NeuroWell AI: A Hybrid Quantum-Classical Diagnostic Pipeline for Early Cognitive Decline Detection in Pediatric Brain Tumor Survivors

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Introduction

Cognitive decline is a pervasive but underdiagnosed consequence in pediatric brain tumor survivors, manifesting during treatment and often persisting for years post-therapy. These neurocognitive changes—ranging from memory deficits and slowed processing to executive dysfunction—can significantly impair academic performance, emotional development, and quality of life. While fatigue is one early symptom, broader patterns of decline often go unnoticed until functional impairment occurs. Traditional detection methods rely heavily on periodic neuropsychological assessments, which are resource-intensive and reactive. NeuroWell AI introduces a novel, scalable, and wearable-integrated system combining classical convolutional neural networks (CNNs) with quantum-enhanced neural networks to identify early signs of cognitive decline, including fatigue, in real time. This approach not only improves diagnostic speed and sensitivity but aligns with the growing push toward personalized, continuous monitoring in survivorship care. While preliminary findings are based on synthetic data, they lay the groundwork for future trials using real-world cohorts and validated instruments.

Health Psychology Framework

NeuroWell AI is grounded in Nola Pender's Health Promotion Model (HPM), which emphasizes personal agency, behavioral awareness, and the interaction of individual and environmental factors in shaping health outcomes. Cognitive decline, if left unmanaged, disrupts self-efficacy and motivation—core constructs in HPM. By enabling early detection through seamless monitoring, NeuroWell AI reinforces a survivor's sense of control and fosters supportive caregiver engagement. The system supports self-regulation by delivering timely indicators of neurocognitive fatigue, memory variability, and attentional drift, along with adaptive suggestions for rest or engagement. For example, real-time alerts derived from wearables enable behavioral adjustments (such as cognitive pacing or task switching), strengthening perceived control and engagement in health-promoting routines. From a behavioral standpoint, it empowers survivors and families to participate in recovery planning, reinforcing health-promoting actions and minimizing psychological and academic regression.

System Architecture

The NeuroWell AI pipeline is composed of two primary layers:

- **CNN Feature Extractor (TensorFlow)**: This layer processes grayscale images (e.g., T1-weighted MRI slices or thermal imaging mapped to 1-channel tensors) through a 3-layer convolutional neural network. It outputs a flattened feature vector that captures critical spatial features. Grad-CAM overlays are generated for interpretability, enabling clinicians to visualize which regions of an image influence the model's decision.

- **Hybrid Quantum-Classical Layer (PennyLane + PyTorch)**: The CNN feature vector is passed to a quantum-enhanced neural network composed of variational quantum circuits (VQCs). These circuits use parameterized quantum gates (e.g., RY rotations and entangling layers) and data re-uploading strategies to perform nonlinear transformations. They are particularly well-suited for discovering subtle signal shifts in small or imbalanced datasets. The hybrid model outputs a binary classification (e.g., Decline vs. No Decline) along with calibrated confidence scores.

Quantum Layer Role

Quantum computing enhances the system's ability to detect complex patterns in small, noisy datasets—common in rare disease populations like pediatric brain tumors. The hybrid model leverages the expressivity of quantum circuits to explore richer decision boundaries compared to classical kernels. While empirical superiority of quantum models remains an area of active investigation, simulated studies show potential for improved convergence and generalization in low-variance domains. In NeuroWell AI, the quantum layer augments decline prediction by encoding higher-order interactions that classical models may overlook. This positions the system for future integration with emerging quantum processors, enabling real-time, on-device inference. Care is taken to avoid overclaiming; instead, quantum advantage is framed as a potential enhancement for scenarios where conventional models struggle due to data sparsity or early-stage signal noise.

Simulated Results

Initial simulations using synthetic T1-weighted MRI data and behavioral signal vectors (e.g., derived from eye tracking and speech rhythm patterns) show promising trends. The baseline CNN achieved ~87% accuracy in binary classification, with Grad-CAM visualizations highlighting areas associated with frontal and parietal cognitive workload. When paired with the hybrid quantum model, accuracy rose to ~91% with notable gains in borderline cases—instances where early cognitive decline signals were minimal or confounded by variability. The hybrid model also demonstrated robustness to noise perturbation, suggesting improved resilience. These results, while preliminary, support the hypothesis that quantum-informed models may better distinguish early, subtle decline markers. Further validation using empirical datasets and statistical benchmarks (e.g., AUC-ROC, F1-score) is planned.

Deployment & Interface

NeuroWell AI is designed for practical integration into home and clinic environments. Wearables such as smart glasses, biosensing earbuds, and motion trackers provide continuous input. Data is encrypted and transmitted to a secure cloud layer, where the CNN+Quantum pipeline operates with minimal latency. Outputs include individualized cognitive risk scores, fatigue probability, longitudinal trend trajectories, and actionable suggestions. A web-based dashboard for clinicians offers detailed visualizations (e.g., Grad-CAM maps, longitudinal trends), while caregivers and patients receive simplified mobile feedback. Data privacy protocols adhere to HIPAA and GDPR standards. Emphasis is placed on user experience—ensuring alerts are non-intrusive, interfaces are child- and caregiver-friendly, and reports support shared decision-making.

Conclusion & Future Work

NeuroWell AI represents a hybrid, interdisciplinary approach to digital survivorship care. By combining classical AI, quantum computing, and behavioral science, it addresses a pressing need in pediatric oncology—detecting cognitive decline early, with interpretability and accessibility. Future priorities include clinical validation with real-world cohorts, expansion to include EEG and multimodal behavioral signals, and development of a mobile platform for daily use. As quantum hardware matures, the backend will be migrated from simulation to true quantum processors, positioning NeuroWell AI at the frontier of applied quantum health diagnostics. Ethical considerations such as algorithmic bias, informed consent, and equitable access will remain central to development and deployment.