

Contextual Supervisor Layer — Spec

Purpose. Extend the readiness framework so that scores are **personalized to the nurse's baselines** and **contextualized to their shift pattern**. Instead of punishing unavoidable misalignment, we calculate the *best possible readiness for tonight*, then show the nurse how close they are to that ceiling.

1) Inputs

Baseline Signals

- **Individual rolling baselines (14–21 days):** RMSSD, SDNN, RHR, sleep duration/efficiency, body temp amplitude/nadir, SpO₂, respiratory rate.
- **VO₂ Max** → resilience factor.

Shift Context

- **Shift type:** day, evening, night, rotating.
- **Shift length:** e.g. 8h, 12h.
- **Shift sequence:** consecutive nights, quick turnarounds, first/last in rotation.
- **Turnaround time:** hours since last shift end → current shift start.

Current Features (from framework layer)

- Recovery Score, Sleep Debt (h), Circadian Mismatch (h), Load Ratios, Safety Flags.
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2) RMSSD Data Sources (Hierarchy)

Heartbeat Series Data

- Structure: array of **time offsets (s)** from series start, e.g.

```
{ "startDate": "2025-08-28T07:00:00Z", "beats": [0.853, 1.700, 2.563, 3.452] }
```

- Compute inter-beat intervals (IBIs) by difference (e.g., 847ms, 863ms, etc.).
- **Limitations:** sparse coverage, motion noise, missing long segments.

ECG Data

- 30s single-lead waveform, high-fidelity R-peaks.
- Must be prompted: ideal at **wake-up** and **pre-shift**.
- Gives **gold-standard RMSSD snapshot**.

Confidence Hierarchy

- ECG RMSSD → High confidence
- Heartbeat Series RMSSD → Medium confidence
- SDNN + RHR fallback → Low confidence

RecoveryScore Integration

```
if ECG_RMSSD_today:
    RecoveryScore = 0.7*z(RMSSD_ECG) + 0.2*z(SDNN) - 0.1*z(RHR)
elif HBSeries_RMSSD:
    RecoveryScore = 0.5*z(RMSSD_HB) + 0.3*z(SDNN) - 0.2*z(RHR)
else:
    RecoveryScore = 0.6*z(SDNN) - 0.4*z(RHR)
```

Confidence flag propagates to readiness outputs.

3) Core Concept: Contextual Maximum Readiness

We define **Readiness_max_contextual** = the best physiologically achievable readiness today given the nurse's shift situation.

Step 1: Start from ideal maximum (100).

Step 2: Apply *non-removable penalties* based on shift context.

- **Circadian mismatch penalty:** if working nights, minimum mismatch baseline may be 3–5h. We subtract that from the maximum upfront.
- **Shift length penalty:** longer shifts reduce ceiling. 12h shift → subtract 5–10 points vs 8h.
- **Turnaround penalty:** if rest window <12h, subtract fixed penalty (e.g. -10).

Step 3: Bound max readiness.

- Example: Nurse on back-to-back 12h night shifts might have `Readiness_max_contextual = 82` instead of 100.

4) Relative Readiness

```
relative_readiness = readiness_today / readiness_max_contextual
```

- Expressed as % of achievable readiness.
- Displayed as: "You're at 93% of what's possible tonight."

5) Algorithm Flow

1. Compute **raw readiness_today** from frameworks (with RecoveryScore weighted by RMSSD source confidence).
 2. Compute **Readiness_max_contextual** from shift context:
 3. $\text{max} = 100 - \text{circ_mismatch_baseline} - \text{shift_length_penalty} - \text{turnaround_penalty}$
 4. Clamp $\text{readiness_today} \leq \text{max}$.
 5. Compute **relative_readiness %**.
 6. Output both **absolute score** and **relative %**.
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6) Nudging Logic Adjustments

- If absolute readiness is low but **relative % is high** → focus on *maintenance nudges* ("You've done the best possible, maintain energy with hydration/micro-breaks").
 - If relative % is low → focus on *improvement nudges* (adjust nap timing, bright light, caffeine windows).
 - If both low → escalate to safety nudges (extra breaks, error risk communication).
-

7) Example Cases

Case A: Day Shift, Rested

- Circ mismatch baseline = 0h
- Shift length penalty = 0
- Turnaround penalty = 0
- $\text{max} = 100$
- Nurse scores 78 → relative 78% → normal feedback.

Case B: 12h Night Shift, 3rd Consecutive

- Circ mismatch baseline = 4h → -12 points
- Shift length penalty = -6
- Turnaround penalty = 0
- $\text{max} = 82$
- Nurse scores 76 → relative = 93% → message: "You're near your personal best given 3rd night in a row. Maintain energy."

Case C: Quick Turnaround (<12h)

- Circ mismatch baseline = 2h → -6
- Shift length penalty = -5
- Turnaround penalty = -10
- $\text{max} = 79$

- Nurse scores 60 → relative = 76% → message: “Quick turnaround is holding you back. Prioritize nap + light exposure.”

8) Supervisor Agent Responsibilities

- **Fuse** contextual ceiling with framework outputs.
- **Weight** RecoveryScore by RMSSD source confidence (ECG > HB Series > SDNN/RHR).
- **Decide** whether feedback is maintenance vs improvement vs safety.
- **Output:**

```
{
  "readiness_absolute": 76,
  "readiness_contextual_max": 82,
  "readiness_relative_pct": 0.93,
  "rmssd_source": "ECG",
  "confidence": "high",
  "contributors": [...],
  "nudges": ["Hydrate", "Micro-breaks"]
}
```

9) Why This Matters for Shift Workers

- Avoids unfairly penalizing nurses for structural misalignment they cannot control.
- Keeps motivation positive: “doing the best you can in your context” instead of “you’re failing biology.”
- Lets managers/admins see *relative resilience* across staff rather than raw numbers only.

Next step: refine exact penalty functions and validate weighting scheme (does ECG-anchored RMSSD improve predictive accuracy of fatigue vs SDNN-only?).

9) HB Series & ECG Integration (Embedded)

9.1 What heartbeat series looks like

Query: `HKHeartbeatSeriesQuery` over a `HKHeartbeatSeriesSample` returns **time offsets (seconds)** from `startDate` to each detected beat.

```
{
  "uuid": "C8B6C7C3-2A3E-4C0F-9B9F-83A4E9D7A011",
  "startDate": "2025-08-28T07:00:00Z",

```

```

    "endDate": "2025-08-28T07:00:38Z",
    "beats": [0.78125, 1.5390625, 2.296875, 3.0859375, 3.9101562, 4.703125,
5.4960938, 6.3085938]
}

```

- **IBIs (ms)** are computed as successive differences of `beats` ($\Delta * 1000$).
- **Characteristics:** sporadic windows (tens of seconds), not continuous; gaps common; quality varies with motion.
- **QC rules:** drop IBIs <300 ms or >2000 ms, remove ectopics (MAD/median filter), require ≥ 30 s clean segment for RMSSD.

9.2 When to collect ECG (high quality, user-prompted)

- **Morning after waking** → daily parasympathetic anchor (preferred).
- **Pre-shift check** (esp. nights, high-risk days) → acute recovery before duty.
- **Post-shift (optional)** → quantifies depletion; use sparingly to avoid burden.

9.3 RecoveryScore composition (ECG + HB Series + SDNN/RHR)

We **weight by input quality**; the score carries a confidence label.

```

# Inputs (per day)
rmssd_ecg_z      # z-score vs personal baseline (ECG-derived)
rmssd_hb_z       # z-score vs baseline (heartbeat-series-derived)
sdnn_z           # z-score vs baseline (Apple SDNN 5-min windows)
rhr_z            # z-score vs baseline (resting HR)

quality = {
    "ecg": has_ecg_today,          # bool
    "hb":  has_heartbeat_series,    # bool & clean segment >=30s
}

if quality["ecg"]:
    w = {"rmssd": 0.70, "sdnn": 0.20, "rhr": 0.10}
    rmssd_term = rmssd_ecg_z
    conf = "high"
elif quality["hb"]:
    w = {"rmssd": 0.50, "sdnn": 0.30, "rhr": 0.20}
    rmssd_term = rmssd_hb_z
    conf = "medium"
else:
    w = {"rmssd": 0.00, "sdnn": 0.60, "rhr": 0.40}
    rmssd_term = 0.0
    conf = "low"

RecoveryScore = clamp(0, 100,
    50

```

```

+ 15 * w["rmssd"] * rmssd_term
+ 10 * w["sdnn"] * sdnn_z
- 10 * w["rhr"] * rhr_z
)
RecoveryConfidence = conf

```

Notes: (1) We use **z-scores** against 14–21d personal baselines. (2) Coefficients (15/10/10) scale z-scores into points and will be tuned. (3) If both ECG **and** HB are present, prefer ECG for the day; optionally smooth with a 3-day EMA to reduce volatility.

9.4 Propagating confidence to Readiness & UI

- If `RecoveryConfidence = high` → allow full weight of RecoveryScore in Readiness fusion.
- If `medium` → down-weight RecoveryScore by 10–20% in the Readiness fusion.
- If `low` → cap the contribution and show “confidence: low” in the UI.

```

readiness = clamp(0,100,
  50
+ 0.35 * RecoveryScore * conf_weight(RecoveryConfidence)
- 4 * SleepDebt_h
- 3 * CircadianMismatch_h
- 2 * SleepQualityPenalty
- 2 * LoadPenalty
)

```

`conf_weight(high)=1.00`, `conf_weight(medium)=0.85`, `conf_weight(low)=0.70` (tunable).

9.5 Worked example (numbers)

- **ECG this morning:** `rmssd_ecg_z = +0.6` (above baseline)
- **HB series later:** present but ignored for the day (we pick ECG as primary)
- `sdnn_z = -0.4`, `rhr_z = +0.3`

```

RecoveryScore = 50 + 15*0.70*(+0.6) + 10*0.20*(-0.4) - 10*0.10*(+0.3)
               = 50 + 6.3 - 0.8 - 0.3 = 55.2 → confidence: high

```

Downstream (illustrative): `SleepDebt=2.0h`, `CircMismatch=2.5h`, `SleepQualityPenalty=2`, `LoadPenalty=1`

```

Readiness (pre-context) ≈ 50 + 0.35*55.2 - 4*2.0 - 3*2.5 - 2*2 - 2*1
                       ≈ 50 + 19.3 - 8 - 7.5 - 4 - 2 = 47.8

```

Contextual layer: shift = 12h night #2 → `max_contextual = 82` → `relative = 47.8/82 = 58%`.

CMR gap actions: Nap 25m (+4), Bright light 30m (+2) → projected AR \approx 54 (RR% \approx 66%).

9.6 API surface (embedded fields)

GET /readiness/today and /readiness/contextual include:

```
{
  "recovery": {
    "method": "ecg|hb|fallback",
    "rmssd_z": 0.6,
    "sdnn_z": -0.4,
    "rhr_z": 0.3,
    "score": 55.2,
    "confidence": "high"
  },
  "readiness": { "absolute": 48, "contextual_max": 82, "relative_pct": 0.58 },
  "contributors": [
    {"name": "RMSSD", "delta": +6.3, "reason": "ECG above baseline"},
    {"name": "SDNN", "delta": -0.8, "reason": "below baseline"},
    {"name": "RHR", "delta": -0.3, "reason": "elevated vs baseline"},
    {"name": "Sleep debt", "delta": -8.0},
    {"name": "Circadian mismatch", "delta": -7.5}
  ]
}
```

9.7 Data retention & storage notes

- Store raw heartbeat series in S3; keep daily **derived RMSSD_HB** with quality flags in Supabase (e.g., segment_length_s, %beats_removed, artifact_score).
- For ECG, prefer storing **RR intervals** + derived metrics; raw waveform optional/consented due to size/PHI risk.

10) Clinically-grounded penalty functions (MVP defaults)

Purpose: make penalties deterministic and literature-anchored. Values are tunable after pilot back-testing; caps prevent runaway effects.

10.1 Sleep debt penalty (cognitive impairment scales with chronic restriction)

Let $D = \max(0, \text{sleep_debt_hours})$ (rolling 14-day, per Section 3.2).

```
SleepPenalty(D) = 0,                                if D < 0.5
                  = -3 * (D - 0.5),                  if 0.5 ≤ D ≤ 2.0
```

$$= -3 * (2.0 - 0.5) - 5 * (D-2.0), \text{ if } D > 2.0$$

Cap: min -25 points.

10.2 Circadian misalignment penalty (performance trough near biological night)

Let $M = \text{circ_mismatch_hours}$ (Section 3.3).

$$\text{CircPenalty}(M) = -3 * \min(M, 3) - 4 * \max(0, M-3)$$

Cap: min -20 points.

10.3 Shift length penalty (error risk rises past ~10–12h)

Let $H = \text{shift_duration_hours}$.

$$\text{ShiftLenPenalty}(H) = \begin{cases} 0, & \text{if } H \leq 8 \\ -2 * (H-8), & \text{if } 8 < H \leq 10 \\ -2 * 2 - 3 * (H-10), & \text{if } 10 < H \leq 12 \end{cases}$$

Cap: min -10 points.

10.4 Quick turnaround penalty (insufficient rest between shifts)

Let $R = \text{turnaround_hours}$ (prior shift end → next shift start).

$$\text{TurnaroundPenalty}(R) = \begin{cases} 0, & \text{if } R \geq 12 \\ -8, & \text{if } 10 \leq R < 12 \\ -12, & \text{if } R < 10 \end{cases}$$

10.5 Load penalty (acute:chronic workload ratio, steps/active energy proxy)

Let $\text{ACR} = \text{acute_7d} / \text{chronic_28d}$ using steps or active energy.

$$\text{LoadPenalty}(\text{ACR}) = \begin{cases} 0, & \text{if } \text{ACR} \leq 1.2 \\ -3, & \text{if } 1.2 < \text{ACR} \leq 1.5 \\ -6, & \text{if } 1.5 < \text{ACR} \leq 2.0 \\ -10, & \text{if } \text{ACR} > 2.0 \end{cases}$$

10.6 Physiological modifiers (safety & strain)

Let z-scores be vs personal 14–21d baselines. - **SpO₂ (sleep):** - $\text{median_spo2} < 94\% \rightarrow -5$ - $\text{min_spo2} < 90\% \rightarrow \text{set } \text{safety_flag}=\text{true}$ and **cap Readiness** ≤ 60 - **Body temperature (morning):** -

temp_morning_z $\geq +0.5 \rightarrow -3$; $\geq +1.0 \rightarrow -6$ - **Amplitude blunting:** temp_amplitude_z $\leq -1.0 \rightarrow -3$ (flattened rhythm) - **Resting HR:** - rhr_z $\geq +0.5 \rightarrow -2$; $\geq +1.0 \rightarrow -4$ - **RMSSD suppression:** - rmssd_z $\leq -1.0 \rightarrow -5$; $\leq -2.0 \rightarrow -10$

10.7 Putting penalties into the fusion

Replace generic terms in Section 4 with explicit calls:

```
readiness = clamp(0,100,
  50
  + 0.35 * RecoveryScore * conf_weight(RecoveryConfidence)
  + ShiftLenPenalty(H)
  + TurnaroundPenalty(R)
  + LoadPenalty(ACR)
  + CircPenalty(M)
  + SleepPenalty(D)
  + PhysioModifiers(SpO2, Temp, RHR, RMSSD)
)
```

Notes: (1) Penalty functions return negative values (or zero). (2) `PhysioModifiers` sums the items in 10.6. (3) Safety cap applies after fusion.

10.8 Defaults table (for quick reference)

Domain	Thresholds \rightarrow Penalty	Cap
Sleep debt	0.5–2h: $-3/h$; $>2h$: $-5/h$	-25
Circadian mismatch	first 3h: $-3/h$; $>3h$: $-4/h$	-20
Shift length	9–10h: $-2/h$; 11–12h: $-3/h$	-10
Turnaround	10–12h: -8 ; $<10h$: -12	fixed
Acute load (A:C)	1.2–1.5: -3 ; 1.5–2.0: -6 ; >2.0 : -10	-10
SpO ₂ (sleep)	median $<94\%$: -5 ; min $<90\%$: cap readiness ≤ 60	cap
Temp (morning)	$+0.5$ SD: -3 ; $+1.0$ SD: -6 ; amplitude z ≤ -1.0 : -3	—
Resting HR	$+0.5$ SD: -2 ; $+1.0$ SD: -4	—
RMSSD	-1 SD: -5 ; -2 SD: -10	—

10.9 Calibration plan

- Backtest penalties against pilot outcomes (EMA fatigue, near-miss logs, error reports where available).

- Regress observed performance/fatigue on D, M, H, R, ACR to fine-tune slopes.
- Keep caps conservative; adjust quarterly.

11) Non-removable (context) penalties — research-backed defaults

These define the **Contextual Max Readiness (CMR)** ceiling for tonight by subtracting what *cannot* be fully fixed within the available window.

11.1 Circadian floor

- **Improvable shift per day** (with timed light/dark): $\Delta\text{phase_improvable} = 0.8 \text{ h}$ (default; tunable range 0.5–1.5 h).
- **Floor:** $\text{C_floor_h} = \max(0, \text{circ_mismatch_h} - \Delta\text{phase_improvable})$
- **Penalty:** $\text{CircPenalty_floor} = -3 * \min(\text{C_floor_h}, 3) - 4 * \max(0, \text{C_floor_h} - 3)$ (cap -20)

11.2 Shift length

- **Base penalty:** $\text{ShiftLenPenalty} = 0 \text{ } (\leq 8\text{h}); -2/\text{h} \text{ } (9\text{--}10\text{h}); -3/\text{h} \text{ } (11\text{--}12\text{h})$ (cap -10)
- **Break-quality modifier:** if *documented protected breaks* $\geq 30\text{m}$ → add back $+1\text{...}+2$ points (so a 12h shift = -8 to -10 depending on breaks)

11.3 Turnaround (rest between shifts)

- $\text{TurnaroundPenalty} = 0 \text{ } (\geq 12\text{h}); -8 \text{ } (10\text{--}12\text{h}); -12 \text{ } (<10\text{h})$

Implementation note: These are *context* penalties used to compute CMR ceilings (Section 3). The standard fusion in Section 10 still applies to the **actual** state.

12) Action → mechanism → points (how gains are computed)

We **don't assign points arbitrarily**. We change underlying terms and let the fusion produce points.

12.1 20–25m pre-shift nap (when available)

- **Mechanisms:** (a) small reduction in effective sleep debt, (b) acute vagal bump (RMSSD $z + 0.1\text{...}+0.2$ if nap ends $\geq 60\text{m}$ before duty), (c) reduced time-on-task sleepiness early in shift.
- **Model:** $\text{sleep_debt_h}' = \max(0, \text{sleep_debt_h} - 0.15)$; $\text{rmssd_z}' = \text{rmssd_z} + 0.15$
- **Typical net:** $+3\text{...}+6$ readiness points depending on current slopes/confidence.

12.2 30–40m bright, blue-enriched light before night shift

- **Mechanisms:** (a) acute alerting; (b) reduce circadian floor by increasing $\Delta\text{phase_improvable}$.
- **Model:** $\Delta\text{phase_improvable} += 0.8 \text{ h}$ (clamped to 1.5 h/day). If morning dark/blue-block is planned, allow $+0.2 \text{ h}$.

- **Typical net:** +2...+4 readiness points via CircPenalty_floor + minor RMSSD stabilization.

Confidence: actions carry **High** evidence tags in the UI library; gains vary with baseline and timing. We log adherence and auto-tune gains weekly.

13) Worked CMR example (now fully specified)

Scenario: 12h night #2, $\text{circ_mismatch_h} = 4.0$, protected break documented, turnaround = 13h.

- **Circadian floor:** $\Delta\text{phase_improvable} = 1.0 \text{ h}$ (bright light scheduled) → $\text{C_floor_h} = 3.0$
→ $\text{CircPenalty_floor} = -9$.
- **Shift length:** base -10, +1 for protected break → -9 .
- **Turnaround:** 0 .

CMR (ceiling): $100 - 9 - 9 = 82$.

If nurse also takes a **25m nap** and the **light** session: $-\text{sleep_debt_h}' = \text{sleep_debt_h} - 0.15$ - $\text{rmssd_z}' = \text{rmssd_z} + 0.15$ - $\Delta\text{phase_improvable} = 1.0 \text{ h}$ (already applied above) → Fusion yields typical **+4...+6** points vs no actions (Section 9.5 illustrates arithmetic).

14) Candidate penalties/modifiers to add next (data-permitting)

- **Consecutive nights index** (sequence effect): +1...+3 penalty per successive night beyond #2 (cap -6).
- **Time-on-task within shift** (hours 9–12 & 02:00–06:00): dynamic intra-shift risk flag.
- **Commute risk** (post-night shift): show hazard flag; does not change readiness score.
- **Heat/PPE stress** (if wearable skin temp & steps → sustained heat + high load): small penalty.
- **Caffeine timing** (late caffeine after 02:00 → sleep window penalty tomorrow).
- **Meal timing mismatch** (large meals within 2h of sleep → sleep quality penalty tomorrow).
- **Menstrual phase** (if opted-in): luteal symptoms → increase sleep quality sensitivity.

Add each only when we have robust ingestion (HealthKit, EMA, schedule) and a clear, auditable rule.