Proactive Prediction of Mental Workload in Robotic-Assisted Surgery via Time-to-Event Modeling

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Synopsis

Robotic-assisted surgery (RAS) improves dexterity and visualization but imposes high mental workload (MWL) due to technical complexity and altered interaction (Wong and Crowe 2024; Wong and Wong 2025). Mental overload degrades cognitive performance and can compromise patient safety, highlighting the need for effective MWL management. While subjective surveys and performance metrics are retrospective, physiological signals (e.g., EEG and eye tracking) enable continuous MWL monitoring. Existing machine-learning approaches primarily detect current MWL and therefore support only reactive interventions. To address this limitation, we introduce a time-varying Cox proportional hazards framework (Zhang et al. 2018) that models time-to-overload/recovery, enabling real-time MWL inference and proactive overload prediction.

Background

Although RAS improves surgical precision and visualization, its technical complexity and altered human–machine interaction substantially increase surgeons' mental workload. Mental overload is associated with degraded cognitive performance and elevated error risk. Existing MWL assessment methods rely largely on retrospective subjective reports or instantaneous MWL detection methods, limiting their ability to support timely MWL management. Proactive MWL management requires predictive models that account for the temporal evolution of workload rather than instantaneous state estimation alone.

Methods

This study recruited ten participants, comprising five novice operators and five experienced surgeons. Participants were ask to complete a set of representative RAS tasks, including suturing, anastomosis, and chicken wing dissection. During task execution, EEG and eye-tracking signals were continuously recorded to capture dynamic changes in mental workload. The time-varying Cox proportional hazards model was first trained on gaming-task data to learn general MWL dynamics and subsequently fine-tuned on RAS data through baseline hazard adaptation to support task-specific overload prediction.

Results

The proposed time-varying Cox framework achieved stable real-time proactive MWL prediction across tasks and skill levels, with balanced accuracy generally ranging from approximately 55% to 72%. Sensitivity increased with longer prediction horizons, rising from about 45–75% at shorter horizons to approximately 65–85% at longer horizons, indicating improved ability to anticipate impending overload. Task-dependent differences were observed, with the chicken wing dissection task yielding the strongest performance, while suturing and anastomosis showed more moderate results. Overall, the model demonstrated robust proactive prediction capability across heterogeneous tasks and expertise levels.

Discussion

This work presents a time-to-event modeling framework for real-time and proactive mental workload assessment in robotic-assisted surgery. By formulating MWL dynamics using a time-varying Cox model and fine-tuning the baseline hazard for task-specific adaptation, the proposed approach enables reliable short-horizon prediction of impending overload across tasks and skill levels. These findings demonstrate that modeling MWL as a time-to-event process provides a

principled way to extend instantaneous MWL assessment toward short-horizon overload prediction, supporting future adaptive MWL-aware surgical systems.

References

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