

Mimic: A Personalised AI and Soft-Robotic Wearable for Facial Paralysis Rehabilitation and Functional Facial Reanimation

A detailed creative R&D and pre-clinical engineering concept paper — Version 4.0

Syed Mujtaba Zaidi · Version 4.0 — September 2026 · Research status: conceptual / pre-clinical engineering proposal; not a clinically validated medical device

Revision note (v4.0). This version responds to external review of v3.0 and makes four substantive changes: (1) the paper’s central inferential assumption — that healthy-side sEMG is informative about affected-side intention — is now argued explicitly rather than asserted; (2) a new section situates Mimic against surgical, neuromuscular-retraining and existing biofeedback/sEMG-actuator alternatives; (3) synkinesis is elevated from a risk-table entry to a dedicated design section, since it is the dominant residual presentation in the population most likely to seek this device and is the condition under which the core sensing logic is weakest; (4) the regulatory section is made classification-specific rather than generically cautious. The mathematics in the modelling sections is explicitly reframed as methodological scaffolding rather than a claim of algorithmic novelty. Author-supplied product-style renders (v3.0 Figure 9) are removed from the main text; see the closing appendix note.

Revision note (v4.1, same session). A targeted prior-art search was then run against the specific question of whether Mimic’s core concept already exists. It does: “facial pacing” (EMG-triggered facial reanimation, healthy side to paralysed side) is a named field dating back decades, and non-electrical soft-actuator equivalents — most directly an active, multi-year EPFL programme (Konstantinidi et al.) — already occupy much of the space this paper proposed as extension. Section 3 is rewritten accordingly with a direct novelty verdict, and the paper’s contribution claim is narrowed to four specific, falsifiable gaps rather than the sensing-to-actuation concept as a whole.

Abstract

Facial paralysis can affect facial expression, oral competence, communication, social interaction and quality of life. Existing rehabilitation approaches — facial exercise, neuromuscular retraining, mirror feedback and biofeedback — show heterogeneous outcomes, and the mapping between intended movement, residual neuromuscular activity and visible movement varies substantially between individuals and between clinical presentations (flaccid paralysis versus synkinesis). Mimic proposes a personalised wearable engineering platform combining surface electromyography (sEMG), computer vision, participant-specific machine learning, compliant/soft actuation and closed-loop movement sensing. A calibration stage synchronises healthy-side and affected-side biological signals with video-derived facial landmarks; a personalised temporal model estimates a target movement vector from recent signal history; an independent safety and control layer constrains that target before any actuation is permitted. The physical demonstrator is deliberately limited to an artificial facial model and an artificial eyebrow, allowing displacement, latency, tracking error, force and failure modes to be characterised without human actuation.

This version separates the paper's two kinds of claims: an architectural claim — that prediction and actuation should be separated by an independent safety layer, defensible on engineering-safety grounds alone — and an empirical claim — that personalised, multimodal sEMG-to-movement inference is tractable, which is unproven and treated here as falsifiable. The paper situates Mimic against surgical, neuromuscular and existing sEMG-actuator alternatives, and treats synkinesis as a first-class design constraint rather than a residual risk. No claim of clinical efficacy, conformity or regulatory approval is made.

Keywords

facial paralysis; Bell's palsy; synkinesis; sEMG; electromyography; computer vision; personalised machine learning; soft robotics; assistive technology; facial reanimation; closed-loop control; speech and language therapy; AIaMD; medical device regulation

1. Introduction

Facial movement is a coordinated neuromuscular process in which small changes in muscle activation produce meaningful changes in expression, oral competence and communication. Facial nerve dysfunction therefore has consequences that extend beyond appearance. The engineering challenge Mimic addresses is the mismatch between an individual's intention to perform a facial action and the reduced, delayed or asymmetric movement that may be visible on the affected side.

The central proposition is not that a single generic facial model can reconstruct a patient's movement. Mimic treats the face as a participant-specific system that must be calibrated. The research programme therefore separates (i) sensing and calibration, (ii) personalised inference, (iii) bounded control and (iv) physical assistance. This separation matters because an AI prediction should never be treated as an unrestricted actuator command — a principle argued on engineering-safety grounds independent of whether the underlying prediction problem turns out to be tractable (Section 4 addresses tractability directly).

The proposed development pathway begins entirely outside the human body: camera-based facial measurement, signal-processing experiments, artificial-face simulation and an artificial-eyebrow bench prototype. Human feasibility is a later research stage, conditional on engineering verification, risk management, ethics review and determination of the applicable regulatory pathway.

2. Personal Motivation and Research Rationale

The research is motivated in part by the author's lived experience of recurrent Bell's palsy and multiple episodes of facial paralysis over approximately two decades. This experience informs the practical research question: whether technology could make the relationship between attempted movement, measurable neuromuscular activity and rehabilitation assistance more personalised and measurable.

The personal experience is presented as research motivation, not clinical evidence. Mimic is not proposed as a replacement for neurologists, facial rehabilitation specialists, physiotherapists, reconstructive surgeons or speech and language therapists. Its intended research role is to

investigate whether sensing, modelling and compliant assistance can augment clinician-directed rehabilitation.

3. Prior Art, Novelty Assessment and Competitive Landscape

This section was substantially rewritten following a targeted literature search prompted by external review, and its conclusion should be read as the paper’s headline finding, not a footnote. The central architectural idea — measuring activity on the relatively healthy side of the face and using it to drive assistance on the paralysed side — is not new. It is a named, decades-old research field usually called **facial pacing**, and the specific combination of surface EMG plus a soft or compliant actuator (rather than the field’s original electrical-stimulation approach) is the subject of an active, multi-year research programme, not an unclaimed gap. This section lays out that landscape directly, then states precisely what, if anything, remains for Mimic to contribute.

Search methodology note. The assessment below is based on a targeted web search conducted in September 2026 — general search engines and open bibliographic sources, checked against the specific question of whether Mimic’s sensing-to-actuation concept already exists. It is not a systematic database review and not a formal patent-landscape search. That is sufficient to overturn a naive claim of novelty, which is this section’s purpose, but it is not sufficient to certify that the four gaps identified below are exhaustive or clear of prior art. Anyone relying on this section for a funding application, a patent filing, or a publication’s novelty statement should commission an independent systematic review first; this section should be read as a provisional, falsifiable position, not a completed clearance.

Facial pacing (EMG-triggered functional electrical stimulation). The concept of measuring EMG on the healthy side and using it to trigger stimulation of the paralysed side was introduced several decades ago and has been studied continuously since: feasibility surveys of surface EMG for this purpose [17], device-level studies with real-time FPGA processing [18], waveform and comfort studies [19], a completed human clinical trial (ClinicalTrials.gov NCT03496025) [20], and closed-loop implantable EMG-driven stimulation research going back to rodent models [21]. The field’s own name for Mimic’s core sensing idea — “measure the healthy side, drive the paralysed side” — already exists, and the paper’s earlier framing (Sections 1–2, v3.0) did not engage with it.

Non-invasive soft/compliant actuator programmes (the closer comparator). Because Mimic proposes mechanical rather than electrical actuation, the more directly comparable prior art is soft-actuator facial reanimation research, which is itself an established, active area rather than a single precedent:

- **Kozaki, Suzuki and colleagues** (2017–2018) developed a soft wearable “Eyelid Gating Mechanism” that supports eyelid closure on the paralysed side, driven by voluntary eyelid closure detected on the healthy side, and reported a clinical study with facial paralysis patients [22]. This is a fielded, clinically tested example of exactly Mimic’s proposed sensing-to-actuation loop, for one movement channel, using mechanical rather than sEMG sensing.
- **Walker, Firouzeh, Robertson, Mengüç and Paik** (EPFL, 2022) built a 3D-printed actuator–sensor module with closed-loop control that translates smiling signals from

the healthy side directly into actuation of the paralysed side, explicitly for augmented physiotherapy [23].

- **Konstantinidi and colleagues** (EPFL, 2022–2026) have run a sustained, multi-paper programme — not a single conference paper as the v3.0 manuscript implied — developing dielectric-elastomer-actuator (DEA) facial neuroprostheses driven by a non-invasive myoelectric interface synchronised to healthy-muscle activity, including dedicated work on the actuator’s dynamic modelling and control [9, 24, 25]. This programme already occupies much of the space the v3.0 manuscript proposed as an extension of a single 2024 result: real-time sEMG-driven soft actuation with ongoing control-system development.
- **Eyelid-specific closed-loop devices** continue to be published, including EMG-triggered contralateral stimulation with real-time artifact blanking, magnetic actuator blink restoration, and “Bionic Blink” real-time closure systems [26], alongside a 2026 scoping review of implantable and prosthetic dynamic facial reanimation devices that surveys this landscape comprehensively [27].

Surgical and retraining alternatives. Cross-face nerve grafting, masseteric-to-facial nerve transfer and free functional muscle transfer restore movement biologically rather than mechanically, at the cost of surgical risk and donor-site effects; clinician-led facial retraining, mirror feedback and sEMG biofeedback [1–3] remain the non-invasive standard of care but provide no physical assistance during the movement itself. Neither category is displaced by Mimic, and neither is where Mimic’s actual competitors sit.

Consumer facial-EMG and expression-recognition wearables (e.g. patented EMG earpiece/glasses controllers [28, 29], facial-EMG expression-recognition research [30]) establish that wearable facial-EMG sensing and gesture classification are mature, commercially deployed technologies in their own right — further reducing any claim that facial-sEMG sensing per se is a novel contribution.

Novelty verdict. Judged against this landscape, the honest position is: (1) the core sensing-to-actuation loop is not novel and should not be presented as such; (2) sEMG-driven soft/compliant actuation specifically is an active area with a multi-year incumbent research programme (Konstantinidi et al.) whose trajectory overlaps substantially with Mimic’s proposed extensions; (3) the closest genuinely open gaps this paper can identify in the surveyed literature are — an explicit, independently-testable safety/control layer stated as a design principle rather than implicit in the control code; participant-specific temporal machine-learning models with per-session recalibration and an explicit confidence/quality-gating state, in place of fixed thresholds or simpler classifiers; simultaneous multimodal calibration combining bilateral sEMG, video-derived landmarks and affected-side movement sensing, where the reviewed systems are predominantly single-modality; and synkinesis-aware detection treated as a first-class, separately-evaluated design requirement (Section 15) rather than an unaddressed limitation. None of these four gaps is confirmed absent from the field by this search alone — a full systematic review and, ideally, a patent-landscape search are recommended before any claim of novelty is used in a funding or publication context — but they are the specific, falsifiable claims this paper is prepared to stand behind, in place of the broader and unsupportable claim that the sensing-to-actuation concept itself is new.

Why now, and why AI/data science specifically. A fair objection to the four gaps above is: why could this not have been done a decade ago? The honest answer is an enabling-technology one rather than a conceptual one. The foundational facial-pacing literature predates practical participant-specific machine learning entirely — it used fixed thresholds and simple triggering logic, not learned temporal models. The incumbent soft-actuator programme (Konstantinidi et al.) is itself recent, but its published control work is physics-based dynamic modelling of the actuator (a DEA plant model), not a data-driven, continuously-recalibrated personalisation pipeline fitted to an individual participant’s signals. What has changed since both of those research lines were established is that temporal deep-learning frameworks, transfer-learning and few-shot personalisation techniques, and lightweight MLOps tooling for versioning and monitoring a continuously-updated model are now mature, well-documented and inexpensive to deploy on commodity hardware — they were either immature or unavailable when the original facial-pacing work was done, and they remain only partially exploited in the current soft-actuator literature. This paper’s proposed contribution is therefore not “apply AI to facial pacing” as an abstract idea — that framing would repeat the mistake Section 3 was rewritten to avoid — but the specific, falsifiable claim that a modern, participant-specific, quality-gated data science pipeline (Section 10, and the toolkit in Section 18) can be built and evaluated in a way that was not practical when the comparator literature was written.

4. Scientific Foundation and the Central Inferential Assumption

Systematic reviews of facial exercise therapy report evidence of potential benefit alongside substantial heterogeneity in study design and intervention [1–3]. Other literature documents speech, communication and oral-motor consequences of peripheral facial palsy [4–6]. These findings support treating facial movement as a functional system rather than only an aesthetic outcome, and they motivate measurement, but they do not by themselves establish that Mimic’s sensing strategy will work.

The load-bearing assumption stated explicitly. Mimic’s architecture depends on one inferential step that receives comparatively little scrutiny in the wider literature it draws on: that surface EMG recorded from the relatively *healthy* side of the face is informative about the patient’s *intended* movement on the affected side. This is not the same claim as “healthy-side EMG reflects healthy-side movement,” which is well supported. The healthy side is not doing anything different from what it would do in an unaffected face — it is simply the side where efferent signals still reach the muscle. The inferential leap Mimic requires is from *central motor intention* (which cannot be measured directly) to *healthy-side muscle activation* (which can), used as a proxy for what the affected side is being asked, but failing, to do.

This proxy relationship is plausible for **bilaterally symmetric, co-activated movements** — a voluntary smile, a brow raise, forced eye closure — where cortical drive to homologous muscle groups on both sides is normally near-simultaneous, and where the Konstantinidi precedent [9] demonstrates feasibility for one such channel (upper-face/brow). It is considerably less plausible for **movements that are not naturally symmetric or co-activated**, such as many oral-motor and speech-articulation gestures (Section 16), where healthy-side and affected-side muscles may not share a common intended target even in an unimpaired system, or where unilateral articulatory adjustments are a normal compensatory strategy rather than a signal of impaired intention.

The research programme therefore treats generalisation beyond symmetric upper-face movement as an open empirical question rather than an assumption, and RQ1–RQ3 (Section 6) are written to test the proxy relationship directly — by comparing prediction accuracy for symmetric movements (where the proxy is expected to hold) against asymmetric or oral-motor movements (where it is not) — rather than only measuring aggregate prediction error across an undifferentiated movement set, which could mask exactly this failure mode.

Why this reframing matters. A paper that states its predictive claim as “personalised sEMG predicts intended facial movement” invites the objection that the mechanism is unexplained. Stating it as “healthy-side activation is a testable proxy for intention, expected to hold for symmetric co-activated movements and expected to degrade for asymmetric or synkinetic ones” turns that objection into the paper’s own falsification criterion, and gives Phase 5 (Section 17) a specific negative result to look for, rather than only a positive one to hope for.

5. From FaceMirror to Mimic

The earliest concept was framed as FaceMirror: observe movement on the relatively unaffected side and reproduce a corresponding movement on the affected side. The concept evolved into Mimic because the research problem is broader than visual mirroring, and — per Section 4 — because mirroring is a proxy expected to hold unevenly across movement types. The system is conceived as a closed-loop assistive platform: Sense → Predict → Assist → Measure → Correct.

The loop closes through measured movement, not around the safety layer

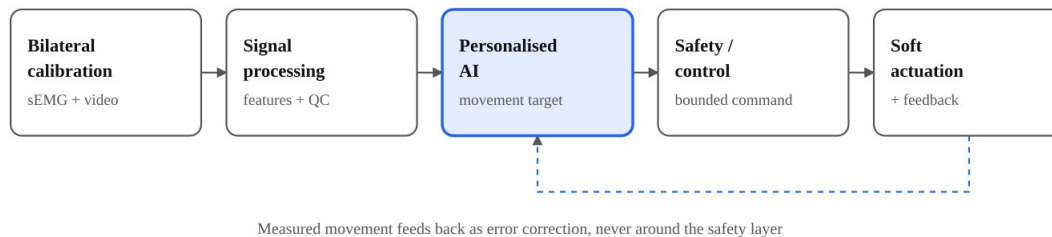


Figure E. Graphical abstract of the Mimic closed loop, carried forward and updated from the v3.0 manuscript (Appendix).

During calibration, the camera provides an external ground-truth modality for facial geometry and movement. Bilateral sEMG provides information about muscle activation, while affected-side movement sensing provides a direct measure of what the impaired side actually does. The model can therefore learn relationships among attempted movement, biological signals and observed movement, rather than relying solely on image symmetry.

A major design principle is to distinguish a training/calibration architecture from an everyday-use architecture. The former may be multimodal and camera-dependent; the latter may eventually use fewer sensors. Whether a one-sided or camera-free wearable can achieve

adequate inference remains an empirical research question (Section 14), and — following Section 4 — is expected to be movement-dependent rather than uniformly true or false.

6. Research Questions and Hypotheses

RQ1. Can participant-specific facial sEMG features predict selected intended facial movement variables with useful temporal accuracy, and does predictive accuracy differ systematically between symmetric/co-activated movements and asymmetric/oral-motor movements?

RQ2. Does synchronised video and bilateral movement sensing improve calibration relative to sEMG-only models?

RQ3. Do participant-specific models generalise better across sessions than a population-level model?

RQ4. Can a bounded controller translate predicted movement targets into reproducible motion on an artificial facial model?

RQ5. Does movement feedback reduce tracking error and false activation relative to open-loop actuation?

RQ6. Can camera dependence be reduced after sufficient multimodal calibration, and does this vary by movement type?

RQ7. Can selected oral-motor tasks relevant to speech and language therapy be measured and, subject to validation, physically assisted?

RQ8 (new). In participants presenting with synkinesis rather than flaccid paralysis, does the healthy-side-to-intention proxy (Section 4) degrade in a measurable, characterisable way, and can the system detect — from signal features alone — that it is operating in a synkinetic rather than flaccid regime, so that it can withhold assistance rather than act on a corrupted proxy? (See Section 15.)

- **H1** — participant-specific sEMG contains predictive information about selected intended facial movements, with accuracy expected to be higher for symmetric/co-activated movements than for asymmetric or oral-motor movements.
- **H2** — multimodal calibration improves target estimation relative to single-modality calibration.
- **H3** — participant-specific temporal models reduce prediction error relative to simple population models.
- **H4** — a bounded actuator can reproduce selected movement trajectories on an artificial-face bench model.
- **H5** — closed-loop feedback reduces tracking error and unsafe/false activation compared with open-loop assistance.
- **H6** — the amount of camera information required for operation can potentially be reduced after calibration for symmetric movement channels; complete camera removal, or removal for asymmetric channels, is not assumed.
- **H7** — selected speech-related facial tasks can be represented as measurable movement targets suitable for future clinician-directed assistance.

- **H8 (new)** — synkinesis produces a detectable signature in sEMG feature space (e.g. co-contraction patterns absent in flaccid paralysis) that a quality-gating classifier can use to distinguish “reliable proxy” from “unreliable proxy” states, independent of whether movement prediction itself succeeds in either state.

7. System Architecture

Mimic is organised into five logical layers: sensing, signal processing, personalised inference, safety/control and actuation/feedback. This architecture allows each layer to be tested independently and reduces the risk that an opaque AI model becomes the sole safety-critical decision mechanism — an architectural claim defensible on engineering-safety grounds regardless of how well the inference layer ultimately performs (Section 4).

Sensing comprises surface electrodes on the relatively healthy side during calibration, optional affected-side sEMG where measurable, affected-side displacement/strain sensing, and a camera used initially for facial landmarks and visual ground truth. An IMU may be investigated later for head-motion compensation.

Signal processing converts raw sEMG into features suitable for modelling: timestamping, signal-quality checks, filtering, rectification, envelope/RMS extraction, participant-specific normalisation and temporal windowing.

The inference layer receives a recent sequence of processed features and estimates a movement target, together with a per-channel confidence/quality state (Section 15 extends this to a synkinesis-specific reliability flag). The output is a normalised movement vector — eyebrow elevation, eyelid aperture, mouth width, lip rounding or cheek displacement — rather than a raw servo angle.

The safety/controller layer receives the AI target but remains architecturally independent of the AI model. It enforces range, velocity, acceleration and force limits; rejects invalid or low-confidence states; monitors sensor and communication health; and provides a fail-safe disable state.

The actuation layer converts a permitted target into a bounded physical action. Early work uses a servo/tendon mechanism or another low-energy compliant actuator on an artificial face. Movement sensing closes the loop by providing the measured output required to calculate tracking error.

The AI inference layer is separated from the safety/control layer

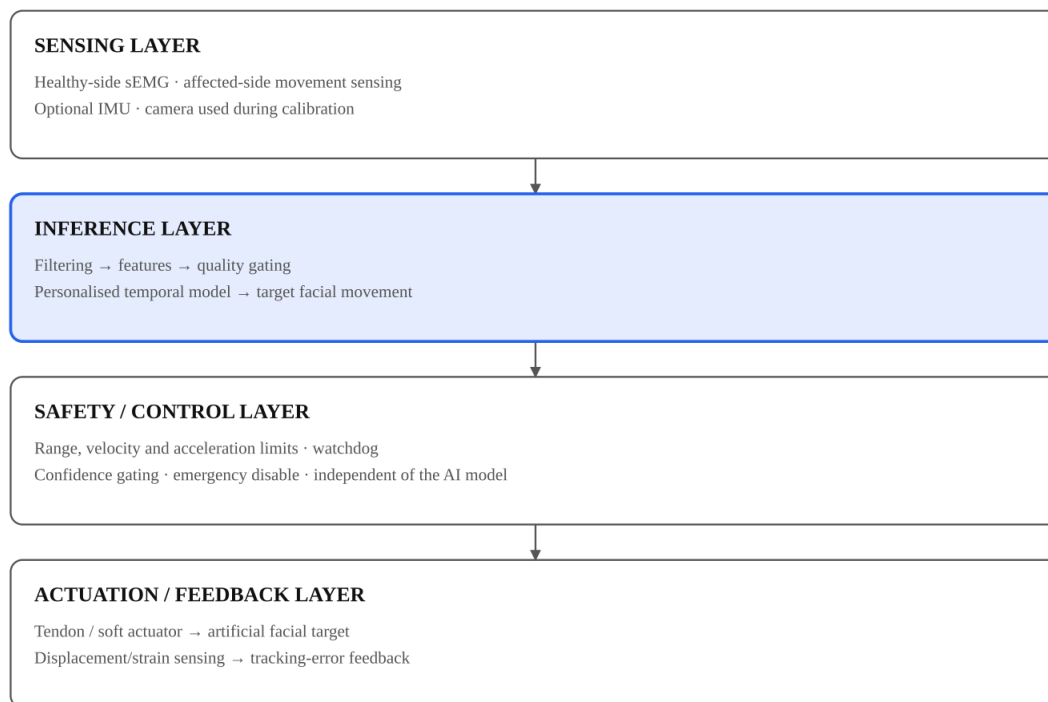


Figure A. Mimic technical architecture — four layers.

8. Facial Coordinate System and Computer Vision

The visual subsystem is primarily a calibration and measurement reference. Facial landmarks are expressed relative to a participant-specific coordinate frame rather than a fixed image coordinate, reducing sensitivity to camera translation, head position and framing.

A baseline frame is acquired during a neutral expression. For each landmark $p_i(t)$, movement is represented relative to the baseline $p_i(0)$. Where bilateral landmarks exist, a reflection or correspondence transform is estimated around the participant-specific facial midline.

Useful initial landmarks include inner and outer eye points, eyebrow points, nose reference points and left/right mouth corners. The system records raw landmarks, transformed landmarks, movement vectors and quality indicators so that later researchers can reproduce the feature engineering.

Landmarks sit relative to a participant-specific midline, not image coordinates

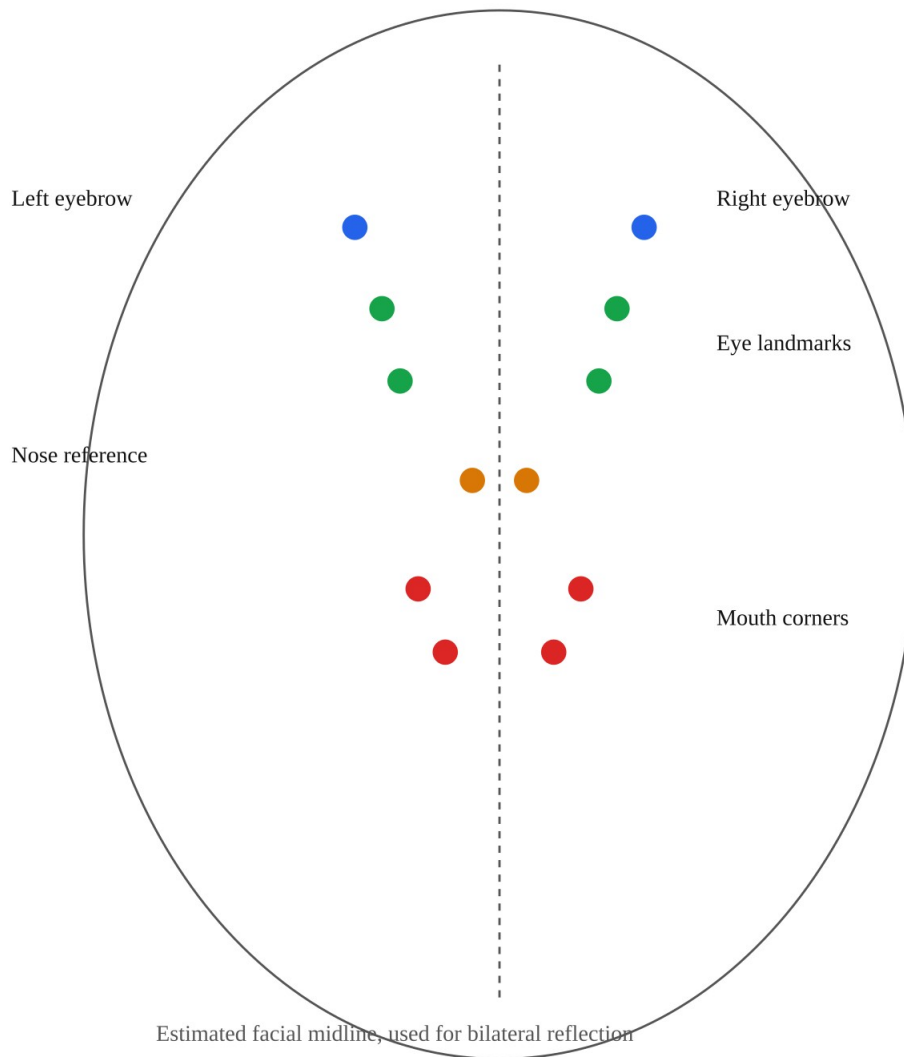


Figure F. Facial coordinate system used for calibration, carried forward and updated from the v3.0 manuscript (Appendix).

The initial dataset contains repeated examples of neutral expression, eyebrow elevation, frown, eye closure/opening, smile, large smile, lip rounding, pucker, 'ee', 'ah', 'oo', laughter and selected functional facial gestures — explicitly including both symmetric movements (expected to test the core proxy relationship favourably) and asymmetric/oral-motor movements (expected to stress it, per Section 4). Repetitions are distributed across sessions to test generalisation rather than allowing random frame-level splitting to create artificially optimistic performance.

9. Surface EMG Acquisition and Signal Processing

Surface electromyography provides a non-invasive measurement of electrical activity associated with skeletal muscle activation. Facial sEMG is technically challenging because

muscles are small and closely spaced, making electrode placement, crosstalk, skin impedance, movement artefact and inter-session variation important sources of uncertainty.

The proposed pipeline is: raw signal → timestamp synchronisation → band-pass filtering → mains-interference rejection where required → artefact detection → rectification → envelope/RMS extraction → participant-specific normalisation → temporal feature construction → model inference.

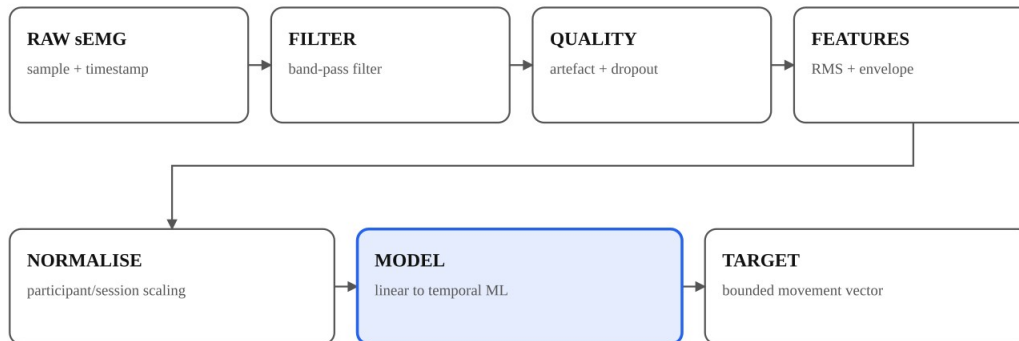
An experimental starting point is a configurable acquisition rate around 1 kHz, with filtering parameters selected and justified for the chosen acquisition hardware and facial muscle signals. These are engineering starting values, not clinical requirements. Every acquisition configuration is logged with electrode placement, session date, channel identity, gain and sampling settings.

For a window containing N samples x_i , the root-mean-square amplitude is:

$$\mathrm{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N x_i^2}$$

Normalisation is participant-specific: a simple approach divides by a reference activation statistic established during calibration; more sophisticated approaches use robust scaling across sessions. The chosen normalisation is treated as part of the model pipeline and frozen when evaluating held-out data.

Each stage narrows raw sEMG to a bounded movement target



Quality gating can reject a window before it ever reaches the model (Section 15).

Figure G. sEMG acquisition and processing pipeline, carried forward and updated from the v3.0 manuscript (Appendix).

Temporal modelling matters because facial movement is dynamic: a model receives a sequence rather than a single instantaneous feature vector. Candidate models progress from linear regression to multilayer perceptrons, temporal convolutional networks or recurrent architectures only after the simpler baseline has been evaluated.

10. Personalised Model: Formalisation and a Note on Novelty

The formalism below is standard signal-processing and control notation, included so the pipeline is unambiguous and reproducible — it is presented as methodological scaffolding, not

as a claim that any individual mathematical component is novel. As argued in Section 3, Mimic’s claim to contribution is architectural (the separation of prediction from actuation) and experimental (testing the proxy relationship of Section 4 across movement types), not algorithmic.

Let $X_t \in \mathbb{R}^n$ denote the processed feature vector at time t and $Y_t \in \mathbb{R}^m$ the target facial movement vector. The primary temporal model is:

$$\hat{Y}_t = f_{\theta}(X_{t-K+1:t})$$

where K is the temporal window length and θ the learned parameters. The first benchmark is a multivariate linear model:

$$\hat{Y}_t = W\bar{X}_t + b$$

where $\bar{X}_t$ is the feature vector or window summary, W the learned weight matrix and b the intercept vector. This baseline is deliberately simple and provides a reference against which more complex models must demonstrate measurable benefit — a discipline particularly important here, since a complex model can appear to outperform a simple one on aggregate error while doing so entirely on the symmetric-movement subset of the data and no better (or worse) on the asymmetric subset (Section 4). Per-movement-category error breakdown is therefore a required reporting element, not an optional one.

For an actuator channel j , the movement tracking error is:

$$e_j(t) = Y_{d,j}(t) - Y_{m,j}(t)$$

where $Y_{d,j}$ is the desired bounded movement target and $Y_{m,j}$ the measured movement. A future constrained controller may optimise:

$$J = \sum_j [w_e e_j(t)^2 + w_v v_j(t)^2 + w_a a_j(t)^2] + \lambda U(t)$$

subject to predefined displacement, velocity, acceleration and force constraints, where $U(t)$ represents control effort or another bounded-use penalty. This formulation is a research model, not a validated clinical control law.

The architecture explicitly prevents the AI from bypassing these constraints: in software terms, the model returns a target object, and a separate controller validates, clips, rejects or transforms that target before an actuator command is generated.

11. Feature Engineering and Model Development

The first modelling dataset retains both raw and processed signals. Derived features may include RMS amplitude, moving-average envelope, waveform length, zero-crossing counts where meaningful, signal variance, inter-channel ratios and temporal derivatives. The initial study avoids uncontrolled feature proliferation.

Model evaluation separates training, validation and test sessions wherever feasible. Frame-level random splitting is insufficient when adjacent frames originate from the same movement episode, because it can leak temporal information across partitions; a stronger protocol is

leave-one-session-out or grouped cross-validation, stratified by movement category (symmetric vs. asymmetric/oral-motor, and — where present — flaccid vs. synkinetic presentation; Section 15) so that aggregate metrics cannot mask category-specific failure.

The model produces a confidence or quality state alongside the movement estimate. If signal quality falls below a predefined threshold, the system enters a no-assistance or hold-safe state rather than extrapolating aggressively from corrupted input.

A model registry records dataset version, preprocessing configuration, feature definitions, model architecture, training parameters, software version and evaluation results, supporting reproducibility and future regulatory traceability.

12. Soft-Robotic Actuation

The eyebrow is the first physical target because its movement can be represented with a relatively small number of degrees of freedom and visually assessed on an artificial face. The first demonstrator does not actuate a human face.

A low-cost servo can pull a tendon or flexible cable attached to an artificial eyebrow. This deliberately simple mechanism allows the research team to characterise commanded displacement, mechanical hysteresis, latency, repeatability and failure behaviour before considering more complex soft actuators.

The first demonstrator moves an artificial eyebrow, not a human face

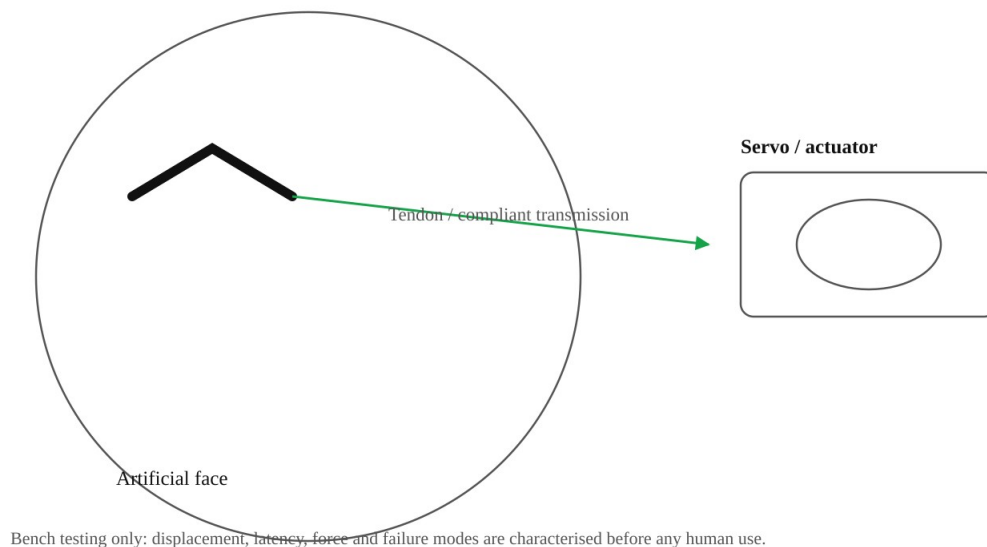


Figure H. First physical prototype concept — artificial eyebrow on an artificial face, carried forward and updated from the v3.0 manuscript (Appendix).

Later prototypes can investigate compliant tendon transmissions, pneumatic artificial muscles, dielectric-elastomer actuators or shape-memory systems. Selection is based on displacement, force, compliance, response time, power demand, heat generation, packaging, control complexity and failure mode.

The mechanical design uses a physical travel limit and an independent software limit. For human-facing prototypes, force and displacement limits require formal safety justification rather than being chosen because they appear comfortable.

13. Closed-Loop Control and Safety

The proposed closed-loop chain is: EMG → AI target → safety controller → actuator → movement sensor → tracking error → controller. The feedback signal is essential because the system must distinguish what it intended to produce from what the mechanism actually produced.

A watchdog monitors acquisition status, signal quality, communications, actuator state and controller timing. Failure conditions cause the actuator to stop or move to a defined safe state. Fault-injection tests deliberately introduce sensor dropout, communication interruption, implausible measurements and model-output errors to confirm that the safety layer behaves predictably.

The AI does not directly control unrestricted motor angle. Instead, the control interface exposes bounded target variables. A simplified control sequence is: validate target → apply range constraint → apply rate constraint → check force/position feedback → permit command → monitor response → disable on fault.

Closed-loop performance is assessed using tracking error, overshoot, settling time, false activation rate, command latency and repeatability, first obtained on the artificial-face bench model.

Measured movement closes the loop and reveals tracking error

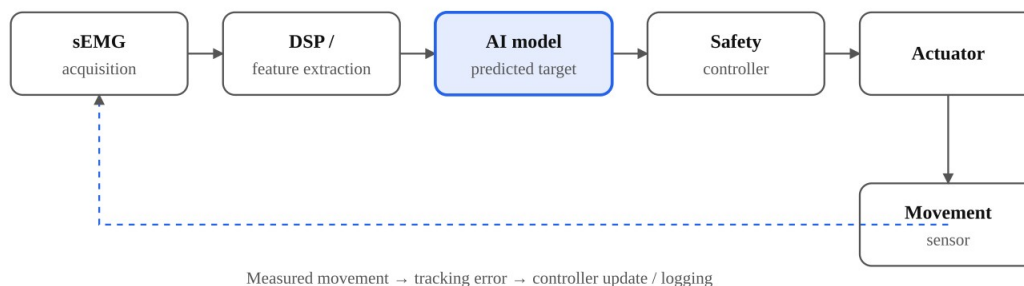


Figure B. Closed-loop control architecture.

14. Potential One-Sided Wearable Architecture

One longer-term ambition is a predominantly one-sided wearable that does not require a visible camera during daily use. The proposed calibration architecture uses the relatively healthy side as a source of sEMG information, while video and affected-side movement sensing provide reference labels.

A later system might attempt to infer intention using residual affected-side sEMG, local mechanosensing, strain sensors, another physiological signal or a reduced set of sensors. However, the affected side may not contain enough independent information for reliable

inference, particularly where denervation or synkinesis is present (Section 15). One-sided operation is a hypothesis to be tested, not a promised endpoint, and — per Section 4 — is expected to be substantially more achievable for symmetric channels than for asymmetric or oral-motor ones.

The practical research sequence is to establish whether prediction remains accurate as modalities are progressively removed: bilateral sEMG + video → sEMG + movement feedback → reduced sensing → candidate wearable configuration.

15. Synkinesis: A Distinct Design Problem

Synkinesis — involuntary co-contraction of facial muscles during an unrelated voluntary movement (e.g. the eye narrowing during a smile) — is common after facial nerve injury and is, for a substantial fraction of the population this device would target, the dominant residual presentation rather than a secondary complication. It is treated in v3.0 of this paper as one line in a risk table; that placement understates its significance and is corrected here.

Why synkinesis is the hard case, not a risk-table entry. The core sensing logic (Sections 4–6) depends on treating healthy-side activation as a proxy for intended affected-side movement, and on treating affected-side sEMG or movement, where measurable, as a signal of what the impaired side is actually doing. Synkinesis breaks both assumptions simultaneously: (a) the affected side may already be moving — involuntarily — in response to a command unrelated to the one the system is trying to assist, so affected-side signals can no longer be read as a clean error term; and (b) motor intention on the healthy side may itself trigger unwanted co-contraction on the affected side, meaning the very act of attempting the calibration movement can produce affected-side activity that looks like a response but is not the response the system is trying to elicit or assist.

This matters more, not less, for the population most likely to want the device: many Bell’s palsy patients whose paralysis persists long enough to become a research and rehabilitation priority have done so precisely because of incomplete recovery, and synkinesis is a common feature of incomplete recovery. A system validated only on early-stage flaccid paralysis participants risks being least reliable for the population it is ultimately meant to serve.

Design implications.

- Participant screening and stratification (Sunnybrook or equivalent facial grading, with explicit synkinesis sub-scoring [8]) is a required part of the calibration protocol from Phase 3 onward, not an optional refinement.
- RQ8/H8 (Section 6) make synkinesis detection itself a primary research output: the system should be evaluated on its ability to recognise when it is in a synkinetic regime and to withhold or down-weight assistance, not only on its ability to predict movement within that regime.
- The safety/control layer’s quality-gating (Sections 7, 11) should treat “co-contraction detected on a channel not intended by the current task” as a distinct low-confidence state, separate from generic signal-quality degradation, because its cause and appropriate response differ (hold-safe rather than re-filter).

- Evaluation protocols (Sections 6, 11, 20) must report accuracy separately for flaccid and synkinetic participant subgroups; a pooled accuracy figure across both is not an adequate description of system performance and should not be reported as a single headline number.
- The paper does not claim a solution to synkinetic inference. It claims that failing to solve it should present as a *known, detected, safely-handled* limitation rather than as silent degraded performance — which is itself a testable design requirement (SR-13, Section 20).

16. Potential Speech and Language Therapy Application

Facial nerve dysfunction can influence oral competence and aspects of speech communication. A future Mimic-SLT programme could investigate measurable movement targets including lip closure, lip spreading, lip rounding, oral aperture and selected bilabial tasks.

As Section 4 notes, many of these are precisely the asymmetric, non-mirrorable movement class where the healthy-side proxy is weakest, so this application should be read as the research programme's hardest test case for RQ1, not as a straightforward extension of the eyebrow/brow-raise work. The system would not diagnose speech disorders or independently generate speech; it could, subject to validation, provide measurement and, after appropriate clinician oversight, controlled physical assistance under a speech and language therapist's protocol.

A future study could synchronise facial movement measures with selected speech tasks and acoustic or linguistic annotations, to investigate whether improved lip movement corresponds to measurable functional changes. Any clinical outcome claim would require a properly designed clinical study and validated outcome measures.

17. Experimental Methodology and Development Phases

Phase 0 — computational environment and governance. Python environment, data structure, version control, consent/data-management framework for any future research data, and a reproducible experiment log.

Phase 1 — computer vision. Facial landmark acquisition, baseline estimation, participant-specific coordinate normalisation and movement feature extraction.

Phase 2 — symmetry model. Compare left/right facial landmark trajectories and investigate whether a reflected healthy-side trajectory can act as a useful target representation, explicitly separating symmetric from asymmetric movement classes.

Phase 3 — participant calibration. Collect repeated movement trials, quantify within- and between-session variability, and record facial-grading/synkinesis-subscore data (Section 15) for every participant.

Phase 4 — synchronised sEMG + video. Acquire bilateral or targeted facial sEMG alongside video and movement references; align timestamps and create a labelled dataset stratified by movement category and, where present, flaccid/synkinetic status.

Phase 5 — model comparison. Evaluate linear regression, static nonlinear models and temporal models using grouped, stratified session-based validation; report accuracy separately by movement category and clinical presentation, per Sections 4 and 15 — not only as a pooled figure.

Phase 6 — artificial eyebrow. Implement servo/tendon actuation on an artificial face and test target tracking independently of human use.

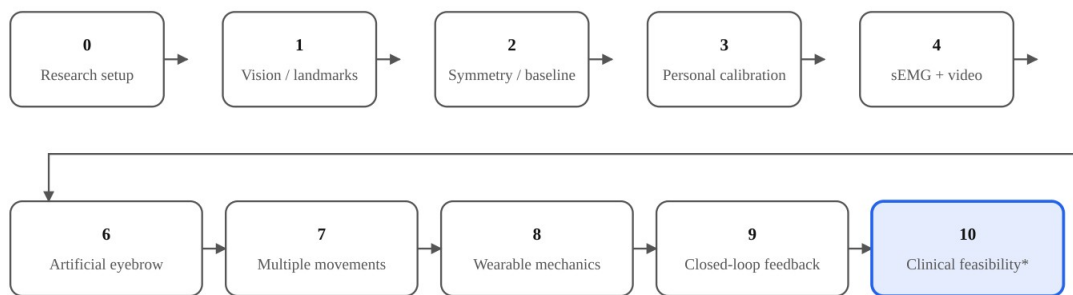
Phase 7 — multiple movements. Extend the bench system to additional facial movement degrees of freedom, deliberately including at least one asymmetric channel to test generalisation beyond brow-raise.

Phase 8 — wearable mechanics. Attachment, flexible materials, routing, cable/tendon geometry, packaging and sensor placement.

Phase 9 — closed-loop feedback. Integrate movement sensing, tracking error, controller limits, watchdogs and fault injection.

Phase 10 — clinically supervised feasibility. Only after engineering verification, formal risk assessment, ethics review and determination of the applicable regulatory pathway.

Ten phases, gated by verification and ethics review before any human use



*Only after engineering verification, risk assessment, ethics review and applicable regulatory determination.

Figure C. Progressive development pathway — Phases 0-10.

18. Prototype Hardware and Software Specification

- **Laptop/PC** — initial AI training, computer vision, data management and experiment logging.
- **USB camera** — calibration and visual ground truth during early phases; not assumed to be part of the final wearable.
- **sEMG electrodes** — participant-specific facial muscle measurements during research calibration.
- **EMG acquisition hardware** — analogue front-end and digitisation; candidate research platforms may include MyoWare-class modules or OpenBCI-class acquisition systems, selected after channel, sampling and interface requirements are defined.
- **ESP32-class microcontroller** — embedded sensor/controller layer for prototype actuation and feedback; not intended to replace the laptop/PC for model development.

- **Servo or compliant actuator** — first artificial-eyebrow actuation mechanism.
- **Tendon/cable and guide** — mechanical transmission from actuator to artificial eyebrow.
- **Strain/displacement sensor** — bench movement feedback.
- **Optional IMU** — head-motion or wearable-motion compensation in later phases.
- **Battery and protection circuitry** — later wearable phase only, after electrical architecture is defined.
- **TPU/flexible enclosure and attachment system** — later wearable phase; material choice requires biological-safety consideration before skin-contact testing.
- **Python software stack** — OpenCV, MediaPipe or equivalent landmarking, NumPy, pandas, SciPy, scikit-learn and a selected temporal ML framework.

AI and data-science toolkit, by function. The bullet above names the general stack; the list below is the candidate toolkit this specific research programme would draw on, organised by the function each tool performs rather than as an undifferentiated list — selection within each category is an engineering decision made during Phase 0–1, not a commitment made here.

- **Biosignal processing and feature extraction** — SciPy and NeuroKit2 for filtering, rectification and envelope/RMS extraction; MNE-Python if EEG-style epoching and artefact-rejection conventions prove useful for sEMG; pandas for windowed feature tables.
- **Computer vision and facial landmarking** — MediaPipe Face Mesh or OpenCV/dlib landmark detectors for the participant-specific coordinate frame (Section 8); OpenCV for camera calibration and frame synchronisation.
- **Classical and baseline machine learning** — scikit-learn for the linear baseline model (Section 10), cross-validation utilities adapted for grouped/session-based and stratified splitting (Section 11), and classical classifiers for the synkinesis quality-gating state (Section 15).
- **Temporal and deep-learning models** — PyTorch or TensorFlow/Keras as the underlying framework; sktime, tsai or GluonTS for temporal-model scaffolding (windowing, recurrent/temporal-convolutional architectures) rather than building this tooling from scratch.
- **Personalisation and transfer learning** — participant-specific fine-tuning or few-shot calibration on top of a population-pretrained base model, so each new participant's per-session recalibration (Section 11) does not require training from zero; standard transfer-learning utilities in the chosen deep-learning framework are sufficient at this stage rather than a bespoke meta-learning system.
- **Experiment tracking, data and model versioning** — MLflow or Weights & Biases for run tracking and model registry (Section 11); DVC or an equivalent data-versioning tool so that every reported result is traceable to an exact dataset version, model version and hyperparameter set (Section 23).
- **Statistical validation** — statsmodels or SciPy's statistical routines for the stratified, per-movement-category and per-clinical-presentation reporting required by SR-15 (Section 20), including appropriate corrections for multiple comparisons across categories.

- **Edge/embedded inference** — ONNX Runtime or TensorFlow Lite to export a trained model for the ESP32-class microcontroller or an attached single-board computer once a candidate architecture is fixed, keeping the heavier training stack laptop/PC-side (Section 19 latency targets apply to this exported form, not the training pipeline).

This toolkit is presented as the concrete mechanism behind the enabling-technology argument in Section 3: each row above is mature, widely documented, open-source tooling that was either unavailable or far less accessible when the comparator facial-pacing and soft-actuator literature was published, and it is what makes the participant-specific, continuously-recalibrated, quality-gated modelling approach in Sections 10–11 and 15 practical to build rather than only theoretically appealing.

Concept flow: sensors and electronics feed a separate AI/data core and safety layer

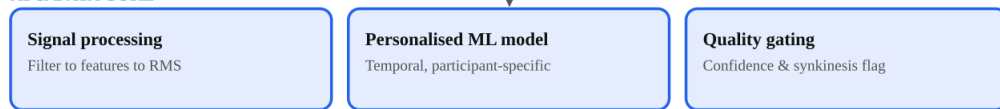
SENSORS & HARDWARE (INPUTS)



ACQUISITION ELECTRONICS



AI & DATA CORE



SAFETY / ACTUATION (NON-AI)



Toolkit implementing the AI/data core is listed in Section 18; the safety/actuation layer is deliberately kept independent of it (Section 13).

Figure D. Conceptual flow from sensors and acquisition electronics into the AI/data core, kept architecturally separate from the non-AI safety and actuation layer.

19. Provisional Engineering Targets

The following are development targets for bench research, not clinical safety limits. They should be measured, justified and revised as the prototype develops.

- **Acquisition** — configurable facial sEMG sampling around 1 kHz as an initial engineering setting, subject to the selected acquisition hardware and signal bandwidth.
- **Signal processing** — configurable band-pass and mains-interference rejection; exact filter design documented with phase/latency implications.
- **Inference window** — initial temporal windows in the approximate 100–500 ms range compared experimentally rather than assumed optimal.
- **End-to-end latency** — measure sensing-to-target latency and report median and high-percentile values; an initial research target below approximately 100 ms can be investigated for responsive assistance.

- **Actuation** — artificial-face prototype must have independently characterised travel, velocity, acceleration and force limits before dynamic tests.
- **Safety** — hardware/software emergency disable and watchdog timeout must be demonstrated before any closed-loop human-facing concept is considered.
- **Data** — preserve raw signal, processed signal, timestamps, model version and experiment metadata for every evaluated run, tagged by movement category and clinical presentation (Section 15).

20. System Requirements Specification

The requirements below convert the concept into testable engineering statements and form a living requirements baseline as the prototype evolves. Requirements are engineering targets for the research prototype, not clinical safety limits.

ID	Domain	Requirement	Verification
SR-01	Sensing	Synchronised sEMG and reference movement data with timestamp integrity.	Replay/timestamp validation
SR-02	sEMG	Configurable acquisition and filtering suitable for facial sEMG experiments.	Bench signal validation
SR-03	Inference	AI outputs a bounded movement target rather than unrestricted motor commands.	Software inspection
SR-04	Latency	End-to-end sensing-to-target latency is measured before actuation tests.	Instrumented latency test
SR-05	Actuation	Bench actuator has defined displacement, velocity and force limits.	Mechanical characterisation
SR-06	Safety	Independent controller enforces limits and provides fail-safe disable.	Fault-injection test
SR-07	Feedback	Movement sensing permits tracking-error calculation.	Calibration/repeatability test

ID	Domain	Requirement	Verification
SR-08	Data	Training, validation and test data are separated by session where feasible.	Dataset audit
SR-09	AI lifecycle	Model version, data provenance and performance are recorded.	Experiment-log audit
SR-10	Wearability	Future skin-contact design specifies materials, attachment, duration and biological-safety assessment.	Design review
SR-11	Human factors	User-facing control includes obvious stop/disable behaviour.	Usability/fault test
SR-12	Governance	Human testing starts only after applicable ethical/regulatory pathway is determined.	Governance review
SR-13	Quality state	System exposes signal-quality/uncertainty state, including a synkinesis/co-contraction flag distinct from generic signal degradation, and can reject unreliable input.	Injected-noise/dropout and synkinesis-simulation test
SR-14	Reproducibility	Preprocessing and model configuration are version controlled.	Re-run audit
SR-15 (new)	Evaluation	Reported accuracy is broken out by movement category (symmetric vs. asymmetric/oral-motor) and clinical presentation (flaccid	Evaluation-report audit

ID	Domain	Requirement	Verification
		vs. synkinetic); a pooled figure alone does not satisfy this requirement.	

21. Preliminary Risk Management

Risk management is maintained throughout the project rather than added after the prototype has been built. The hazard analysis below is deliberately conservative and should be expanded into a formal risk-management file if the project moves toward human investigation.

Hazard	Cause	Potential harm	Mitigation
Incorrect AI prediction	Noise, crosstalk, drift, model error	Unintended or inappropriate movement	Bounded targets; independent safety controller; watchdog; quality gating
Excessive actuator force	Control or mechanical fault	Pain or tissue injury	Low-force artificial-face prototype; force limiting; mechanical stops; characterisation before any human-facing test
Unexpected movement	Software bug, communication loss, sensor failure	Unintended actuation	Fail-safe state; timeout; actuator disable; fault-injection testing
Eye-area contact	Poor fit or actuator misalignment	Ocular injury risk	No early human actuation; anatomical clearance; mechanical stops; specialist clinical review
Skin reaction	Adhesive/material incompatibility	Irritation or sensitisation	Traceable materials; contact-duration limits; biological evaluation before clinical use
Electrical hazard	Battery fault, short circuit, inadequate insulation	Burn, shock or device damage	Protected battery; current limiting; insulation; electrical testing
Data leakage	Poor de-	Privacy harm	Data minimisation;

Hazard	Cause	Potential harm	Mitigation
	identification or access control		pseudonymisation; encryption; access control; retention limits
Model drift	Adaptive retraining or sensor changes	Performance degradation	Version locking for studies; change control; revalidation
False intention detection (synkinesis-driven)	Synkinesis or involuntary movement	Assistance applied to unintended action	Movement-specific and presentation-specific calibration; dedicated co-contraction detection (SR-13); uncertain/reject state; supervised protocols — see Section 15 for why this is treated as a design driver, not only a hazard
Mechanical detachment	Adhesive/fastening failure	Loss of assistance or local hazard	Attachment inspection; retention strategy; safe release
Head-motion artefact	Camera motion or sensor movement	Incorrect target estimate	Coordinate normalisation; IMU investigation; quality gating
Sensor crosstalk	Close muscle anatomy / electrode placement	Incorrect feature attribution	Placement protocol; channel review; participant-specific calibration
Undetected subgroup performance gap	Evaluating only on flaccid or only on symmetric-movement data	False confidence in system reliability for the general target population	Mandatory stratified reporting (SR-15); no publication of pooled-only accuracy figures

22. Evaluation Protocol

Primary engineering metrics include prediction MAE and RMSE, end-to-end latency, actuator tracking error, false activation rate, repeatability, sensor dropout rate, model confidence calibration, mechanical hysteresis and power consumption — each reported overall and broken out by movement category and clinical presentation (Sections 4, 15, 20).

Mean absolute error is defined as:

$$\mathrm{MAE} = \frac{1}{N} \sum_{i=1}^N \left| Y_i - \hat{Y}_i \right|$$

Root mean square error is:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(Y_i - \hat{Y}_i \right)^2}$$

For facial trajectories, additional measures include movement amplitude error, temporal alignment error, symmetry error and trajectory smoothness. For later clinical research, validated facial grading and functional outcome measures (e.g. Sunnybrook [8]) are selected with appropriate clinical collaborators, and the synkinesis subscore is reported as a stratification variable, not folded into a single composite score.

23. Data, Reproducibility and AI Lifecycle

Each recording has a unique session identifier, participant pseudonym, sensor configuration, camera configuration, timestamp source, movement-task label, clinical presentation label (flaccid/synkinetic, Section 15) and software version. Raw data is preserved separately from derived data.

Training, validation and test data are separated by session where feasible. Model artefacts are versioned. Changes to preprocessing, feature definitions, architecture or training data create a new model version rather than silently replacing the previous model.

The system logs uncertainty and signal-quality states, including the synkinesis/co-contraction flag (SR-13). A model that is accurate on clean laboratory data but fails during electrode movement, sweat, cable motion, altered attachment or synkinetic co-contraction should not be treated as ready for wearable deployment.

24. UK and International Regulatory Considerations

Mimic is designed with reference to the current UK medical-device and AIaMD regulatory framework. It is not, at this stage, UK-law compliant, CE/UKCA compliant, clinically approved or clinically effective, and no such claim is made.

Likely classification trajectory. In Great Britain, the principal statutory framework is the UK Medical Devices Regulations 2002 (UK MDR 2002), as amended [11]. MHRA guidance explains that software and AI can fall within medical-device regulation depending on intended purpose [10]. Given an intended purpose along the lines of “measurement and clinician-directed assistance of facial movement for rehabilitation,” Mimic’s likely trajectory — stated here as a working hypothesis for planning, not a determination — sits toward the lower end of risk classification (broadly comparable to Class I or IIa software/general medical devices under the UK’s risk-based rules) while the device is confined to measurement and low-force, clinician-supervised, reversible assistance; classification would need formal reassessment if actuation force, autonomy of operation, or proximity to high-risk anatomy (notably the eye, Section 15’s cross-reference in the risk table) increased. The intended-purpose statement must be finalised

before any formal classification claim is made, and a qualified regulatory consultant should confirm classification before human investigation.

AI-specific considerations. Because Mimic’s inference layer is patient-specific and updates as calibration data accumulates, it falls within the class of adaptive/continuously-learning AI-enabled medical technologies that current UK and international guidance treats as needing explicit lifecycle and change-control planning, distinct from a fixed algorithm. Relevant reference points include MHRA’s AI Airlock programme and related regulatory-development work [10], and the direction of travel in international guidance (e.g. IMDRF’s work on machine-learning-enabled medical devices and the EU’s MDCG guidance on AI under the Medical Device Regulation), which the project should monitor as it firms up its own regulatory-development resources rather than statutory approval routes. Locking model versions per study (SR-09, SR-14) is the practical safeguard already built into this paper’s requirements baseline pending fuller regulatory guidance.

Clinical investigation. If Mimic progresses to human clinical investigation, the project would need to address the applicable classification and conformity route, clinical evidence, risk analysis, biological safety, software lifecycle considerations, human factors and, where applicable, clinical-investigation submission requirements [12–15], including MHRA’s specific guidance for electrically powered devices [15] and biological safety assessment [16].

The current manuscript separates research design from regulatory claims. The prototype is a conceptual/pre-clinical engineering research platform.

25. Ethics, Safety and Human Factors

Early development uses artificial-face bench models. No electrical nerve stimulation, unrestricted facial force, high-voltage actuation or unvalidated eye-area actuation is required for the research programme.

If human testing is eventually proposed, the protocol specifies inclusion/exclusion criteria (explicitly including flaccid and synkinetic presentations as distinct strata, Section 15), clinician oversight, informed consent, stopping rules, incident reporting, skin-contact duration, electrical safety, mechanical limits, emergency disable behaviour and data governance.

The eye region is a particularly high-consequence area. Any future ocular-adjacent mechanism requires anatomical clearance, force/displacement justification and specialist clinical review before human use.

Facial images and biosignals are minimised, pseudonymised where appropriate, access-controlled and retained according to a documented governance plan. The research avoids collecting more identifiable information than is necessary for the scientific question.

26. Limitations and Falsifiable Failure Conditions

Mimic remains an unvalidated concept. Facial sEMG is susceptible to crosstalk, electrode-placement effects, fatigue, skin impedance and inter-session variability. Facial anatomy and residual nerve function differ substantially between individuals.

The mapping from healthy-side activation to desired affected-side movement is not one-to-one (Section 4), and is expected, on stated grounds rather than as a hedge, to be markedly weaker for asymmetric and oral-motor movements than for symmetric ones. Synkinesis (Section 15) can cause simultaneous or unintended muscle activation that degrades both the input signal and the interpretability of affected-side feedback. A camera-derived symmetry target may also be an imperfect representation of a patient's natural movement.

The concept is explicitly falsifiable. It would not be a failure of the research programme if one-sided sensing proved inadequate, if camera-free operation remained necessary, if the healthy-side proxy held only for a narrow subset of symmetric movements, if synkinesis detection proved unreliable, or if some facial movements could not be reproduced safely. These outcomes would define the limits of the proposed architecture, and Sections 6, 15 and 20 specify in advance how each would be measured and reported rather than discovered informally.

A successful artificial-face demonstration establishes engineering feasibility only. It does not establish clinical efficacy, rehabilitation benefit or regulatory acceptability.

27. Conclusion and Next Technical Milestone

Mimic proposes a structured engineering programme linking facial sEMG, computer vision, personalised temporal modelling, compliant actuation and closed-loop control. Its central architectural principle — separating prediction from safety-critical actuation, so that an independent controller determines what physical action is permissible — is defensible on engineering-safety grounds independent of the paper's central empirical bet: that healthy-side sEMG is a usable, if uneven, proxy for affected-side intention (Section 4), an assumption this version treats as the paper's primary falsifiable claim rather than a background premise.

The immediate technical milestone is not a wearable device on a person. It is a reproducible, stratified calibration dataset (symmetric vs. asymmetric movement; flaccid vs. synkinetic presentation) followed by an artificial-eyebrow bench system demonstrating the complete loop: sensed biological signal → personalised prediction → bounded command → artificial movement → measured feedback — with per-category performance reported from the first evaluation onward, not added retrospectively once results look favourable in aggregate.

If that loop proves reproducible, and if the stratified evaluation in Phase 5 supports the proxy relationship for at least the symmetric-movement subset, the project can progress systematically toward multiple movement targets, more compliant actuation, wearable packaging and, eventually, appropriately governed human feasibility research.

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Appendix: Note on Figures

Figures 1–8 of the v3.0 manuscript (graphical abstract, technical architecture, closed-loop diagram, sEMG pipeline, prototype hardware architecture, facial coordinate system, artificial-eyebrow bench concept and development pathway) have been recreated for this version as Figures A–H throughout the body text, updated to reflect this version’s four-layer architecture, stratified evaluation approach and AI/data-core concept flow (Sections 7, 8, 9, 12, 13, 17, 18, 20).

The v3.0 manuscript’s Figure 9 — an author-supplied, product-style concept render depicting a finished flexible membrane wearable with marketing-style claims (battery life, “customisable & adjustable”) — is removed from this version. Its tone (a polished consumer-product visual with feature callouts) sits inconsistently against a manuscript that elsewhere makes no performance or product claims, and a reviewer encountering it alongside the paper’s stated research status is likely to read the two as contradictory. The underlying reference photographs (v3.0 Figure 10) are not included in this version; this paper contains no photograph of the author.