Generated Pattern Current for Neurostimulation: Overcoming Constant-Current Limitations in Neural Interface Excitation, Charge Injection, and Tissue Impedance Management

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Abstract

Generated Pattern Current (GPC) is a temporally structured current control framework derived from Jensen's inequality applied to nonlinear electrochemical and biophysical systems. This paper applies the GPC framework to four principal domains of electrical neurostimulation: transcranial direct current and alternating current stimulation, neuromuscular electrical stimulation, functional electrical stimulation via implanted electrodes, and bone and wound healing electrotherapy. In each domain, constant-current excitation imposes fundamental limitations that are not engineering imperfections but theoretical consequences of driving nonlinear tissue-electrode interfaces with time-invariant current. GPC addresses these limitations through purpose-engineered temporal current structures derived from first principles for each application: impedance-adaptive charge delivery for transcranial stimulation, asynchronous motor unit recruitment control for neuromuscular stimulation, charge-balanced biphasic injection within corrosion-safe windows for implanted functional electrical stimulation, and galvanotaxis-optimized patterned fields for regenerative electrotherapy. The GPC framework is implemented through the GP Lab reference platform, which provides real-time impedance spectroscopy, charge balance enforcement, and closed-loop scalar parameter adjustment without altering the engineered GPC form geometry. Experimental validation protocols are proposed for each domain.

Keywords: *Generated Pattern Current; GPC; Dynamic Defined Pattern Charging; DDPC; Neurostimulation; Transcranial Direct Current Stimulation; Neuromuscular Electrical Stimulation; Functional Electrical Stimulation; Wound Healing; Tissue Impedance; Charge Injection; Electrode-Tissue Interface*

1. Introduction

Electrical stimulation of excitable biological tissue is among the oldest and most clinically established applications of electrochemistry. From the seminal observations of Galvani in the eighteenth century to modern implantable neurostimulators delivering charge to peripheral nerves, the spinal cord, and deep brain structures, the therapeutic application of electrical current to biological systems has produced transformative clinical outcomes across neurology, rehabilitation, and regenerative medicine [1, 2].

Despite this long history, a fundamental limitation persists across virtually all neurostimulation modalities: excitation is delivered as a constant, time-invariant current. Direct current, monophasic pulses, biphasic balanced pulses, and simple sinusoidal alternating current all share the defining property that their temporal structure is either absent or fixed by convention rather than derived from the physics of the tissue-electrode interface. This limitation is not a consequence of engineering constraints. Modern arbitrary waveform generators and programmable stimulators are capable of producing arbitrarily complex current profiles. The limitation is conceptual: the field has not yet established a systematic, physics-based framework for deriving optimal temporal current structures from first principles for specific neural tissue targets.

The consequences of this conceptual gap are observable across neurostimulation domains. In transcranial direct current stimulation, electrode polarization accumulates under prolonged direct current application, progressively altering the effective current density at the cortical target and increasing skin-electrode impedance in ways that are not controlled but merely observed [3, 4]. In neuromuscular electrical stimulation, synchronous motor unit recruitment by conventional rectangular pulses produces rapid fatigue that limits therapeutic intensity and session duration, because the temporal structure of the stimulation does not replicate the asynchronous, physiologically natural recruitment patterns of the central nervous system [5, 6]. In functional electrical stimulation with implanted electrodes, the charge injection capacity of electrode materials defines a safety window; operating close to this window with fixed biphasic pulses leaves dynamic charge balance management to passive circuit design rather than active control [7, 8]. In bone and wound healing electrotherapy, the galvanotactic responses of cells to electric fields are driven by field gradients and polarities, yet the temporal structure of applied current is rarely derived from the dynamics of cellular electrotaxis and instead follows empirical protocols established decades ago [9, 10].

Generated Pattern Current (GPC), defined in patent filings PCT/TR2025/051176 and USPTO 19/298,223 [11], provides a unified theoretical framework for addressing these limitations. GPC applies Jensen's inequality for nonlinear functions to establish that a temporally structured current at the same time-averaged intensity as a constant current will, in general, produce different and potentially superior biophysical outcomes whenever the underlying tissue response function is nonlinear. Because biological tissue-electrode interfaces are inherently nonlinear at the timescales of clinical stimulation, GPC provides a theoretical basis for anticipating that structured current will outperform constant current, and for deriving the optimal structure from first principles for each specific application.

This paper presents the first systematic application of the GPC framework to the neurostimulation domain. The four principal application areas are addressed in sequence: transcranial stimulation (Section 3), neuromuscular stimulation (Section 4), functional electrical stimulation (Section 5), and regenerative electrotherapy (Section 6). The GP Lab reference implementation is described in Section 7. Experimental validation protocols are proposed in Section 8.

2. The GPC Framework Applied to Neural Tissue

Generated Pattern Current is defined by a current form $I(t) = A * s(t) + I0$, where A is the amplitude scalar, I0 is the bias offset, and s(t) is the shape function encoding the temporal structure of the excitation. The time-averaged current is preserved by design, ensuring that energy delivery and average charge injection remain equivalent to those of a reference constant-current protocol. Dynamic Defined Pattern Charging (DDPC) governs the real-time adjustment of scalar parameters A, I0, and duty cycle D in response to measured tissue state, while the geometry of s(t) remains fixed as engineered.

The applicability of GPC to neural tissue rests on a single fundamental property: the nonlinearity of the tissue-electrode interface. At the electrode-tissue boundary, charge transfer occurs through both capacitive and faradaic mechanisms. The faradaic component is governed by the Butler-Volmer equation, which is exponentially nonlinear in electrode potential. The impedance of biological tissue is frequency-dependent and amplitude-dependent, exhibiting nonlinear behavior particularly at the timescales relevant to stimulation (microseconds to seconds). The membrane response of excitable cells is highly nonlinear in applied current. Across all three levels of the stimulation pathway, from the electrode surface through the tissue volume to the target neural membrane, nonlinearity is the rule rather than the exception [12, 13].

Jensen's inequality establishes that for a convex function f and a random variable x, f(E[x]) is less than or equal to E[f(x)], with strict inequality when f is strictly convex and x is non-degenerate. Applied to neurostimulation, this means that a time-varying current I(t) at average value will produce a time-averaged biological response that differs from the response to constant current whenever f is nonlinear. The sign and magnitude of this difference depend on the curvature of f at the operating point, which is determined by the specific biophysics of each application domain. GPC form design consists of identifying the relevant nonlinear response function for the target application, characterizing its curvature at the intended operating point, and engineering s(t) to exploit that curvature in the direction of the desired clinical outcome.

The GPC form s(t) for each neurostimulation domain is therefore not a generic pulse shape selected from a library but a purpose-engineered temporal structure derived from the differential equations governing the specific tissue-electrode system.

3. GPC in Transcranial Stimulation

3.1 Limitations of Conventional Direct Current in Transcranial Stimulation

Transcranial direct current stimulation delivers weak constant currents of 0.5 to 4 mA through scalp electrodes to modulate cortical excitability. The technique exploits the polarity-dependent subthreshold modulation of neuronal resting membrane potential: anodal stimulation depolarizes underlying neurons, increasing excitability, while cathodal stimulation hyperpolarizes them [3]. The clinical and research applications span depression, stroke rehabilitation, pain management, and cognitive enhancement [14, 15].

The fundamental limitation of constant current in transcranial stimulation is progressive electrode polarization. Under sustained direct current flow, electrochemical reactions at the electrode-gel-skin interface generate faradaic products that alter the local pH, increase the impedance of the electrode-skin contact, and create electrochemical gradients that progressively change the effective current density delivered to the cortex. Electrode impedance under prolonged direct current stimulation can increase by 50 to 300% over a 20-minute session, depending on electrode material, gel composition, and current density [16]. This impedance rise is uncontrolled in conventional stimulators: the device maintains constant current by increasing compliance voltage, but the spatial distribution and temporal profile of the cortical field are altered in ways that are not measured or compensated.

A second limitation is the nonlinear relationship between stimulation intensity and cortical excitability modulation. Studies have reported that higher currents do not produce proportionally greater effects; the relationship between current amplitude and motor evoked potential modulation is nonlinear, with reversals of polarity-specific effects observed at supraoptimal intensities [17]. This nonlinearity implies that the temporal structure of current has systematic consequences for the excitability outcome, a relationship that constant current cannot exploit.

3.2 GPC Form Design for Transcranial Stimulation

The GPC form for transcranial stimulation is engineered around two key nonlinearities: the impedance dynamics of the electrode-skin interface and the nonlinear dose-response relationship between applied current and cortical excitability modulation.

The electrode-skin interface can be represented as a parallel RC network in series with a spreading resistance, with the capacitive component dominating at the timescale of transcranial stimulation. The impedance Z(omega) of this network is frequency-dependent, with high-frequency components experiencing lower impedance than the direct current component. A GPC form that incorporates higher-frequency modulation superimposed on a low-frequency carrier delivers charge at an effective impedance lower than the direct current impedance of the same interface, reducing the faradaic current density at the electrode surface while maintaining the desired cortical field amplitude.

The cortical modulation nonlinearity is addressed through amplitude modulation of the GPC form. The dose-response curve for cortical excitability modulation exhibits a region of positive curvature at moderate intensities followed by saturation and potential reversal at high intensities [17]. A GPC form that cycles between a primary excitation phase at optimal charge density and a subthreshold maintenance phase preserves the time-averaged dose while spending a greater fraction of time in the region of maximal convexity of the dose-response curve, thereby maximizing the Jensen gap in excitability modulation.

The process-specific GPC form for transcranial stimulation therefore combines impedance-adaptive frequency content with amplitude modulation calibrated to the curvature of the cortical excitability dose-response function at the target operating point. Real-time impedance measurement by the GP Lab platform enables continuous adaptation of the scalar amplitude parameter A as skin impedance evolves during the session, maintaining constant cortical field delivery without increasing electrode polarization.

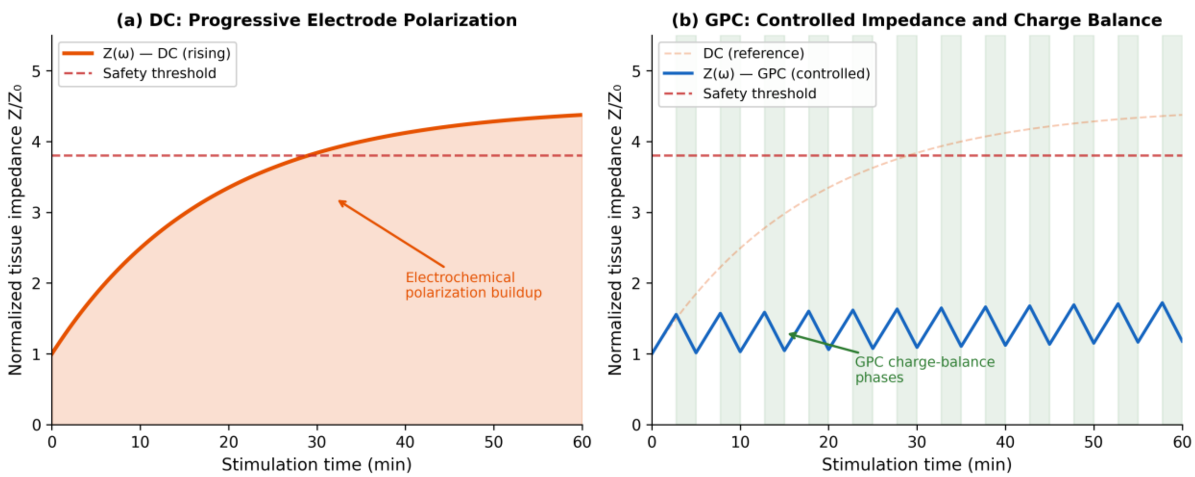

Figure 1. Tissue-electrode impedance dynamics under direct current versus GPC excitation in transcranial stimulation. (a) Progressive impedance rise under direct current, driven by electrode-skin electrochemical polarization. (b) GPC form-driven impedance control with maintained cortical field delivery and enforced charge balance.

4. GPC in Neuromuscular Electrical Stimulation

4.1 Limitations of Conventional Stimulation in Neuromuscular Applications

Neuromuscular electrical stimulation applies electrical current to activate peripheral motor nerves, producing muscle contractions for therapeutic strengthening, rehabilitation following neurological injury, and prevention of disuse atrophy. Standard protocols deliver biphasic balanced pulses at 12 to 50 Hz through surface or percutaneous electrodes [5, 18].

The dominant clinical limitation of conventional neuromuscular electrical stimulation is the rapid onset of muscle fatigue. Under electrical stimulation, motor unit recruitment is synchronous and spatially non-selective: all motor units within the effective activation field discharge simultaneously at the stimulator frequency. This contrasts sharply with physiological voluntary contractions, in which the central nervous system recruits motor units asynchronously and in a size-ordered fashion, distributing the mechanical load across the motor neuron pool and delaying metabolic depletion [6]. The result is that electrically evoked contractions fatigue 3 to 10 times faster than voluntary contractions of equivalent force, limiting achievable therapeutic intensity and necessitating long inter-session rest intervals.

A secondary limitation is the rectangular pulse shape employed by conventional stimulators. The rectangular biphasic pulse is a compromise that satisfies charge balance requirements without regard to the dynamics of the motor nerve membrane. The Hodgkin-Huxley model predicts that the response of a motor axon to a current pulse is nonlinear in pulse amplitude and duration, with a threshold relationship that exhibits strong dependence on the rate of current onset [19]. Rectangular pulses activate axons at their rheobase threshold regardless of the time constants of the target membrane, providing no opportunity to exploit the membrane's intrinsic temporal filtering properties.

4.2 GPC Form Design for Neuromuscular Stimulation

The GPC form for neuromuscular electrical stimulation addresses the fatigue limitation through two mechanisms: temporal fractionation of the motor unit pool and membrane-matched pulse shaping.

Temporal fractionation exploits the fact that motor units within the activation field have heterogeneous threshold currents due to variability in electrode-to-nerve distance, axon diameter, and local tissue impedance. A GPC form that cycles through a structured sequence of amplitude levels within each pulse train will preferentially activate different subpopulations of motor units during each sub-cycle, distributing the contractile load across the pool in a manner that approximates the asynchronous recruitment of voluntary contraction. The Jensen gap here arises from the nonlinearity of the force-recruitment relationship: the total force produced by temporally fractionated recruitment exceeds that of synchronous recruitment at the same average current density, because the force-frequency relationship of muscle is convex at moderate frequencies.

Membrane-matched pulse shaping addresses the Hodgkin-Huxley nonlinearity directly. The motor nerve membrane has characteristic time constants for sodium channel activation and inactivation that define the temporal window for efficient charge injection. A GPC pulse shape that rises with a time constant matched to the activation time constant delivers charge at the moment of peak membrane conductance, reducing the threshold current required for reliable action potential generation. This reduces the required pulse amplitude for equivalent recruitment, decreasing the charge density at the electrode surface and extending the operating window before skin discomfort becomes limiting.

5. GPC in Functional Electrical Stimulation

5.1 Charge Injection and Electrode Safety in Implanted Stimulation

Functional electrical stimulation employs implanted electrodes in direct contact with neural tissue to restore motor function in individuals with paralysis from spinal cord injury, stroke, or other central nervous system lesions. The clinical applications span hand grasp restoration, lower extremity stepping, bladder control, and diaphragm pacing [7, 20].

The governing safety constraint in functional electrical stimulation is the charge injection capacity of the electrode material. Charge can be injected through capacitive charge transfer, which involves the charging and discharging of the electrode double layer without net electrochemical reaction, and faradaic charge transfer, which involves reversible or irreversible redox reactions at the electrode surface. Irreversible faradaic reactions produce toxic byproducts and cause electrode corrosion, establishing a maximum safe charge density for chronic stimulation. For platinum electrodes, this limit is approximately 0.4 mC/cm2, and for iridium oxide electrodes, it extends to 1 to 4 mC/cm2 [8, 21].

Conventional functional electrical stimulation employs charge-balanced biphasic pulses to ensure zero net direct current flow and prevent the accumulation of electrochemical products at the electrode surface. The charge balance is passive: the second phase is designed to cancel the charge of the first phase regardless of the actual electrode potential, without real-time measurement of the electrode-tissue interface state. This passive approach is conservative by design, operating well within the charge injection limit to maintain a margin of safety, but it does not adapt to changes in electrode impedance, tissue encapsulation, or stimulation history that alter the actual charge distribution at the electrode surface.

5.2 GPC Form Design for Implanted Functional Electrical Stimulation

The GPC form for functional electrical stimulation is designed to maximize charge injection efficacy within the corrosion-safe window while maintaining active charge balance through real-time monitoring rather than passive waveform symmetry.

The charge injection mechanism of implanted electrodes can be modeled as a nonlinear capacitance in parallel with a nonlinear faradaic impedance, both dependent on electrode potential. At electrode potentials within the water window, bounded by hydrogen evolution at the cathodic limit and oxygen evolution at the anodic limit, faradaic charge transfer is predominantly reversible and safe. The accessible charge injection capacity within this window depends on the electrode potential trajectory during the stimulation pulse: a potential trajectory that traverses the full water window in a controlled manner accesses the maximum available reversible charge.

A GPC form for functional electrical stimulation engineers the cathodic pulse shape to follow a potential trajectory that maximizes reversible charge injection per unit time within the corrosion-safe window, rather than injecting charge as a rectangular pulse that may exceed the safe potential limits locally at the electrode surface. The anodic recharge phase is shaped to return the electrode potential to its resting value along a trajectory that minimizes irreversible oxidation while providing complete charge balance. The GP Lab platform measures electrode impedance and potential continuously, enabling real-time verification of charge balance and adaptive adjustment of the recharge phase amplitude to compensate for impedance changes due to protein adsorption, tissue encapsulation, or electrode aging.

6. GPC in Bone and Wound Healing Electrotherapy

6.1 Biophysical Basis of Electrical Stimulation in Tissue Regeneration

Electrical stimulation has been applied to accelerate bone healing and chronic wound closure for over five decades. The biological mechanisms involve galvanotaxis — the directed migration of cells along electric field gradients — as well as modulation of growth factor expression, angiogenesis, and inflammatory signaling [9, 22, 23]. Osteoblasts, fibroblasts, keratinocytes, and endothelial cells all exhibit galvanotactic responses to applied electric fields, with migration direction and velocity dependent on field polarity, amplitude, and frequency [24].

Approved clinical applications include direct current electrical bone growth stimulators for fracture non-unions, pulsed electromagnetic field devices for delayed fracture healing and spinal fusion, and high-voltage pulsed current devices for chronic wound management [25, 26]. Despite this regulatory recognition, clinical outcomes remain inconsistent, and the optimal stimulation parameters for each clinical indication are not established. A principal source of this inconsistency is the variability in stimulation protocols across studies and devices, and the absence of a theoretical framework for deriving optimal parameters from the biophysics of the cellular response.

The galvanotactic response of cells to electric fields is nonlinear. The migration velocity of cells along a field gradient does not increase linearly with field strength; cells exhibit a saturation response at high field strengths and a threshold response at low field strengths, with maximal migration rate in an intermediate window [27]. The time course of the response also depends on the field history: cells adapt to sustained constant fields over minutes to hours, reducing their sensitivity to a stimulus that initially drove strong migration. These nonlinearities — saturation, threshold, and adaptation — are precisely the conditions under which GPC predicts that temporally structured excitation will outperform constant current.

6.2 GPC Form Design for Regenerative Electrotherapy

The GPC form for regenerative electrotherapy addresses two nonlinear mechanisms: the galvanotactic saturation-threshold response and the cellular adaptation to sustained fields.

The galvanotactic dose-response curve is approximately sigmoidal in field amplitude: below a threshold field, negligible directed migration occurs; above a saturation field, migration velocity plateaus and cell viability may be compromised. The maximum curvature of this function occurs at the inflection point between threshold and saturation, typically in the range of 10 to 100 mV/mm for most cell types relevant to wound healing and bone regeneration [27, 28]. A GPC form that cycles between a superthreshold excitation phase near the inflection point and a subthreshold rest phase maximizes time-averaged migration velocity at a lower effective field amplitude than constant current at the same average dose.

Cellular adaptation to constant fields is addressed through temporal patterning at a frequency matched to the adaptation time constant of the target cell population. Keratinocytes in wound healing applications exhibit field adaptation time constants of 10 to 60 minutes; osteoblasts in bone healing applications adapt over 1 to 4 hours [29]. A GPC form with a modulation period matched to the adaptation time constant maintains the cell population near its maximum galvanotactic sensitivity throughout the stimulation session, preventing the desensitization that limits the effectiveness of continuous constant-field stimulation.

The GPC form for regenerative electrotherapy therefore incorporates low-frequency amplitude modulation, with modulation period calibrated to the target cell adaptation time constant, superimposed on a carrier field at the inflection point of the galvanotactic dose-response curve. This structure is derived entirely from the biophysics of the cellular response rather than from empirical parameter optimization.

7. GP Lab Reference Implementation

7.1 System Architecture

The GP Lab system provides a laboratory reference implementation of the GPC framework for neurostimulation research. GP Lab interfaces with any standard research or clinical stimulator through its output stage interface, requiring only current and voltage sensing at the stimulator output terminals. No modification of the electrode system, stimulation target, or clinical protocol is required.

GP Lab connects to the stimulator Power Source input terminals and sends I_ref(t) and V_ref(t) control signals. The Power Source applies the current to the electrode-tissue system. The electrode-tissue system connects to the Power Source only. GP Lab is the control and intelligence layer, not a power source. Feedback signals, including measured current I, electrode voltage V, and when available tissue temperature T, return from the Power Source to GP Lab. GP Lab computes the tissue impedance Z(omega), equivalent series resistance, charge balance index, and tissue stress index sigma in real time, and updates the scalar parameters A, I0, and D via the DDPC algorithm while maintaining the fixed GPC form geometry.

7.2 Process-Specific GPC Form Design for Neurostimulation

For each neurostimulation application domain, the GP Lab executes a process-specific GPC form engineered from first principles.

The GPC form for transcranial stimulation is derived from the frequency-dependent impedance model of the electrode-skin-skull-tissue stack, with the modulation frequency selected to target the reactive component of the scalp contact impedance while preserving the direct current component of the cortical field. The amplitude modulation envelope is calibrated to the curvature of the cortical excitability dose-response function at the target stimulation intensity.

The GPC form for neuromuscular stimulation is derived from the Hodgkin-Huxley time constants of the target motor nerve population and the force-frequency relationship of the recruited muscle fiber types. The inter-pulse structure is engineered to produce temporally fractionated motor unit recruitment while maintaining the average contractile force at the therapeutic target.

The GPC form for functional electrical stimulation is derived from the electrode potential model of the target implant material, with the cathodic phase trajectory engineered to maximize reversible charge injection within the corrosion-safe potential window and the anodic recharge phase shaped for complete charge balance.

The GPC form for regenerative electrotherapy is derived from the galvanotactic dose-response function of the target cell population and its adaptation time constant, with modulation parameters calibrated to maintain maximum cellular field sensitivity throughout the stimulation session.

All GPC forms preserve the time-averaged current. Each process-specific GPC form is loaded into the GP Lab as a firmware configuration and is updatable as process parameters or target specifications evolve.

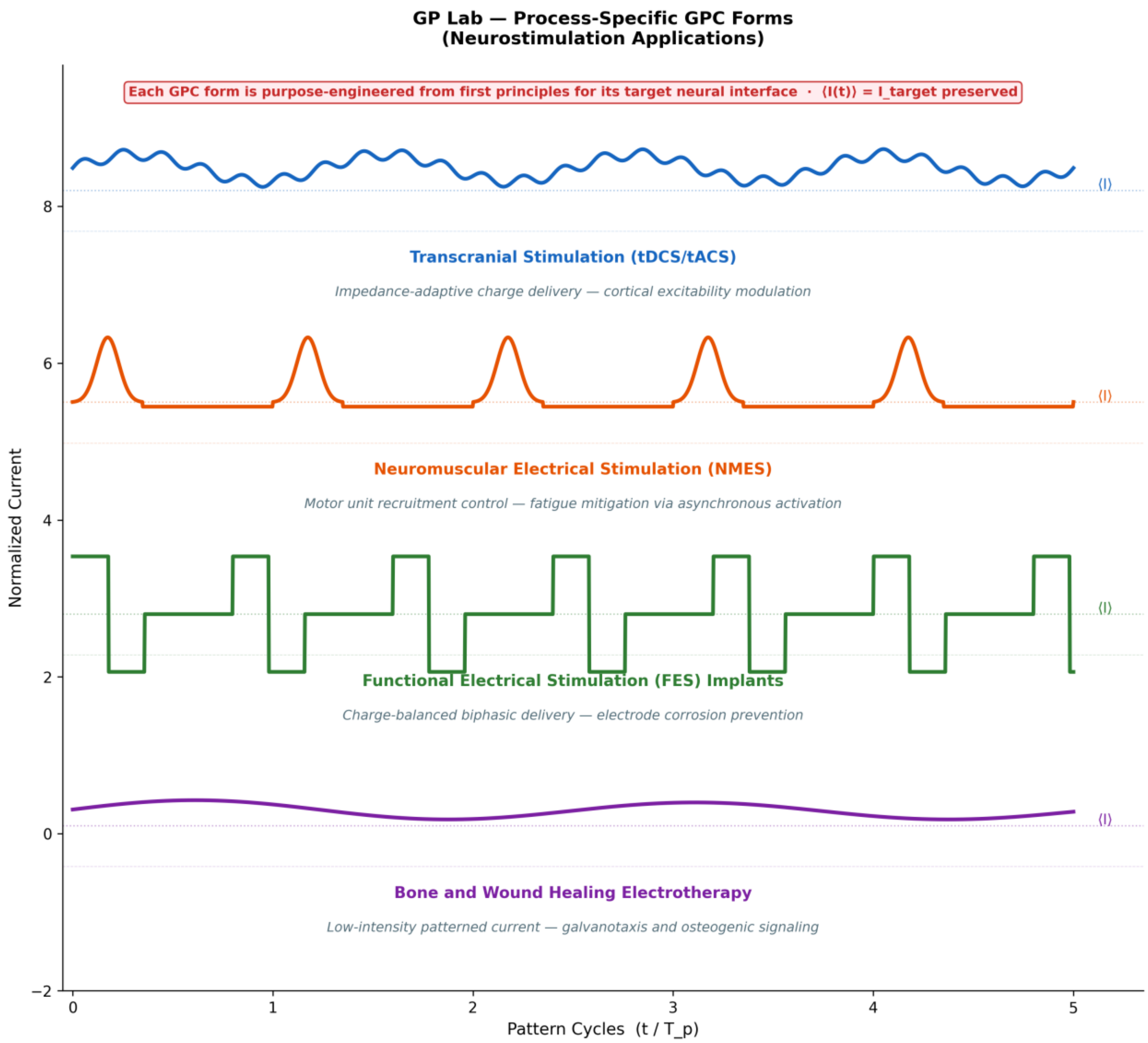

Figure 2. Process-specific GPC forms for the four neurostimulation application domains, deployed via GP Lab firmware. Each form is purpose-engineered from first principles based on the biophysics of the target tissue-electrode interaction. Time-averaged current is preserved across all forms.

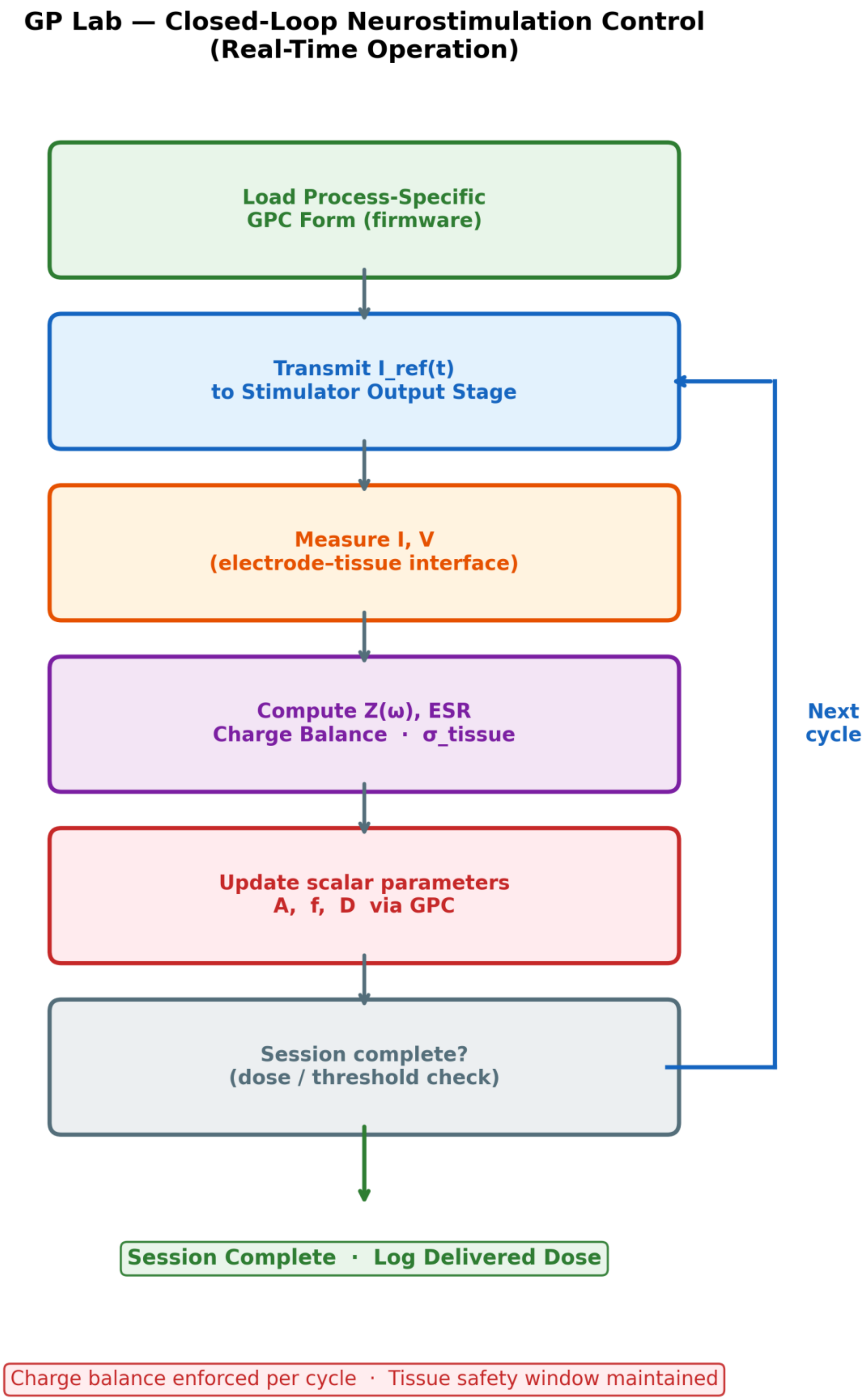
GP Lab — Closed-Loop Neurostimulation Control
(Real-Time Operation)
Load Process-Specific
GPC Form (firmware)
Transmit I_ref(t)
to Stimulator Output Stage
Measure I, V
(electrode-tissue interface)
Compute Z(ω), ESR
Charge Balance · σ_tissue
Update scalar parameters
A, f, D via GPC
Session complete?
(dose / threshold check)
Next
cycle
Session Complete · Log Delivered Dose
Charge balance enforced per cycle · Tissue safety window maintained

Figure 3. GP Lab closed-loop neurostimulation control flow. The module loads the process-specific GPC form, transmits I_ref(t) to the stimulator output stage, measures electrode-tissue feedback, computes impedance Z(omega), charge balance index, and tissue stress index sigma, and updates scalar parameters A, f, and D via the GPC algorithm. The cycle repeats until session completion criteria are met.

8. Experimental Validation Framework

The GPC framework for neurostimulation generates specific, testable predictions for each application domain. The following validation protocols are proposed for researchers wishing to test these predictions using standard laboratory equipment and the GP Lab reference implementation.

For transcranial stimulation validation: establish a direct current baseline at 1 mA for 20 minutes with standard sponge electrodes, measuring electrode impedance Z(t) and motor evoked potential amplitude at 5-minute intervals. Repeat with the process-specific GPC form at identical average current of 1 mA. Key metrics include electrode impedance rise (GPC prediction: 30 to 50% reduction relative to direct current) and motor evoked potential modulation at session end (GPC prediction: equivalent or greater than direct current at lower electrode stress).

For neuromuscular stimulation validation: establish a biphasic pulse baseline at 35 Hz with 300 microsecond pulse width over quadriceps. Measure force output and fatigue index at 5 minutes relative to initial force at identical average current. Repeat with the process-specific GPC form at identical average current. Key metrics include the fatigue index at 5 minutes (GPC prediction: improvement of 20 to 40% based on theoretical fractionation analysis [5, 6]) and force output at equal average current.

For functional electrical stimulation validation: establish a charge-balanced biphasic pulse baseline with platinum or iridium oxide electrode in saline phantom. Measure electrode impedance evolution and charge injection capacity over 1000 stimulation cycles. Repeat with the process-specific GPC form at identical average charge per cycle. Key metrics include charge injection capacity utilization (GPC prediction: 15 to 30% increase within the corrosion-safe window) and electrode potential excursion (GPC prediction: reduced maximum excursion relative to rectangular biphasic).

For regenerative electrotherapy validation: establish a direct current baseline with in vitro keratinocyte scratch assay at 50 mV/mm for 4 hours. Measure wound closure rate and migration velocity. Repeat with the process-specific GPC form at identical average field. Key metrics include wound closure rate at 4 hours (GPC prediction: 20 to 35% improvement based on galvanotactic nonlinearity analysis [27, 28, 29]) and cell viability.

9. Discussion

The application of the GPC framework to neurostimulation reveals a common theoretical structure underlying four application domains that have historically been treated as distinct disciplines: brain stimulation, rehabilitation engineering, neuroprosthetics, and regenerative medicine. In each case, the biological target is a nonlinear system, constant-current excitation does not exploit that nonlinearity, and a purpose-engineered temporal current structure derived from first principles can be expected to outperform constant current at the same average dose.

The GPC approach differs from prior work on pulsed and modulated stimulation in a critical respect. Variable frequency stimulation, burst stimulation, and other empirical departures from constant-current protocols are based on experimental observation rather than theoretical derivation. The GPC form for each application domain is not selected empirically but derived analytically from the differential equations governing the specific tissue-electrode system. This derivation provides both a theoretical prediction of the expected performance gain and a systematic basis for experimental validation.

The charge balance constraint in functional electrical stimulation deserves particular attention. The conventional approach treats charge balance as a passive property of the pulse waveform. GPC treats charge balance as an active control objective, with the recharge phase shaped in real time based on measured electrode impedance and potential. This active approach can maintain charge balance under conditions of electrode impedance drift, protein fouling, and tissue encapsulation that would cause passive balance to fail, potentially extending the safe operational lifetime of implanted devices.

The GPC framework does not require new electrode materials, new surgical techniques, or new stimulator hardware. The process-specific GPC form is delivered as a firmware configuration to any programmable current source capable of outputting the required current profile. GPC is proposed as an open framework for researchers across the neurostimulation community to adopt, test, and refine.

10. Conclusion

This paper has established the Generated Pattern Current framework as a unified theoretical basis for advancing current control across four principal neurostimulation domains: transcranial stimulation, neuromuscular stimulation, functional electrical stimulation, and regenerative electrotherapy. The common foundation is Jensen's inequality applied to the nonlinear biophysics of the tissue-electrode interface: a temporally structured current at the same average intensity as constant current will, in general, produce different and exploitable biological outcomes whenever the underlying response function is nonlinear.

For transcranial stimulation, GPC provides impedance-adaptive charge delivery that reduces electrode polarization while maintaining cortical field delivery. For neuromuscular stimulation, GPC provides temporal motor unit fractionation that extends the therapeutic window before fatigue. For functional electrical stimulation, GPC provides active charge balance management that maximizes safe charge injection within the corrosion window of implanted electrodes. For regenerative electrotherapy, GPC provides galvanotaxis-optimized patterned fields that maintain cellular field sensitivity throughout the stimulation session.

The experimental validation protocols proposed in Section 8 provide a roadmap for the research community to test these predictions using standard laboratory equipment. The patent filings (PCT/TR2025/051176 and USPTO 19/298,223) protect the core GPC architecture while the scientific framework is fully disclosed here to enable independent experimental evaluation.

Declaration of Competing Interest

Ibrahim Karakoc holds the intellectual property and commercial rights through GigaPulse Energy, Izmir, Turkey.

Data Availability Statement

No experimental data were generated or analyzed in this study. This paper presents a theoretical framework. Data sharing is not applicable.

Declaration of Artificial Intelligence and Automated Tools

During the preparation of this work, the author used AI-assisted writing tools for language editing and structural review. The author reviewed and edited all content and takes full responsibility for the integrity and accuracy of the published work.

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