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Explainable AI for Optimizing Prosthetic Control: Real-Time Adaptation to Neuromuscular Signals in Lower Limb Amputees

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Abstract:

Lower limb amputation severely impairs mobility, and current prosthetic devices ranging from passive mechanical limbs to microprocessor-controlled systems fail to provide intuitive, adaptive control that restores natural gait. A critical barrier is the inability of existing control systems to interpret and adapt to individual users' neuromuscular signals in real time, leading to high cognitive load, gait asymmetry, and elevated fall risk. This paper presents XAI-Prosthesis, an explainable artificial intelligence framework for real-time, adaptive prosthetic control that integrates surface electromyography (sEMG) and inertial measurement unit (IMU) signals from the residual limb to predict user intent and continuously optimize prosthetic joint (knee and ankle) trajectories. The framework comprises three core components: (1) a lightweight temporal convolutional network (TCN) with attention that extracts both transient (intent onset) and sustained (gait phase) features from 8-channel sEMG and 6-axis IMU data at 200 Hz; (2) a real-time adaptation module employing online Bayesian inference that updates model parameters every 100 ms based on error between predicted and actual prosthetic motion, accommodating neuromuscular fatigue, muscle activation pattern drift, and walking terrain changes (level ground, stairs, ramps, uneven terrain); and (3) an explainability layer using SHAP (SHapley Additive exPlanations) and counterfactual explanations that provides users and clinicians with interpretable feedback on why specific control decisions were made, enhancing trust and enabling informed clinical tuning. We validate XAI-Prosthesis on a longitudinal dataset from 24 unilateral transtibial amputees (mean age 48.2 ± 12.4 years, 38% female) who used the system during 6 months of home and community ambulation (total 8,400 hours of walking data). The system achieves intent recognition accuracy of 95.7% for five locomotion modes (level walking, stair ascent/descent, ramp ascent/descent) with average decision latency of 48 ms substantially faster than existing myoelectric control systems (typically 150-250 ms). Real-time adaptation reduces prosthetic joint angle trajectory error from 3.8° to 1.2° RMS compared to non-adaptive baseline (68% reduction). Gait symmetry (symmetry index) improves from 0.21 to 0.09 (57% improvement), and user-reported prosthetic satisfaction (PQ-Score) increases from 58 to 84 out of 100. Explainability feedback enables clinicians to identify problematic neuromuscular patterns and adjust prosthetic parameters without removing the device. Key neuromuscular predictors of gait intent include: integrated EMG of gastrocnemius lateralis (35% predictive weight), co-contraction index of tibialis anterior and soleus (28%), and IMU-derived shank angular velocity (22%). The model runs on an embedded edge device (NVIDIA Jetson Orin Nano, 10W) with inference latency of 12 ms per time step, supporting real-time control. This work establishes that explainable AI, combining deep learning with online adaptation and interpretability, can transform prosthetic control from rigid, user-dependent calibration to personalized, adaptive, and trustworthy human-machine collaboration.

Key words: prosthetic control; explainable ai; neuromuscular signals; surface electromyography (semg); temporal convolutional networks; real-time adaptation; lower limb amputation; human-machine interface

Introduction:

1.1 The Prosthetic Control Challenge:

Lower limb amputation affects over 1.5 million individuals in the United States and 30 million worldwide, with transtibial (below knee) amputation representing approximately 40% of all lower limb amputations. Despite advances in prosthetic hardware including carbon fiber energy-storing feet, microprocessor-controlled knees (e.g., C-Leg, Rheo Knee), and powered ankle prostheses (e.g., BiOM, Empower) the control interface remains the principal limitation to functional restoration. Most commercial prostheses operate in one of two modes: (1) passive devices with fixed mechanical properties requiring the user to compensate with altered gait patterns, or (2) microprocessor devices with finite-state controllers that switch between pre-programmed modes (e.g., walk, stair, ramp) based on simple inertial thresholds [1-32].

These approaches share a fundamental limitation: they do not adapt to the individual user's neuromuscular signals in real time. As a result, users must consciously trigger mode transitions (e.g., via smartphone app, button press, or specific body movement), increasing cognitive load, delaying response, and disrupting natural gait. Moreover, fixed control parameters do not accommodate day-to-day variability in muscle activation patterns due to fatigue, socket fit changes, or learning effects [33-54].

1.2 Neuromuscular Signal-Based Control

Surface electromyography (sEMG) captures residual muscle activity from the amputated limb. In transtibial amputees, the gastrocnemius, soleus, and tibialis anterior muscles remain partially intact and produce consistent activation patterns during walking, transitioning, and standing. These signals, combined with inertial sensors on the prosthesis, provide rich information about user intent. However, myoelectric signals are noisy, non-stationary, and user-specific. Traditional pattern recognition systems require periodic recalibration and fail to generalize across terrains.

1.3 Explainable AI for Trust and Adaptation

A critical barrier to AI-powered prosthetic control is the "black box" problem: users and clinicians cannot understand why a prosthesis made a particular movement decision, leading to low trust and reluctance to adopt autonomous control. Explainable AI (XAI) addresses this by providing interpretable rationales for model outputs, enabling clinicians to validate decisions and users to develop appropriate trust[55-76].

1.4 Contributions

This paper presents XAI-Prosthesis, an explainable AI framework for real-time, adaptive prosthetic control. Contributions include:

A lightweight temporal convolutional network for intent recognition from sEMG+IMU data with 48 ms latency.

- A real-time Bayesian adaptation module that continuously updates model parameters to accommodate neuromuscular drift.
- An explainability layer providing SHAP values and counterfactual explanations for prosthetic decisions.
- Longitudinal validation in 24 amputees during 6 months of home/community use.
- Clinical interpretability framework enabling clinicians to tune prosthetic parameters based on neuromuscular insights.

2. Related Work

2.1 Current Prosthetic Control Systems

Commercial microprocessor-controlled knees use gyroscopes and load cells to detect stance and swing phases, switching between pre-programmed hydraulic resistance settings. Powered ankles (e.g., BiOM) use series elastic actuators and plantar pressure sensing to provide push-off assistance. These systems achieve 80-90% satisfaction rates but are limited to predefined modes and require manual terrain selection in many models [77-90].

2.2 Myoelectric Control for Lower Limbs

Myoelectric control has been extensively studied for upper limb prostheses (pattern recognition of 4-8 hand/wrist movements) but less successfully applied to lower limbs due to higher dimensionality (continuous joint angle trajectories) and safety-critical requirements. Prior studies have achieved 85-92% accuracy for mode classification using sEMG from 4-8 channels, with latencies of 150-300 ms above the 100 ms threshold required for natural gait[91-105].

2.3 Adaptive and Explainable AI

Online learning and domain adaptation have been applied to myoelectric control, with incremental learning algorithms achieving 5-15% accuracy improvements after recalibration. Explainable AI has been proposed for prosthetic control but rarely implemented in real-time systems; no prior work has integrated real-time adaptation with explainability in a lower limb prosthesis [106-122].

2.4 Research Gap

No existing prosthetic control system combines: (1) real-time neuromuscular intent recognition (<100 ms latency), (2) continuous online adaptation to signal drift, (3) explainable outputs for user/clinician trust, and (4) validation during extended home use. XAI-Prosthesis addresses this gap.

3. XAI-Prosthesis Framework

3.1 System Architecture

XAI-Prosthesis comprises three hardware components: (1) a sensor ring with 8 sEMG electrodes (OEM pre-amplified, 200 Hz sampling) and 6-axis IMU (BMI160, 200 Hz) mounted on the prosthetic socket; (2) an edge computing unit (NVIDIA Jetson Orin Nano, 4GB) integrated into the prosthesis pylon; (3) prosthetic actuators (powered knee and ankle, custom series elastic actuators). Communication via CAN bus (1 kHz control loop).

3.2 Intent Recognition: Temporal Convolutional Network

- Input: 8-channel sEMG (bandpass filtered 20-450 Hz, rectified, envelope extracted) + 6-axis IMU (accelerometer, gyroscope) over a 300 ms sliding window.
- Architecture: Three-layer temporal convolutional network with kernel sizes 3, 5, 7; 64, 128, 64 channels; dilation rates (1,2,4) to capture transients (intent onset) and sustained patterns (gait phase). Attention mechanism computes temporal importance weights. Outputs: locomotion mode probabilities (5 classes) and predicted joint angle trajectories (knee and ankle, 50 ms horizon).
- Training: Pre-training on 100 hours of labeled walking data from 10 amputees, followed by online fine-tuning.

3.3 Real-Time Bayesian Adaptation

- **Problem:** Neuromuscular signals change over time due to muscle fatigue, sweat, socket shift, and learning. Fixed models degrade in accuracy by 15-25% after 2 hours of use.
- **Solution:** Recursive Bayesian update of model parameters. At each time step t, we compute prediction error e(t) = predicted joint angle - actual joint angle. A Kalman filter updates the weights of the final TCN layer using observation noise covariance R (estimated from recent errors). Adaptation occurs continuously with a forgetting factor λ=0.95, enabling tracking of signal drift while maintaining stability. Full model retraining is never required; only the output layer updates online (<1% computational overhead)[123-148].
- **Terrain detection**: IMU signals are processed to classify terrain (level/stair/ramp/uneven) with 94% accuracy using a separate lightweight classifier. Terrain context modulates the adaptation rate (faster adaptation on uneven terrain).

3.4 Explainability Layer

- **SHAP values (per-time-step):** For each control decision (mode selection or joint angle command), SHAP computes contribution of each input channel (sEMG electrodes, IMU axes) to the output. Visualized as a bar chart in the clinician dashboard.
- **Counterfactual explanations**: The system generates alternative inputs that would have produced a different output (e.g., "If gastrocnemius activation had been 15% higher, the prosthesis would have initiated stair mode instead of level walking"). Counterfactuals help users understand decision boundaries.
- **Natural language descriptions:** SHAP values are translated into clinician-friendly text: "The prosthesis selected level walking mode primarily due to moderate gastrocnemius activation (35% contribution) and low angular velocity (22%)."
- **Alert system:** When confidence falls below 85%, the system requests user attention (haptic feedback) and logs the event for clinician review [149-163].

3.5 Safety and Fallback

If sensor signals are corrupted (e.g., electrode detachment) or model uncertainty exceeds threshold, XAI-Prosthesis defaults to a safe mode: fixed impedance (walking speed 0.7 m/s) with conservative joint damping. User can override via body movement (e.g., hip hyperextension).

4. Experimental Methodology

4.1 Participants

We recruited 24 unilateral transtibial amputees (9 traumatic, 15 dysvascular) from two prosthetic clinics (2023-2025). Inclusion criteria: age 18-75 years, >6 months since amputation, using a passive prosthesis, able to walk independently. Exclusion criteria: bilateral amputation, severe residual limb pain, cognitive impairment.

Characteristic Value
Age (years, mean±SD) 48.2 ± 12.4
Sex (female, %) 38%
Amputation etiology (traumatic/vascular) 9 / 15
Time since amputation (years, median, IQR) 4.2 (2.1-8.5)
Pre-study prosthesis (passive / microprocessor) 21 / 3
Baseline gait speed (m/s, mean±SD) 0.94 ± 0.21
Baseline PQ-Score (0-100) 58 ± 14

Table 1: *Participant Demographics (N=24)*

4.2 Study Protocol:

- **Phase 1 (Calibration, 1 day):** Users performed structured walking tasks (level ground, stairs, ramps, uneven terrain) while sEMG/IMU and motion capture (Vicon) were recorded. Initial model training.
- **Phase 2 (Clinic adaptation, 2 weeks):** Users trained with XAI-Prosthesis in clinic under therapist supervision. System adaptation enabled.
- **Phase 3 (Home/Community, 6 months):** Unsupervised home use. Data logged continuously (8,400 total hours). Monthly in-clinic assessments.

4.3 Outcome Measures:

Domain Metric

Intent recognition Accuracy, latency, confusion matrix

Control accuracy RMS joint angle error vs. able-bodied template

Gait quality Symmetry index, gait speed, fall rate

User experience PQ-Score, NASA-TLX (cognitive load)

Safety Adverse events, fallback mode activations

Explainability Clinician trust rating (1-5), SHAP plausibility

4.4 Baselines:

Baseline Description

Baseline 1 (fixed myoelectric) Myoelectric pattern recognition, no adaptation

Baseline 2 (finite-state) IMU-based finite-state controller (commercial standard)

Baseline 3 (no adaptation) XAI-Prosthesis with adaptation disabled

Baseline 4 (black-box AI) Same architecture without explainability

5. Results:

5.1 Intent Recognition Performance

Mode Fixed myoelectric Finite-state XAI-Prosthesis
Level walking 86.2% 91.4% 97.1%
Stair ascent 79.5% 72.3% 94.2%
Stair descent 74.8% 68.9% 93.8%
Ramp ascent 81.3% 84.2% 95.5%
Ramp descent 76.1% 79.7% 94.9%
Overall, 81.6% 83.7% 95.7%

Table 2: *Locomotion Mode Classification Accuracy*

Latency: XAI-Prosthesis median decision latency 48 ms (95th percentile 72 ms), compared to 190 ms for fixed myoelectric ($p<0.001$)

well within the 100 ms requirement for natural gait[164-178].

5.2 Real-Time Adaptation Effect

Time (hours)	No adaptation	XAI-Prosthesis	Reduction
0 (baseline)	1.2°	1.2°	—
1	1.8°	1.3°	28%
2	2.5°	1.3°	48%
3	3.1°	1.2°	61%
4	3.5°	1.3°	63%
5	3.7°	1.2°	68%
6	3.8°	1.2°	68%

Table 3: *Prosthetic Joint Angle Error (RMS degrees) Over 6 Hours of Continuous Use*

Key finding: Without adaptation, error increases 3.8-fold over 6 hours (1.2° → 3.8°). XAI-Prosthesis maintains error within 1.2-1.3° throughout, representing 68% error reduction at 6 hours.

5.3 Gait Quality Improvement

Metric	Baseline (passive)	3 months	6 months	Improvement
Gait speed (m/s)	0.94	1.12	1.21	+29%
Symmetry index (0=perfect)	0.21	0.13	0.09	57% improvement
Stance time asymmetry (%)	18%	11%	7%	61% reduction
Fall rate (falls/1000 hours)	8.4	3.2	1.8	79% reduction
PQ-Score (0-100)	58	74	84	+26 points

Table 4: *Gait Metrics at Baseline vs. 6 Months*

Fall rate comparison: Community fall rates for microprocessor prosthesis users typically range 3-5 falls/1000 hours. XAI-Prosthesis achieved 1.8 falls/1000 hours, approaching able-bodied rates (1-2 falls/1000 hours for adults 45-65 years).

5.4 Explainability Impact

Metric	Black-box AI	XAI-Prosthesis	p-value
Clinician confidence in decisions	2.8	4.3	<0.001
Clinician ability to identify errors	2.5	4.1	<0.001
User trust in prosthesis	2.9	4.2	<0.001
User understanding of prosthesis actions	2.1	4.0	<0.001
Willingness to use autonomous mode	3.0	4.4	<0.001

Table 5: *Clinician and User Trust Metrics (1-5 scale)*

SHAP value utilization: Clinicians used SHAP visualizations to identify problematic neuromuscular patterns in 11 of 24 participants, leading to targeted physical therapy (e.g., strengthening specific residual muscles) that further improved outcomes [179-193].

5.5 Neuromuscular Predictors of Intent

Feature	Predictive weight	Most predictive for
Gastrocnemius lateralis EMG (integrated)	35%	Stair ascent, ramp ascent
Tibialis anterior-soleus co-contraction index	28%	Level walking, stance stability
Shank angular velocity (IMU)	22%	Swing phase initiation, terrain transitions
Residual limb temperature (indirect via EMG baseline)	8%	Adaptation rate modulation
Medial gastrocnemius EMG	7%	Push-off power

Table 6: *Feature Importance for Mode Classification (SHAP values)*

5.6 Safety and Reliability

Event Type Count Rate per 1000 hours
Fallback mode activation (low confidence) 112 13.3
Sensor detachment events 24 2.9
User-initiated override 67 8.0
Falls (any) 15 1.8
— Fall requiring medical attention 2 0.24
Prosthesis damage 0 0

Table 7: *Safety Events During 8,400 Hours of Home Use*

All falls occurred during early adaptation period (first 2 months). No fall was attributed to incorrect mode selection; all were due to environmental hazards (ice, uneven surfaces) where able-bodied individuals also fall [194-210].

5.7 Computational Performance

Task Latency (ms) Power (mW)
sEMG/IMU acquisition + filtering 5 120
TCN inference (intent + trajectory) 12 280
Bayesian adaptation (Kalman update) 3 80
SHAP computation (real-time) 8 180
Motor control loop (1 kHz) 1 50
Total control loop 29 710

Table 8: *Edge Computing Benchmarks (Jetson Orin Nano, 10W)*

Total system power (including sensors and motors) averages 15W, within range for battery-powered prosthesis (8-hour operation on 120Wh battery).

6. Discussion:

6.1 Principal Findings:

XAI-Prosthesis demonstrates that explainable AI with real-time adaptation can achieve clinical-grade prosthetic control. Key findings: (1) 95.7% intent recognition accuracy with 48 ms latency meeting real-time requirements; (2) continuous Bayesian adaptation reduces joint angle error by 68% over 6 hours; (3) explainability improves clinician confidence from 2.8 to 4.3 and user trust from 2.9 to 4.2; (4) gait symmetry improves 57% and fall rate reduces 79% compared to passive prostheses; (5) neuromuscular predictors (gastrocnemius EMG, co-contraction index, shank angular velocity) enable interpretable control decisions.

6.2 Comparison with Prior Work:

XAI-Prosthesis improves upon state-of-the-art myoelectric control (81-85% accuracy, 150-250 ms latency) by 10-14 percentage points with 3-5x faster response. The 68% error reduction from online adaptation substantially exceeds incremental learning improvements reported in prior work (typically 15-25%). The 57% gait symmetry improvement exceeds outcomes from microprocessor knees (typically 20-30% improvement). Fall rate (1.8/1000 hours) approaches able-bodied rates, suggesting that AI-powered control may reduce fall risk below current prosthetic standards.

6.3 Explainability as an Enabler:

The most clinically significant finding may be the impact of explainability on trust and utilization. Clinicians using SHAP visualizations identified previously unrecognized neuromuscular deficits (e.g., selective weakness of gastrocnemius lateralis) in 11 participants, enabling targeted therapy. Users reported that counterfactual explanations ("the prosthesis didn't switch to stairs because your shank angular velocity was too low") helped them modify their gait to improve control. This suggests that explainability is not merely an ethical requirement but an active therapeutic tool.

6.4 Limitations:

First, the study enrolled only transtibial amputees; generalization to transfemoral (above-knee) amputees requires validation due to different muscle availability. Second, dysvascular amputees (15 of 24) have poorer baseline function; results may not generalize to younger traumatic amputees. Third, the 6-month follow-up is relatively short; long-term retention of adaptation effects is unknown. Fourth, SHAP computation adds 8 ms latency and 180 mW power; some real-time applications may omit it. Fifth, the system requires initial supervised calibration (1 day), limiting deployment in remote settings [211-213].

6.5 Future Directions:

Multi-limb coordination: Extend to bilateral amputees and integrate with upper limb prostheses.

Anticipatory control: Predict transitions (e.g., level→stair) 200-300 ms before foot contact using early sEMG features.

Generative counterfactuals: Use variational autoencoders to generate visualized alternative gaits that would produce different prosthetic responses [214-219].

Federated learning: Aggregate adaptation data across users to improve base models without sharing private gait data.

Clinical deployment study: Randomized controlled trial comparing XAI-Prosthesis to standard microprocessor prosthesis (N=100, 12 months).

Implantable EMG: Evaluate with intramuscular EMG (higher signal-to-noise ratio) for patients with minimal residual muscle[220-225].

7. Conclusion:

Lower limb prosthetic control remains a grand challenge in rehabilitative engineering. Current systems require users to adapt to rigid device behaviors rather than devices adapting to users' natural neuromuscular signals. This paper introduced XAI-Prosthesis, an explainable AI framework that decodes user intent from sEMG and IMU signals, continuously adapts to neuromuscular drift, and provides interpretable explanations for its decisions. In a 6-month home-use study with 24 transtibial amputees, XAI-Prosthesis achieved 95.7% intent recognition accuracy at 48 ms latency, reduced joint angle error by 68% via real-time Bayesian adaptation, improved gait symmetry by 57%, and reduced fall rate by 79%. Explainability features increased clinician confidence from 2.8 to 4.3 and user trust from 2.9 to 4.2, enabling targeted therapy and informed device use.

The convergence of lightweight deep learning, online adaptation, and explainable AI creates a new paradigm for human-machine interaction: systems that not only perform accurately but also communicate their reasoning, building the trust necessary for clinical adoption. As embedded AI compute continues to improve, XAI-Prosthesis demonstrates that intelligent, adaptive, and transparent prosthetic control is clinically feasible and functionally superior to current standards. This work provides a foundation for next-generation prostheses that restore not just mobility but the intuitive, natural control that amputees deserve.

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