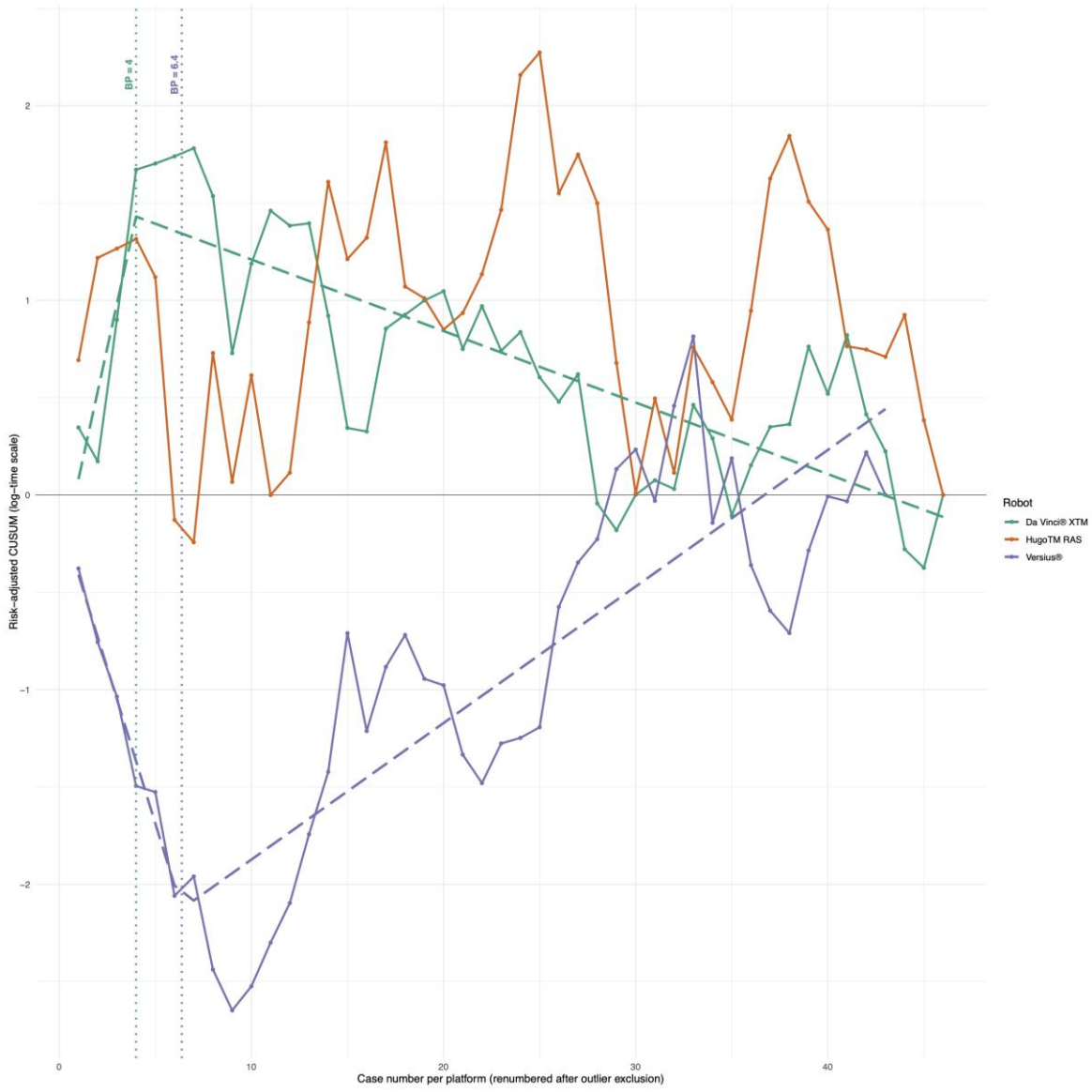


Fig. 2 RA-CUSUM curves for docking time. Significant breakpoints were detected for Da Vinci® X™ (4 procedures) and Versius® (6.4 procedures); no significant breakpoint was detected for Hugo™ RAS

For hysterectomy time (Fig. 3), the Versius® platform showed a marked accumulation of cumulative deviation before reaching a statistically significant transition at 13 procedures, followed by a downward trend. The Hugo™ RAS platform showed substantial variability with no statistically significant transition identified. In contrast, the Da Vinci® X™ platform showed only limited cumulative deviation despite marked oscillations around the zero line. A statistically significant transition was identified at 32 procedures, although variability persisted throughout the study period.

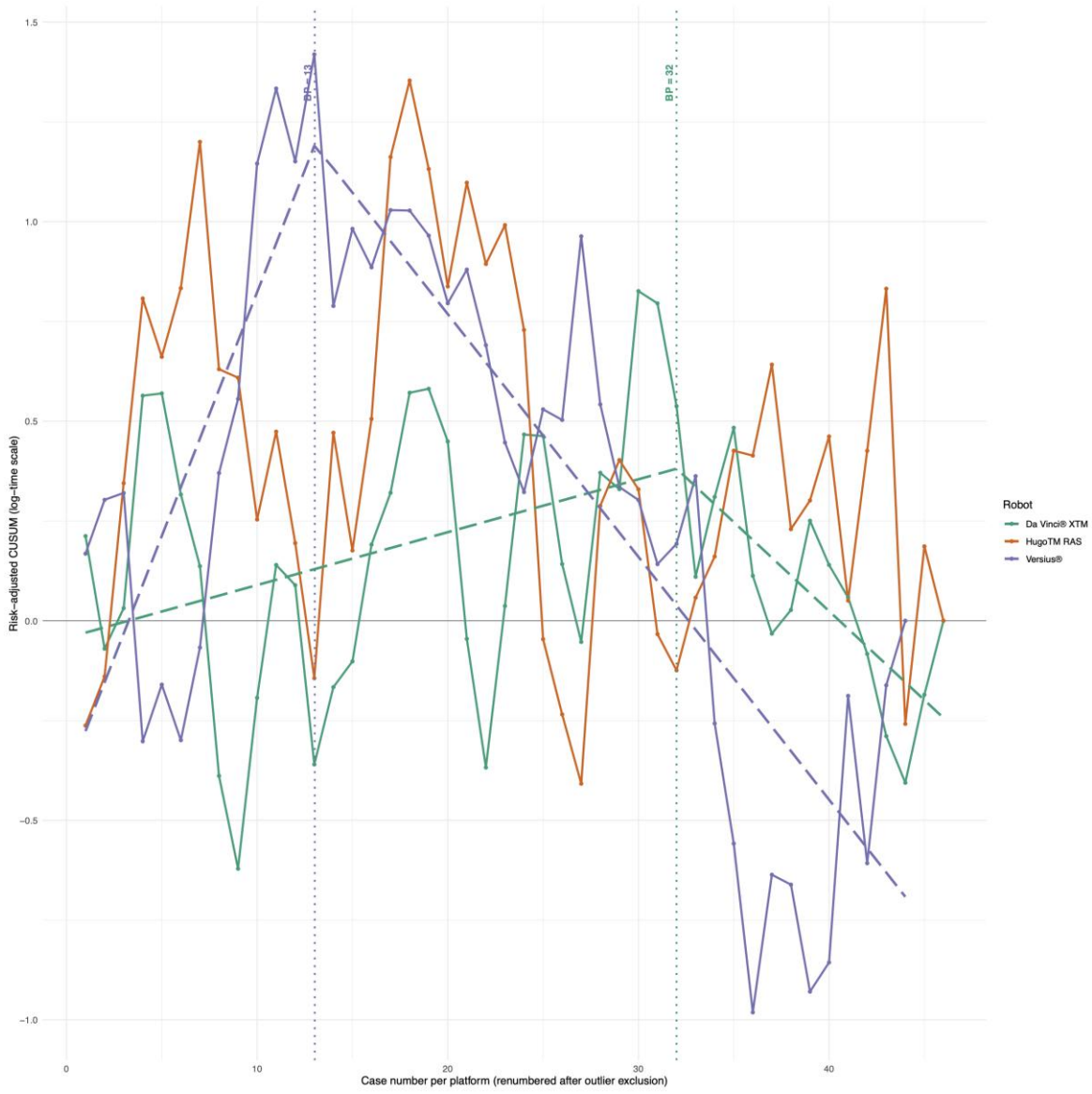


Fig. 3 RA-CUSUM curves for hysterectomy time. Significant breakpoints were detected for Versius® (13 procedures) and Da Vinci® X™ (32 procedures); no significant breakpoint was detected for Hugo™ RAS

For colporrhaphy time (Fig. 4), the Versius® platform showed the greatest cumulative deviation before reaching a statistically significant transition at 33.4 procedures, followed by a downward trend. Hugo™ RAS showed a similar but less pronounced accumulation, with a statistically significant transition at 24.2 procedures and subsequent decline in cumulative deviation. In contrast, the Da Vinci® X™ platform showed only limited cumulative deviation before reaching a statistically significant transition at 5.3 procedures, after which the curve returned toward the zero line.

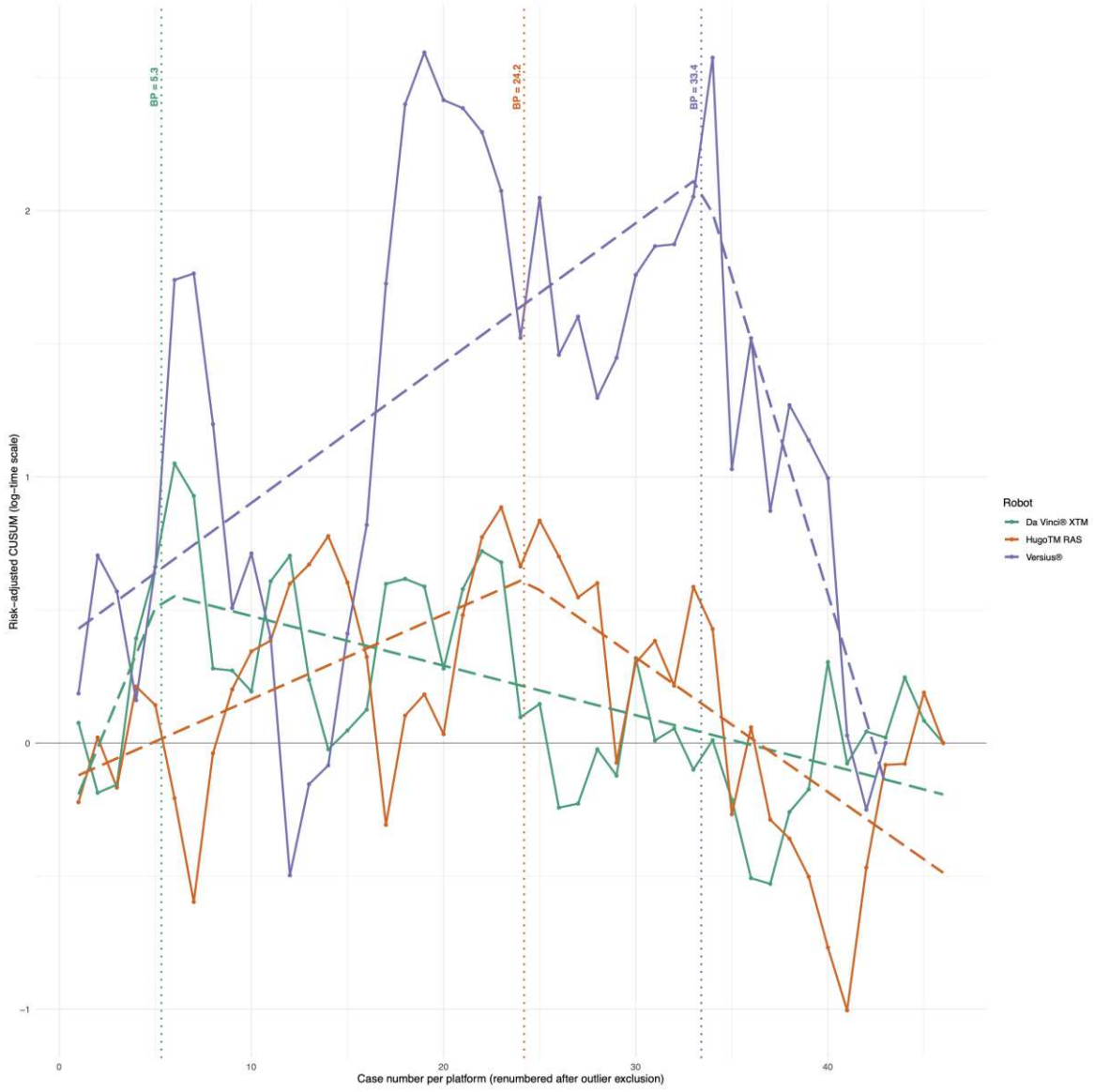


Fig. 4 RA-CUSUM curves for colporrhaphy time. Significant breakpoints were detected for Da Vinci® X™ (5.3 procedures), Hugo™ RAS (24.2 procedures), and Versius® (33.4 procedures)

For undocking time (Fig. 5), the Versius® platform showed an initial accumulation of cumulative deviation before reaching a statistically significant transition at 7.3 procedures, followed by a gradual downward trend. Hugo™ RAS showed a similar pattern, with a statistically significant transition at 15.1 procedures and a more rapid decline in cumulative deviation thereafter. In contrast, the Da Vinci® X™ platform showed a predominantly negative RA-CUSUM with marked oscillations. A statistically significant transition was identified at 29 procedures, after which the curve progressively returned toward the zero line.

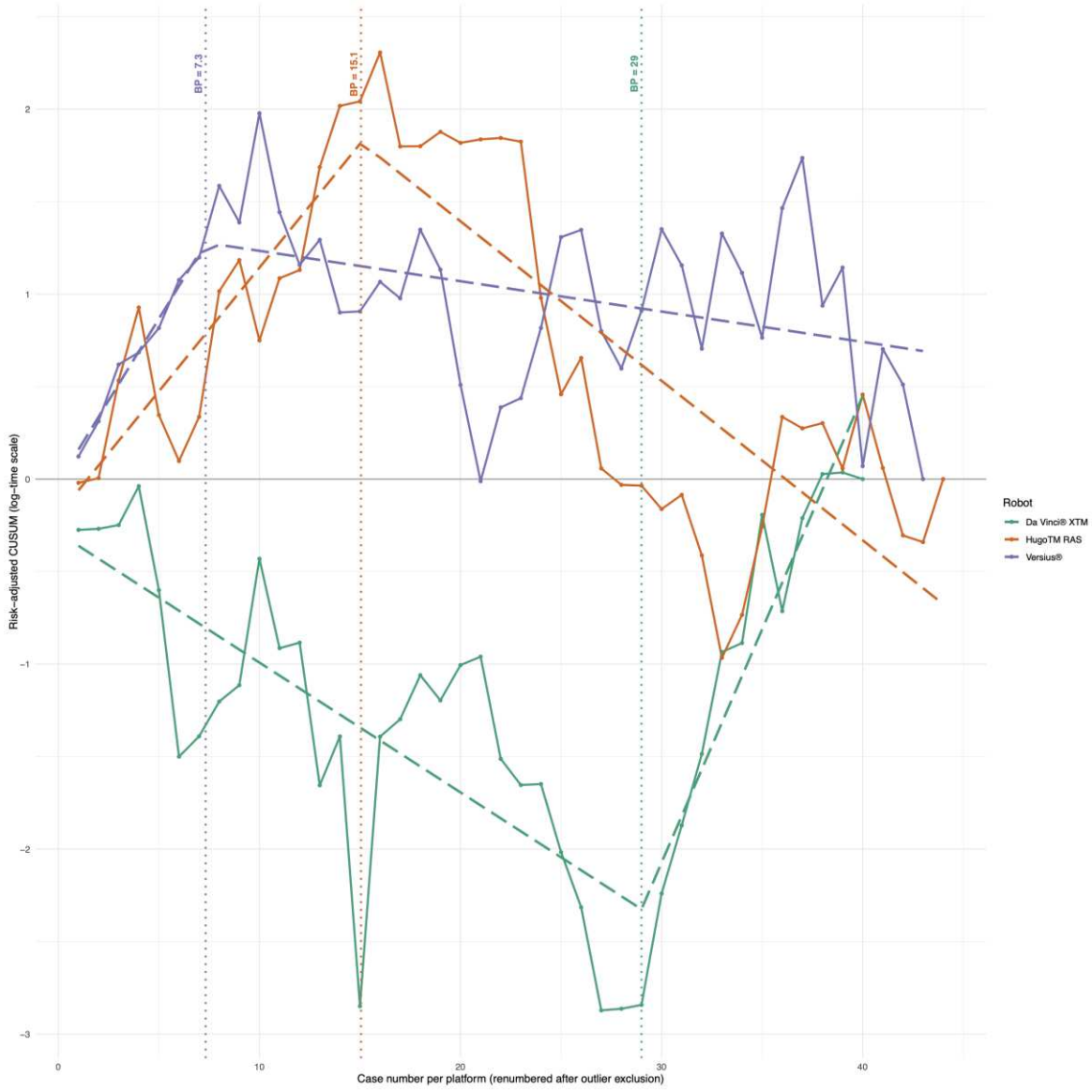


Fig. 5 RA-CUSUM curves for undocking time. Significant breakpoints were detected for Versius® (7.3 procedures), Hugo™ RAS (15.1 procedures), and Da Vinci® X™ (29 procedures)

User experience

Surgeons and surgical staff rated the three robotic platforms differently across multiple domains, including overall experience, robotic control, efficiency, and instrument quality (Table 1B). Overall, the Da Vinci® X™ platform generally received the highest ratings. Compared with Da Vinci® X™, Hugo™ RAS differed significantly only in the overall experience of the bedside assistant and Cadiere forceps quality, whereas Versius® differed across a broader range of domains, including the overall experience of the bedside assistant, robotic control, efficiency, and Cadiere forceps and needle-holder quality.

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	Total (N=144) [1]	Da Vinci® X (N=50) [1]	Hugo™ (N=48) [1]	Versius® (N=46) [1]	p-value[2]
Experience with robotic platform[3]	4.1 (0.8)	4.3 (0.7)	4.1 (0.8)	4.0 (0.7)	0.05
Experience with robotic platform (bedside assistant)	4.0 (0.8)	4.3 (0.7)	3.8 (0.9)	3.8 (0.7)	0.001
Experience with robotic platform (scrub nurse)	3.9 (0.8)	4.1 (0.8)	3.9 (0.8)	3.8 (0.9)	0.108
Depth perception	4.4 (0.5)	4.5 (0.5)	4.4 (0.5)	4.3 (0.5)	0.424
Bimanual dexterity	4.3 (0.6)	4.4 (0.6)	4.2 (0.6)	4.2 (0.6)	0.074
Efficiency	4.1 (0.8)	4.4 (0.7)	4.1 (0.8)	3.9 (0.7)	0.006
Force sensitivity	4.0 (0.9)	4.2 (0.9)	3.8 (1.0)	3.9 (0.8)	0.025
Autonomy	4.3 (0.6)	4.5 (0.5)	4.2 (0.6)	4.1 (0.7)	0.016
Robotic control	4.1 (0.8)	4.4 (0.8)	4.0 (0.8)	4.0 (0.7)	0.006
Instrument rating – scissors	4.2 (0.7)	4.3 (0.8)	4.2 (0.6)	4.2 (0.6)	0.124
Instrument rating – maryland	4.1 (0.8)	4.3 (0.6)	4.0 (0.8)	4.0 (0.9)	0.015
Instrument rating – Cadiere forceps	4.1 (0.7)	4.4 (0.5)	4.0 (0.6)	4.0 (0.8)	<0.001
Instrument rating – needle holder	4.0 (1.0)	4.4 (0.6)	4.2 (0.7)	3.5 (1.3)	0.002

[1] Mean (sd)

[2] Kruskal-Wallis rank sum test

[3] Rated by the primary surgeon

Experience with the robotic platform (primary surgeon): Hugo™ vs da Vinci® X = 0.830, Versius ® vs da Vinci ® X = 0.035, Versius ® vs Hugo™ = 0.587.

Experience with the robotic platform (bedside assistant): Hugo™vs da Vinci ® X = **0.01**, Versius ® vs da Vinci ® X = **0.003**, Versius ® vs Hugo™ = 1.000.

Efficiency: Hugo™ vs da Vinci ® X = 0.117, Versius ® vs da Vinci ® X= **0.005**, Versius ® vs Hugo™ = 0.966.

Force sensitivity: Hugo™ vs da Vinci ® X = 0.065, Versius ® vs da Vinci ® X= 0.055, Versius ® vs Hugo™ = 1.000.

Autonomy: Hugo™ vs da Vinci ® X = 0.094, Versius ® vs da Vinci ® X = 0.021, Versius ® vs Hugo™ = 1.000.

Robotic control: Hugo™ vs da Vinci ® X = 0.064, Versius ® vs da Vinci ® X = **0.005**, Versius ® vs Hugo™ = 1.000.

Instrument – maryland: Hugo™vs da Vinci ® X = 0.029, Versius ® vs da Vinci ® X = 0.06, Versius ® vs Hugo™ = 1.000.

Instrument – cadiere: Hugo™ vs da Vinci ® X = **0.001**, Versius ® vs da Vinci ® X = **0.003**, Versius ® vs Hugo™ = 1.000.

Instrument – needle holder: Hugo™ vs da Vinci ® X = 0.515, Versius ® vs da Vinci ® X = **0.002**, Versius ® vs Hugo™ = 0.05.

Pairwise comparisons were performed only when the global Kruskal–Wallis test was significant and interpreted using the Bonferroni-adjusted significance threshold ($p<0.0167$).

Discussion

This secondary analysis of the COMPAR-HYST study suggests that, in a high-volume surgical team already experienced with the Da Vinci® X™ platform, adaptation to newer robotic systems primarily affected setup-related workflow and suturing-intensive tasks, whereas core console-based surgical performance appeared largely transferable across platforms. Subjective user experience broadly paralleled these objective findings, with greater perceived differences in domains requiring platform-specific interaction.

Learning Patterns in Setup-Related Phases

Because setup-related phases primarily involve team-based activities, the observed learning patterns may largely reflect workflow adaptation rather than surgeon-specific technical proficiency at the console.

Although draping times did not differ significantly between Hugo™ RAS and Versius®, the RA-CUSUM curves suggested more rapid adaptation with Hugo™, whereas the larger cumulative deviation and later transition observed with Versius® may be consistent with a longer period of standardization. One possible explanation is the different draping workflow associated with the modular platforms. However, these observations should be considered in light of the non-randomized sequence of platform introduction, as Versius® was introduced earlier and may have captured part of the team's initial adaptation to a modular architecture.

Docking may represent the setup phase most influenced by platform architecture because it requires coordinated team interaction and reproducible operating-room configuration. Versius® showed evidence of an initial adaptation followed by a more progressive path toward operational standardization, suggesting that early familiarization did not immediately translate into a fully reproducible and standardized docking workflow. This pattern may reflect the intrinsic complexity of a modular system, in which consistency in bedside setup depends not only on technical execution but also on reproducible configuration strategies. Hugo™ RAS, on the other hand, did not show a clearly identifiable statistical transition point. This pattern may reflect greater flexibility in docking configurations, which can increase variability and delay the emergence of a consistent performance trajectory [15].

Undocking showed less distinct adaptation patterns than draping and docking. Both modular systems demonstrated relatively rapid stabilization after the identified transition, suggesting that platform-related adaptation may be less evident during undocking than during draping and docking.

Taken together, these findings suggest that adaptation during setup-related phases varies across procedural steps, with more pronounced learning patterns observed during draping and docking than during undocking. Overall, setup performance tended to approach stability within the first 50 procedures, although adaptation trajectories differed across platforms.

Learning Patterns in Console-Based Surgical Phases

The console-based surgical phases did not show a uniform pattern of adaptation across procedural steps. Whereas hysterectomy showed only limited differences across platforms, colporrhaphy exhibited more pronounced platform-specific learning patterns.

Hysterectomy showed less pronounced adaptation patterns. The learning pattern observed for hysterectomy suggests that this core surgical component is less sensitive to platform transition than the organizational and setup phases. In this context, differences in the locations of statistically detected breakpoints across platforms may reflect distinct early adaptation dynamics. For both modular platforms, the learning curve shifts toward zero after relatively few surgical procedures, although an initial marked increase suggests a brief early phase of adaptation. For the Hugo™ RAS platform, the absence of a statistically significant breakpoint, together with the observed peak followed by a downward trend, is consistent with a gradual adaptation process that is not captured by a discrete transition point. Taken together, these findings suggest that, for the newer systems, performance in the hysterectomy phase approaches stabilization early, with no clear evidence of sustained performance deterioration during platform adoption.

By contrast, the colporrhaphy phase appears to be the console-based step most sensitive to platform transition and the least transferable component of robotic surgical performance. Vaginal cuff closure seems to require a more evident adaptation process, plausibly because it depends more directly on fine instrument control, needle handling, articulation, and surgeon–console ergonomics. In this context, the more prolonged adaptation observed with the newer systems and the marked increase from zero for the Versius® may reflect technical adjustment to platform-specific suturing mechanics that require time to adapt, particularly for Versius®, rather than a lack of underlying surgical proficiency. This finding suggests that suturing-intensive tasks may require platform-specific adaptation, even in surgeons with extensive prior robotic experience. Notably, this interpretation is consistent with the user-experience evaluation, in which differences in needle-holder performance, particularly for the Versius® platform, were reported and may help explain the longer adaptation period observed in this suturing phase. Notably, despite these differences in learning trajectories, the eventual convergence of the RA-CUSUM curves suggests that these challenges are transient and do not translate into persistent performance gaps.

Subjective User Experience and Objective Performance

Overall, the Da Vinci® X™ platform received the most favorable subjective ratings. Hugo™ RAS was rated similarly across most domains, differing mainly in the bedside assistant's overall experience. One possible explanation is the initial complexity in coordinating multiple independent robotic arms. In particular, suboptimal positioning of the camera arm may interfere with the bedside assistant's operative field, requiring new workflow strategies to fully exploit the flexibility and multi-quadrant capabilities of modular systems [14, 15, 27]. A similar explanation may apply to the lower ratings assigned to the bedside assistant when using Versius®, suggesting that early familiarization with modular robotic platforms contributes to subjective differences during platform transition [28, 29].

The additional differences observed when evaluating the needle holder, efficiency, and robotic control for the Versius® may reflect platform-specific characteristics that could require a longer period of familiarization. The subjective differences reported by operators, particularly in suturing-related tasks, were generally consistent with the patterns identified by the RA-CUSUM analyses, most notably during the colporrhaphy phase. At the same time, the progressive convergence of objective time-based performance suggests that subjective perception should not be interpreted as a direct surrogate of procedural efficiency. Rather, these ratings likely capture additional dimensions of platform adoption, including ergonomics, cognitive workload, interface familiarity, and the extent of team

adaptation required during the implementation phase [30, 31]. Accordingly, the more favorable perception of the Da Vinci® X™ platform likely reflects the surgical team's familiarity rather than an intrinsic procedural advantage.

Interpretation in the Context of Previous Evidence

Panico et al. [32] evaluated the learning curve for docking with the Hugo™ system, reporting a breakpoint after approximately 13 cases. In contrast, our results showed that the Hugo™ RAS system exhibited substantial variability in the RA-CUSUM trajectory, with no statistically detectable breakpoint. These differences may be related to variations in study design, case mix, and, importantly, the level of prior robotic experience of the surgical team. Vizza et al. [33] investigated robot-assisted hysterectomy in a robotic-naïve surgical team and reported a substantially longer adaptation time than observed in our cohort. However, these findings should be interpreted only in context because the two studies differ fundamentally in baseline robotic experience. Prior experience with the da Vinci® system may have facilitated transferability of robotic skills and contributed to faster adaptation to newer modular platforms, particularly for console-based tasks, as suggested by prostatectomy studies showing no clinically relevant increase in operative and setup times after transitioning from da Vinci® to Hugo™ [34, 35]. In robot-assisted prostatectomy, direct learning-curve comparisons between da Vinci® and Versius® are not yet available. Nevertheless, one comparative study reported longer operative and setup times after the transition to Versius®, suggesting that adaptation may be more prolonged with this modular platform in selected surgical settings [36].

Strengths and Limitations

This study provides a simultaneous head-to-head comparison of learning curves across the Da Vinci® X™, Versius®, and Hugo™ RAS platforms for the same procedure within a single institutional setting. This design strengthens internal validity by minimizing inter-center heterogeneity and enabling direct comparison under highly standardized technical, organizational, and perioperative conditions. Importantly, this study specifically evaluates platform transition in an already experienced robotic surgical team rather than the primary acquisition of robotic skills, thereby addressing a clinically relevant and increasingly common scenario. Prospective collection of granular procedural timing data enabled phase-specific assessment of platform adaptation. Risk-adjusted CUSUM analysis was applied uniformly across all outcomes using the same comprehensive adjustment strategy, providing methodological consistency across platforms. The integration of objective performance metrics with prospectively collected user-experience data further broadened the interpretation of platform transition by incorporating behavioral, ergonomic, and organizational dimensions of implementation.

However, several limitations warrant mention. First, this was a single-center study with a limited number of cases per platform, and sample size was determined by feasibility rather than formal power calculation, potentially limiting the precision of breakpoint estimation. Second, platform allocation was based on system availability rather than randomization, introducing the possibility of temporal confounding and learning carryover effects related to the sequence of platform implementation. Third, the surgical team had extensive prior experience with the Da Vinci® platform, which likely facilitated skill transfer and attenuated the magnitude of observable learning effects when transitioning to newer systems. Accordingly, generalizability is limited, particularly to high-volume centers with established robotic expertise, and the present findings should not be directly extrapolated to robot-naïve surgeons or lower-volume settings. The identified breakpoints represent statistical transitions rather than absolute clinical

thresholds and should therefore be interpreted together with the magnitude and overall morphology of the RA-CUSUM curves. Furthermore, the use of a single-breakpoint segmented model may not fully capture gradual or more complex adaptation processes, and breakpoint estimation may be influenced by model specification despite the use of a uniform, comprehensive, and stable adjustment strategy across outcomes. When RA-CUSUM curves oscillate around zero or show a limited magnitude, the practical relevance of a statistically significant breakpoint should be interpreted with caution [24]. Finally, subjective assessments of user experience were not blinded and may have been influenced by pre-existing familiarity with the Da Vinci® platform or by operator preference, which should be considered when interpreting differences in perceived efficiency and instrument performance.

Conclusions

This secondary analysis of the COMPAR-HYST study suggests that adaptation to newer robotic platforms is not uniform across different components of robot-assisted hysterectomy. The most evident adaptation patterns were observed during setup-related phases, particularly draping and docking, whereas hysterectomy showed only limited cumulative deviation, supporting substantial transferability of core robotic surgical skills. By contrast, vaginal cuff closure appeared to require the greatest platform-specific adaptation, suggesting that suturing-intensive tasks may remain the least transferable component when transitioning between robotic systems. Overall, prior experience with the Da Vinci® X™ platform may facilitate adaptation to newer robotic systems, although the extent of adaptation appears to depend on the specific procedural component.

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Supplementary Information

Online Resource 1 Procedural time points and definitions for draping, docking, hysterectomy, colporrhaphy, and undocking

Supplementary Files

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