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ORIGINAL RESEARCH

[Haptic Feedback and Tremor Suppression in Teleoperated Surgical Robotics for Improved Precision]

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Abstract

Background: Teleoperated surgical robotics offers enhanced dexterity and access but remains constrained by limited haptic information and operator physiological tremor. Combining high-fidelity haptic feedback with active tremor suppression may improve task precision in minimally invasive procedures. Methods: We developed a bilateral teleoperation testbed integrating configurable haptic rendering (kinesthetic only; combined tactile and kinesthetic) and an adaptive tremor suppression module based on velocity-adaptive filtering and model-based compensation. Thirty-six surgical residents and engineers performed three representative microsurgical tasks (needle placement, fine suture threading, and planar peg transfer) under four control conditions: (1) no haptics, (2) kinesthetic feedback, (3) combined tactile+kinesthetic feedback, and (4) combined feedback with tremor suppression. Primary outcomes were positional error (mm), tremor amplitude (RMS, mm), and task completion time (s). Statistical analysis comprised repeated-measures ANOVA and mixed-effects regression to quantify independent contributions of haptic modality and tremor suppression. Results: Combined tactile+kinesthetic feedback significantly reduced mean positional error relative to no haptics (mean difference 0.42 mm, $p < .01$) and kinesthetic-only (0.19 mm, $p = .04$). Adding tremor suppression yielded the largest improvement (mean error reduction vs. no haptics 0.73 mm, $p < .001$) and reduced tremor amplitude by 68% relative to no-haptics baseline. Mixed-effects regression indicated that tactile feedback and tremor suppression were independent, additive predictors of reduced positional error ($\beta = -0.18$, $p = .02$; $\beta = -0.35$, $p < .001$, respectively). Conclusions: High-fidelity combined haptic feedback improves teleoperated surgical precision; integrating adaptive tremor suppression provides additional, substantial benefit. These results support clinical translation of multisensory haptic interfaces with active tremor mitigation to enhance microsurgical outcomes, and they suggest guidelines for design trade-offs between feedback fidelity and control filtering in surgical teleoperation.

Keywords: teleoperation, haptic feedback, tremor suppression, surgical robotics, precision, bilateral control, adaptive filtering

Introduction Teleoperated surgical robotics has transformed the delivery of minimally invasive procedures by extending surgeon reach and augmenting dexterous manipulation in constrained anatomies. Despite substantial progress in kinematic design and imaging integration, the lack of reliable haptic information and the persistent presence of operator physiological tremor continue to limit microsurgical precision (Okamura, 2004). Haptic feedback conveys contact forces and tissue properties that are central to safe and precise manipulation (Liu et al., 2007; Piccin et al., 2009). Concurrently, tremor—an involuntary oscillatory motor output—reduces positional accuracy during fine tasks and is a critical performance limiter in teleoperation (Tasker, 1998; Ghorbanian et al., 2012).

Prior research has examined discrete aspects of this problem: methods for rendering force and tactile cues in teleoperated surgery (Okamura, 2004; Liu et al., 2007), the performance effects of differing haptic quality (Wildenbeest et al., 2013; Christiansson, 2008), and algorithms for compensating physiological tremor (Ghorbanian et al., 2012). There is limited experimental evidence assessing the joint effect of combined tactile and kinesthetic haptic modalities together with active tremor suppression on representative surgical tasks. Such evidence is essential to inform design trade-offs—for example, between the fidelity and bandwidth of haptic rendering and the stability constraints that arise when integrating control filters for tremor attenuation (Gallagher et al., 2014).

This study investigates whether combined tactile and kinesthetic feedback improves teleoperated surgical precision and whether an adaptive tremor suppression module provides additive benefit. We hypothesised that (1) combined tactile+kinesthetic feedback yields greater precision than kinesthetic-only or no-haptics conditions, and (2) adding tremor suppression further enhances precision and reduces tremor amplitude, with both effects remaining significant when controlling for completion time and task complexity.

Literature Review Haptic feedback in teleoperated surgical systems has been studied for over two decades. Early taxonomies emphasised bilateral master–slave architectures, force-reflection strategies, and the challenges of stability and transparency (Okamura, 2004). High-fidelity haptic simulation has been demonstrated to increase operator performance and task realism in surgical training contexts (Liu et al., 2007; Munawar & Fischer, 2016). Tactile cues (cutaneous stimulation) and kinesthetic cues (force/position) serve complementary roles: tactile feedback enhances local contact discrimination while kinesthetic feedback supports gross force regulation and trajectory control (Lim et al., 2014; Fontana et al., 2013).

Quality and modality of haptic feedback are known to affect task outcomes. Christiansson (2008) and Wildenbeest et al. (2013) found that improved fidelity of haptic feedback reduces task completion time and improves accuracy in teleoperated assembly tasks. In surgical contexts, force-feedback teleoperated needle insertion systems have shown improved control of insertion forces and tissue discrimination (Piccin et al., 2009; Kokes et al., 2009). Bilateral mapping strategies, including generalized force/position mappings, have been proposed to enhance operator control over multiple degrees of freedom (Malysz, 2007).

Physiological tremor has been approached through several technical strategies. Local filtering of input signals (e.g., low-pass, notch, and adaptive filters) can attenuate tremor frequencies while preserving voluntary motion bandwidth (Ghorbanian et al., 2012). Control architectures that combine model-based prediction with sensory augmentation can further suppress tremor without introducing deleterious time delay that would impair transparency (Feng et al., 2011; Gallagher et al., 2014). Recent teleoperation studies have proposed virtual fixtures and environment-based guidance to reduce operator error and provide haptic cues that compensate for limited tactile information (Munawar & Fischer, 2016; Howard & Szewczyk, 2016).

However, integrating high-bandwidth haptic rendering with active tremor suppression raises design tensions. Filtering to remove tremor can reduce haptic fidelity and responsiveness, while aggressive haptic rendering can amplify instability when loop delays exist (Okamura, 2004; Gallagher et al., 2014). Empirical comparisons that quantify the trade-offs between modality-specific feedback and adaptive tremor suppression across representative surgical tasks remain limited. This study addresses this gap by experimentally evaluating combined tactile and kinesthetic haptics with and without an adaptive tremor suppression module in a controlled, within-subjects design.

Methodology We designed a bilateral teleoperation testbed that permits configurable haptic rendering and enables insertion of a tremor suppression module in the master-to-slave command path. The system comprises a 6-DOF master haptic interface capable of combined kinesthetic force rendering and a fingertip tactile array for cutaneous stimulation. The slave manipulator is a high-precision 5-DOF surgical instrument with sub-millimetre positioning accuracy. The bilateral controller follows a standard position/force reflection scheme with passivity safeguards and adjustable virtual damping (Okamura, 2004; Malysz, 2007).

Tremor suppression employed an adaptive filtering strategy combining a frequency-estimation stage with a velocity-weighted low-pass compensation. The algorithm estimates dominant tremor band (typically 6–12 Hz for physiological tremor) in real time and applies a band-stop/attenuation profile adapted to the instantaneous tremor power, while preserving low-frequency voluntary motion. The design follows principles described by Ghorbanian et al. (2012) and incorporates a predictive feedforward term derived from a locally linear motion model to reduce phase lag (Gallagher et al., 2014).

Participants: Thirty-six volunteers (24 surgical residents, 12 biomedical engineers) provided informed consent under a protocol approved by the institutional review board. Average participant age was 31.2 years (SD 4.9); 22 male and 14 female. All participants reported normal or corrected vision and no motor disorders. Participation included a training period to reach stable baseline performance.

Tasks: We selected three microsurgical tasks representative of common precision challenges: (A) needle placement into a simulated lesion target (sub-mm accuracy), (B) fine suture threading through a 1.0 mm aperture, and (C) planar peg transfer requiring repeated insertion of a 1.5 mm peg into aligned holes. Tasks were performed under magnified stereoscopic display to simulate typical operative visual conditions. Each participant completed the three tasks under four control conditions in a counterbalanced Latin-square order to mitigate learning and fatigue effects. Conditions were: (1) No haptics (visual only), (2) Kinesthetic feedback only (force-reflection), (3) Combined tactile + kinesthetic feedback, and (4) Combined feedback with tremor suppression active.

Metrics and data collection: Primary outcome measures were positional error (distance from nominal target in mm), tremor amplitude (RMS of high-frequency positional fluctuations in mm), and task completion time (s). Secondary measures included subjective workload (NASA-TLX) and perceived fidelity (5-point Likert). Data were captured at 1 kHz and post-processed using standardized filters. For statistical inference, we aggregated trial-level measures per participant and condition.

Statistical analysis: We used repeated-measures ANOVA to test the main effects of haptic condition on each outcome, with Greenhouse–Geisser correction when sphericity was violated. Post-hoc pairwise comparisons applied Bonferroni correction. To estimate the independent contributions of tactile feedback and tremor suppression while controlling for participant random effects and task difficulty, we fitted a mixed-effects linear regression model with random intercepts per participant and fixed effects for tactile modality (binary), tremor suppression (binary), task type (categorical), and completion time. Significance was set at $\alpha = 0.05$. All analyses were performed in R (base functions) and validated via bootstrap (1,000 resamples) for key estimates.

Results All 36 participants completed the protocol without adverse events. Raw and aggregated outcomes revealed consistent patterns across the three task types: combined tactile+kinesthetic feedback improved positional accuracy relative to kinesthetic only and no-haptics conditions, and tremor suppression provided additional reductions in positional error and tremor amplitude. Table 1 summarises descriptive statistics across conditions pooled across tasks.

Condition	Positional Error (mm) Mean ± SD	Tremor Amplitude RMS (mm) Mean ± SD	Completion Time (s) Mean ± SD
No haptics	1.12 ± 0.38	0.48 ± 0.14	74.5 ± 21.3
Kinesthetic only	0.94 ± 0.31	0.42 ± 0.12	70.9 ± 19.8
Tactile + Kinesthetic	0.70 ± 0.26	0.30 ± 0.09	72.3 ± 20.1
Tactile + Kinesthetic + Tremor Suppression	0.39 ± 0.15	0.15 ± 0.05	78.0 ± 22.7

Table 1. Descriptive statistics for primary outcomes across experimental conditions (N = 36 participants; pooled across tasks).

As shown in Table 1, the addition of tactile cues to kinesthetic feedback reduced positional error by an average of 0.24 mm relative to kinesthetic-only (paired difference, p = .04 after Bonferroni correction). Introducing tremor suppression produced the greatest decrement in positional error (mean 0.39 mm), which represented a 65% reduction relative to the kinesthetic-only condition. Tremor amplitude RMS declined markedly with tactile feedback and most substantially with tremor suppression engaged (68% reduction vs. no-haptics baseline). Completion time exhibited a slight increase when tremor suppression was active, consistent with conservative filter settings that prioritised accuracy over speed.

Repeated-measures ANOVA confirmed a significant main effect of condition on positional error (F(3,105) = 42.7, p < .001, ηp2 = 0.55). Post-hoc tests indicated significant differences between: no haptics vs. tactile+kinesthetic (p < .01), kinesthetic-only vs. tactile+kinesthetic (p = .04), and tactile+kinesthetic vs. tactile+kinesthetic+tremor suppression (p < .001). Tremor amplitude also showed a significant condition effect (F(3,105) = 61.2, p < .001).

Source	SS	df	MS	F	p
Condition (within-subject)	12.46	3	4.15	42.7	<.001
Task type	3.28	2	1.64	16.9	Condition × Task
1.02	6	0.17	1.75	=.12	Error
10.22	210	0.048			

Table 2. Repeated-measures ANOVA summary for positional error showing main effects of condition and task type.

To estimate the independent effects of tactile feedback and tremor suppression while controlling for task and completion time, we fitted a mixed-effects linear regression (random intercepts per participant). Table 3 presents the model coefficients for positional error (dependent variable). The model explained 64% of the variance in positional error (conditional $R^2 = 0.64$).

Predictor	Estimate (β)	SE	t	p
Intercept (baseline: No haptics, Task A)	1.18	0.07	16.86	<.001
Tactile+Kinesthetic (binary)	−0.18	0.08	−2.25	=.02
Tremor suppression (binary)	−0.35	0.06	−5.83	Completion time (s)
0.002	0.0008	2.50	=.01	Task B (suture threading)
0.28	0.09	3.11	Task C (peg transfer)	0.10
0.08	1.25	=.21		

Table 3. Mixed-effects regression for positional error (β coefficients). Significant negative coefficients indicate reductions in error associated with tactile modality and tremor suppression.

The mixed-effects model corroborated the ANOVA results: both tactile feedback and tremor suppression were significant independent predictors of reduced positional error. Completion time had a small positive association with error, indicating that slower trials were not invariably more accurate, suggesting an accuracy–speed trade-off that was influenced by the tremor suppression filter settings. Bootstrap confidence intervals for the tactile and tremor coefficients excluded zero and supported the robustness of the findings.

Figure 1 illustrates the mean positional error across trials by condition, highlighting the additive performance gain when tremor suppression is combined with high-fidelity haptics. Figure 2 shows the percentage reduction in tremor amplitude across conditions relative to the no-haptics baseline.

Figure 1. line plot of mean positional error by trial across conditions showing convergence and variability

Figure 2. bar chart of tremor amplitude reduction (%) by condition relative to no-haptics baseline

Subjective measures indicated that participants rated tactile+kinesthetic feedback as more informative and stabilising than kinesthetic-only (median perceived fidelity 4/5 vs. 3/5, Wilcoxon signed-rank p < .01). Tremor suppression was perceived as improving steadiness but slightly reducing responsiveness; participants noted a modest learning period to adapt to the filtered dynamics. No participant reported discomfort or cybersickness attributable to the feedback modalities.

Discussion This study evaluated the combined effect of tactile and kinesthetic haptic feedback and adaptive tremor suppression on teleoperated surgical precision. Our results demonstrate that (1) adding tactile cues to kinesthetic feedback improves positional accuracy and reduces tremor amplitude compared with kinesthetic-only and no-haptics conditions, and (2) adaptive tremor suppression yields substantial additional gains, with effects that are independent and additive to the improvements provided by tactile feedback. These findings align with prior work showing the benefits of improved haptic quality for teleoperation performance (Christiansson, 2008; Wildenbeest et al., 2013) and extend them by quantifying the interplay with active tremor compensation strategies (Ghorbanian et al., 2012).

Interpretation and mechanisms: Tactile feedback likely enhances local contact discrimination and provides rapid cutaneous cues that assist in micro-adjustments during alignment and insertion tasks (Lim et al., 2014; Fontana et al., 2013). Kinesthetic feedback supports force coordination and trajectory control. When combined, these modalities provide complementary sensory channels that reduce uncertainty about tool–tissue interactions, enabling improved voluntary movement control and reduced corrective micro-movements that manifest as tremor. Tremor suppression further attenuates involuntary high-frequency oscillations by removing energy in the tremor band while preserving voluntary motion bandwidth via adaptive spectral estimation and predictive compensation. The tremor filter therefore reduces the amplitude of involuntary motion that can otherwise be amplified by the high-gain dynamics typical of force-reflection loops (Okamura, 2004).

Trade-offs and practical considerations: While tremor suppression improved precision, completion times increased modestly when suppression was active. This finding underscores a known trade-off: filters and compensation schemes that reduce tremor often introduce effective smoothing and phase changes that can slow response to intentional commands (Ghorbanian et al., 2012; Gallagher et al., 2014). In clinical settings, conservative filter tuning is advisable for tasks prioritising steady precision (e.g., vitreoretinal microsurgery), whereas more responsive settings may be preferred for tasks requiring rapid adjustments. Our mixed-effects analysis indicates that the benefits of tremor suppression persist after controlling for completion time, suggesting clinical utility even when small temporal penalties are incurred.

Design implications: The results support inclusion of tactile arrays in surgical teleoperation interfaces, particularly for tasks requiring sub-millimetre accuracy. Implementing tactile feedback at the fingertips provides rapid, local cues without requiring higher-force actuators, and can be combined with kinesthetic rendering to improve operator situational awareness (Lim et al., 2014; Fontana et al., 2013). Tremor suppression algorithms should be adaptive to individual tremor spectra and task demands; static low-pass filters risk excessive blunting of voluntary motion. Predictive feedforward components and motion modelling can reduce phase lag and enhance perceived responsiveness (Gallagher et al., 2014). Careful attention to stability and passivity is required when integrating high-bandwidth haptic rendering with control filtering (Okamura, 2004; Malysz, 2007).

Relation to prior work: Our findings extend experimental demonstrations of haptic benefit in teleoperation (Liu et al., 2007; Piccin et al., 2009) by showing that tactile modalities contribute measurably to surgical precision beyond kinesthetic signals alone, consistent with research on combined tactile and kinesthetic roles in minimally invasive contexts (Lim et al., 2014). The observed tremor amplitude reductions are comparable to results reported for physiological tremor compensation techniques in teleoperated systems (Ghorbanian et al., 2012), but our study additionally quantifies the interaction between tremor suppression and haptic modality across representative surgical tasks.

Limitations and future work: The experimental tasks, while representative, were performed in a simulated environment and may not capture all complexities of live tissue interactions, bleeding, or patient movement. Integration with clinical imaging modalities (e.g., MRI guidance) and evaluation in in vivo or cadaveric models will be necessary to confirm transferability (Kokes et al., 2009; Cole, 2013). The tremor suppression algorithm employed conservative settings prioritising safety; exploration of adaptive user-specific tuning and machine-learning approaches to predict voluntary intent may yield further improvements (Ghorbanian et al., 2012; Gallagher et al., 2014). Finally, cognitive workload and long-term adaptation to combined haptic and filtered dynamics warrant deeper investigation, particularly among surgeons performing prolonged procedures (Munawar & Fischer, 2016; Ficuciello et al., 2018).

Conclusion This study demonstrates that combined tactile and kinesthetic haptic feedback improves accuracy in teleoperated surgical tasks and that adaptive tremor suppression provides additional, substantial reductions in positional error and tremor amplitude. The benefits of tactile cues and tremor mitigation were independent and additive, suggesting that future surgical teleoperation systems should integrate both modalities. Designers must, however, balance filter aggressiveness against responsiveness and ensure stability in bilateral control. Our findings inform practical design choices for next-generation surgical robots aiming to deliver sub-millimetre precision in minimally invasive procedures.

Future work should validate these results in clinically realistic scenarios, investigate user-adaptive tremor suppression strategies, and evaluate long-term learning effects among surgeons. The integration of high-fidelity multisensory haptics with robust tremor compensation is a promising pathway to enhance safety and outcomes in robot-assisted microsurgery.