

SMART CAST

A Sensor-Instrumented Orthopaedic Cast with Gamified
Behavioural Feedback for Patients

Research Summary · Engineering Notebook · System Architecture

Document Revision: Rev A

Date: _____

Author: _____

SmartCast

Table of Contents

To populate: right-click the field above in Word and choose "Update Field".

SmartCast

Part 1 — Research Summary

Problem Statement

Immobilisation with a rigid cast is the standard treatment for paediatric limb fractures. Clinical outcome, however, depends heavily on patient compliance during the 4–8 week healing period — a factor that is essentially unmonitored once the patient leaves the clinic. Children, in particular, present three compounding problems:

- Behavioural non-compliance. Young patients continue running, climbing, throwing and impacting the injured limb. Sudden high-acceleration events risk re-displacement of the fracture and prolonged healing.
- Silent complications. Pressure sores, excessive skin temperature, trapped moisture and compromised circulation develop underneath the cast where neither parent nor clinician can observe them. Early warning signs are missed.
- No objective record. Follow-up consultations rely on subjective parental recall rather than measured data. Prescribed rehabilitation exercises are performed inconsistently, if at all.

Proposed Solution

Smart Cast is a low-power wearable electronics module attached to a conventional orthopaedic cast for the upper limb. It continuously monitors the physiological state of the limb beneath the cast and the kinematic behaviour of the limb itself, and streams the data to a companion mobile application used by both the parent (monitoring) and the child (engagement).

The system's distinguishing feature is a dual inertial measurement unit (dual-IMU) architecture: one 6-DoF IMU sits in the main housing at the forearm and a second in a separate housing on the upper arm, connected by a 35 cm cable. Because both sensors measure orientation in a common reference frame, the relative rotation between them yields the elbow flexion angle and full arm posture — information that a single IMU physically cannot recover. This enables posture classification, aggressive-movement detection and closed-loop verification of prescribed rehabilitation exercises.

Behavioural compliance is addressed through gamification rather than restriction. The child's application presents an animated companion character (a cat or a dog, selectable) and awards points for sustained periods without aggressive limb movement. Points are redeemed for rewards that the parent defines and controls within the app — an activity, a treat, or screen time. The parent additionally sets the reward exchange rate and difficulty, and receives real-time alerts for sudden impact events, elevated skin temperature or abnormal heart rate.

Implementation Overview

A single ESP32-C6 MINI module acts as system controller, sensor-fusion processor and wireless gateway. All sensors share a single I²C bus: a MAX30102 pulse-oximetry sensor, a MAX30205 clinical-grade skin temperature sensor, an SHT31 temperature/humidity sensor for the intra-cast microclimate, and two LSM6DSOX 6-DoF IMUs distinguished by hardware address selection. The assembly is powered by a 3.7 V 2000 mAh single-cell Li-Po battery with a mechanical isolation switch, and communicates over BLE. All signal processing is rule-based and runs in real time on the device; no machine learning is used.

Expected Outcome and Contribution

Smart Cast converts a passive medical appliance into an instrumented, data-generating device, and converts a child from a non-compliant patient into an actively engaged one. The intended contributions are: (i) continuous remote visibility of intra-cast physiological conditions; (ii) objective, quantified movement-compliance data for the treating clinician; (iii) measurable improvement in rehabilitation-exercise adherence through positive behavioural reinforcement rather than parental enforcement.

Intended Use and Limitations of Claim

Smart Cast is a monitoring and behavioural-support aid. It is not a diagnostic instrument, it does not replace clinical assessment, and no clinical claim is made regarding healing outcomes. All alert thresholds are configurable and are intended to prompt a parent to seek professional advice, not to establish a diagnosis. The device is non-invasive and makes no contact beneath the skin surface.

SmartCast

Part 2 — Engineering Notebook

This part documents the design in the order in which the system is best understood: the goals it was designed to meet, the overall architecture, then each subsystem in turn.

2.1 Design Goals

The following goals were defined from the problem statement before any component was selected. They are self-imposed engineering targets, and every design decision documented below traces back to one of them.

ID	Design goal	Rationale
G-01	Detect sudden, high-magnitude limb movement	Protect fracture alignment; alert in real time
G-02	Determine arm posture and elbow flexion angle	Distinguish safe motion from unsafe motion; verify exercises
G-03	Monitor skin temperature at the cast–skin interface	Early indication of fever
G-04	Monitor intra-cast humidity and air temperature	Detect humidity of skin
G-05	Monitor heart rate and blood-oxygen saturation	General wellbeing and circulation indication
G-06	Wireless link to parent and child applications	Remote monitoring without a clinic visit
G-07	Battery operation for a full waking day	Practical for a child;
G-08	Low profile, low mass, no sharp edges	Must not create pressure points against the limb or skin
G-09	Parent-configurable thresholds and rewards	Every child and every fracture differs

2.2 System Architecture

The system consists of four cooperating subsystems: the cast firmware, the companion mobile application, a remote server, and the parent dashboard. Figure 1 shows the interconnection between them.

Smart Cast itself is a device running on an ESP32-C6 microcontroller. It carries the sensor set and runs three concurrent tasks: I/O (sensor acquisition), Fusion (filtering and interpretation of sensor data), and BLE (wireless transmission). The second entity is a mobile application developed in Flutter, containing a child mode, a parent area, and the synchronisation logic for the server. The server is built on Flask/FastAPI and presents the stored data as a parent dashboard.

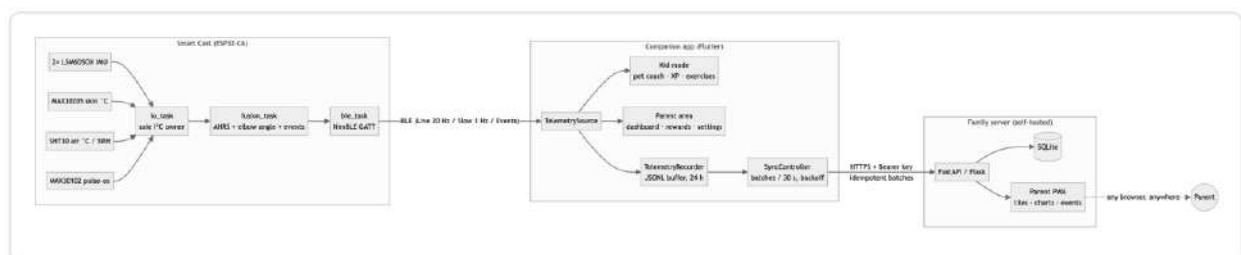


Figure 1 — System architecture: device, mobile application, server and dashboard

The development stack is summarised below.

Entity	Technology stack
Device firmware	ESP-IDF (C), FreeRTOS
Mobile application	Flutter (single codebase, Android and iOS)
Server and dashboard	Flask / FastAPI (Python)

Data flow is as follows:

Sensors → I²C bus → ESP32-C6 (fusion, event detection) → BLE → Mobile app (buffering) → Server → Parent dashboard

A downstream path carries configuration in the opposite direction: thresholds, exercise schedules and reward settings set by the parent propagate from the dashboard through the app to the device.

SmartCast

2.3 Electrical Design

2.3.1 Component selection

Each component was selected against a specific design goal. The rationale for each is given below; full specifications are tabulated in Section 2.3.5.

MAX30102 — Heart-Rate and Pulse-Oximetry Sensor

An integrated optical sensor combining red and infrared LEDs, a photodetector and an on-chip analogue front end. It measures heart rate and blood-oxygen saturation (SpO_2) using reflective photoplethysmography. In Smart Cast it provides a continuous wellbeing indicator and, through changes in blood perfusion, an indirect measure of circulation in the limb below the fracture. Selected because the complete optical front end is integrated in one I²C package, removing the need for custom analogue design. Addresses G-05.

MAX30205 — Human Body-Temperature Sensor

A clinical-accuracy digital temperature sensor (± 0.1 °C around normal body temperature). Placed in contact with the skin, it measures the patient's body temperature directly. A sustained rise at the fracture site serves as an early warning of inflammation or infection under the cast. Addresses G-03.

SHT31 — Temperature and Humidity Sensor

A digital sensor measuring air temperature and relative humidity. It monitors the microclimate of the air trapped inside the cast rather than the patient directly. Sustained high humidity is the primary precursor to skin maceration, irritation and pressure sores, making this a distinct early-warning channel from body temperature. Addresses G-04.

Carrying both the MAX30205 and the SHT31 is deliberate: one measures the patient, the other measures the environment. This allows differential reasoning. A skin-temperature rise accompanied by an ambient rise indicates the child is simply warm or active; a skin-temperature rise with a stable ambient reading points to a localised physiological cause. A single temperature sensor cannot make this distinction, and this is the basis of the alert-suppression logic in Section 2.5.4.

LSM6DSOX — 6-DoF Accelerometer and Gyroscope (IMU)

A 6-degree-of-freedom inertial measurement unit combining a 3-axis accelerometer and a 3-axis gyroscope. Two units are used, one on the forearm and one on the upper arm, on either side of the elbow. This is the central architectural decision of the project and is explained in full in Section 2.3.2. Addresses G-01 and G-02.

ESP32-C6 MINI — Microcontroller

A compact, low-power microcontroller module with integrated Bluetooth Low Energy and Wi-Fi 6. It acts as the system controller: it reads all sensors over the shared I²C bus, performs sensor fusion and event detection on-device, and transmits results wirelessly. Selected for its small module footprint, integrated radio, and sufficient processing headroom to run the fusion and detection pipeline locally. Because only computed results — not raw sample streams — are transmitted, radio activity is minimised, which is the dominant power saving in the system. Addresses G-06 and G-11.

Battery and power isolation

A single-cell lithium-polymer battery (3.7 V nominal, 2000 mAh) powers the device. It is connected to the battery input of the ESP32-C6 MINI through a mechanical slide switch, which provides true galvanic isolation when the device is stored or not in use. The module's on-board regulator generates the 3.3 V rail, from which all sensors are supplied. The battery is charged over the USB-C connector on the ESP32-C6 MINI, so a single port serves both charging and firmware programming. Addresses G-07.

The battery is located in a dedicated recess directly beneath the ESP32-C6 MINI module, which keeps the assembly compact and avoids adding to the enclosure height.

Battery-voltage sensing

Two 100 k Ω resistors form a voltage divider that halves the battery voltage and feeds it to an ADC input on the ESP32-C6. This allows the system to monitor state of charge and report a low-battery condition. Halving keeps a fully charged 4.2 V cell within the microcontroller's 3.3 V input range, while the high resistance minimises the continuous current drawn through the divider, preserving battery life.

2.3.3 Bus topology and signal integrity

All five sensors are placed on a single shared I²C bus in parallel, each device tapping the common SDA and SCL lines. I²C was chosen over SPI to minimise conductor count — a decisive factor when one sensor is tethered 35 cm away across a joint. SPI would have required an additional chip-select line per device and a wider harness.

The two LSM6DSOX devices are distinguished by hardware address selection on the SA0 pin, yielding two distinct addresses on the same bus. No multiplexer is required.

The 35 cm cable increases bus capacitance and noise susceptibility. The following mitigations were adopted:

2.3.4 Prototype construction

The current revision is a functional prototype. The 60 × 40 mm board is a perforated prototyping board (perfboard), not a custom fabricated PCB. Sensor breakout modules and the ESP32-C6 MINI are mounted via pin headers and hand-wired, which allows individual modules to be replaced or repositioned during development. Figure 4 shows the populated board.

2.3.5 Component summary

Component	Function in system	Interface
ESP32-C6 MINI	Controller, sensor fusion, BLE gateway, USB-C charging	I ² C master
MAX30102	Heart rate, SpO ₂	I ² C
MAX30205	Skin (body) temperature, clinical accuracy	I ² C
SHT31	Intra-cast air temperature and relative humidity	I ² C
LSM6DSOX #1	Forearm IMU — forearm link kinematics	I ² C
LSM6DSOX #2	Upper-arm IMU — upper-arm link kinematics	I ² C
Li-Po battery	Energy source, 3.7 V nominal, 2000 mAh	—
Slide switch	Hard power isolation	—
2 × 100 k Ω resistors	Battery-voltage divider to ADC	Analogue
Interconnect cable	35 cm tether to upper-arm IMU housing	I ² C + power

2.3.6 Circuit diagram

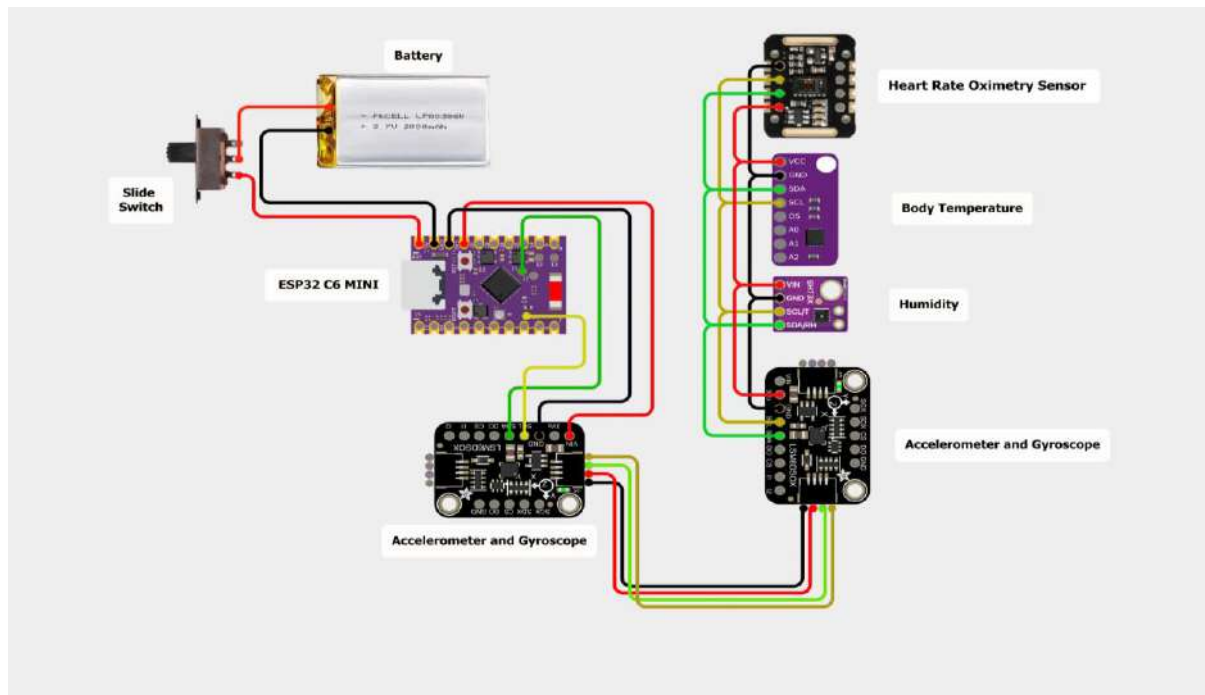


Figure 2 — Circuit / connection diagram

SmartCast

2.4 Mechanical Design

The enclosure was designed in SolidWorks and consists of two printed bodies. The main housing measures $67 \times 47 \times 27.54$ mm with a uniform wall thickness of 3 mm. A second, smaller housing measures $23 \times 30 \times 9$ mm. Both are shown with dimensions in Figure 3.

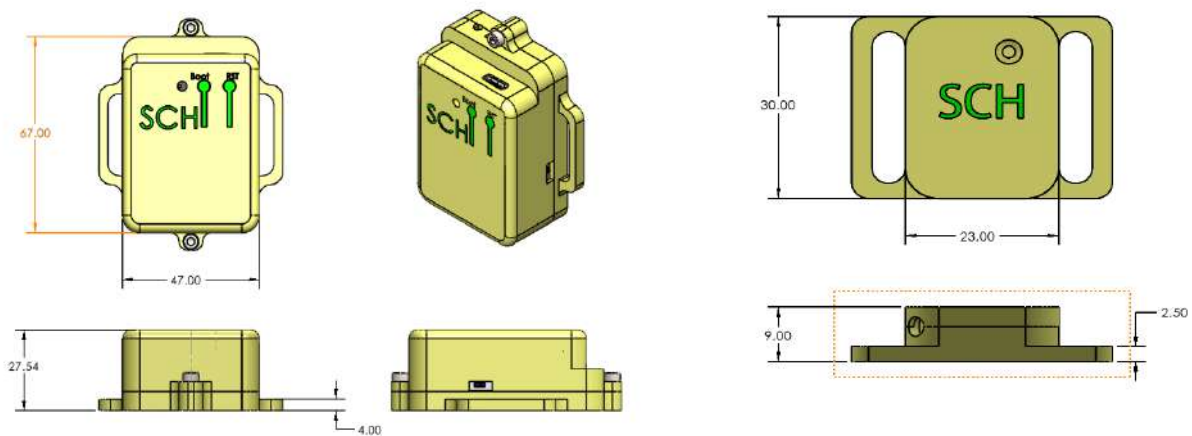


Figure 3 — Technical drawings of both enclosure bodies with overall dimensions

The main housing contains the 60×40 mm prototyping board with pin headers, the ESP32-C6 MINI microcontroller, the battery, the power switch, and the sensor set: a MAX30102 heart-rate and pulse-oximetry sensor, a MAX30205 body-temperature sensor, an SHT31 temperature/humidity sensor, and one LSM6DSOX 6-DoF IMU. Figure 4 shows the populated board and the assembled main housing.



Figure 4 — Main housing: populated board and assembled view

The physical placement of the individual sensors, the power switch and the USB-C port within the assembled device is shown in Figure 5, with each component indicated.

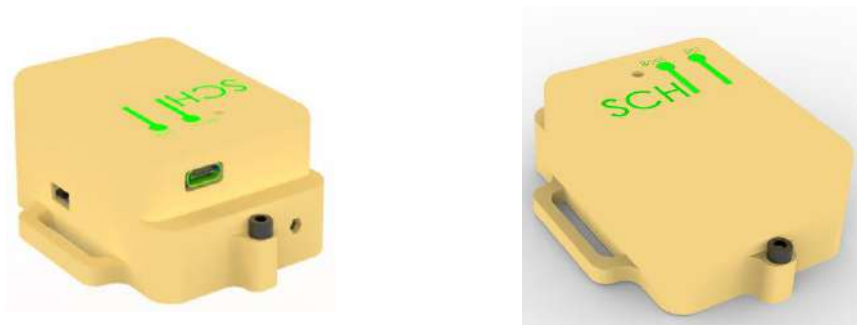


Figure 5 — Component, switch and USB-C port placement within the main housing

The second housing holds a single LSM6DSOX IMU, connected to the main unit by a 35 cm cable and intended to be fixed on the upper arm, so that arm posture and elbow angle can be derived from the relative orientation of the two IMUs. It is shown in Figure 6.



Figure 6 — Second housing containing the upper-arm IMU

2.4.1 Manufacturing

Both parts were manufactured by FDM 3D printing in PLA, with a total material consumption of approximately 50 g. Print parameters were set to 15% infill and a 0.18 mm layer height, balancing structural strength against print time and material use. PLA was selected for its ease of printing, dimensional stability and sufficient rigidity for a low-load wearable enclosure.

2.4.2 Assembly and fixation

The board is secured to the housing using three M2 bolts and heat-set threaded inserts, providing a reliable, reusable fastening interface directly into the printed body. The two halves of the enclosure are joined using two M3 bolts and heat-set inserts, allowing the housing to be opened for maintenance and reassembled without degrading the thread.

Both enclosure bodies include lateral slots along their edges, comparable to watch-case lugs, allowing a strap or cohesive wrap to be threaded through and secured. This provides an adjustable, hardware-free fixation method for both modules that accommodates different limb sizes.

2.4.3 Mechanical constraints observed

- Skin-contact sensors must sit flush against the skin with light, consistent pressure. Excessive pressure risks creating a sore; insufficient pressure corrupts both the optical and the thermal readings.
- The SHT31 must be exposed to the internal air volume rather than pressed against skin, or it will report skin conditions instead of the microclimate.

- The upper-arm IMU must be strapped so that its orientation is fixed relative to the humerus. Any slippage translates directly into angular error in the computed elbow angle.
- The battery sits in a recess where it cannot be compressed between the enclosure and an external surface.

The current enclosure is not water-resistant. Ingress protection is identified as an improvement for a future revision.

SmartCast

2.5 Firmware Design

The project uses simple, transparent algorithms that run in real time on low-cost hardware. No machine learning is used; every decision is based on physical signals, thresholds and time. This is a deliberate choice: rule-based detection is inspectable, adjustable by a clinician or parent, and requires no training data — which does not exist for this application.

2.5.1 Task architecture

The firmware follows a strict three-task design on FreeRTOS, chosen around two hardware constraints: the ESP32-C6 has no floating-point unit, so every float operation is emulated in software, and all sensors share one I²C bus.

- **I/O task (high priority).** The only task permitted to touch the I²C bus. It reads the two IMUs at approximately 100 Hz and the slow sensors (temperatures, humidity, pulse-oximetry, battery) at 1 Hz, pushing raw samples into a queue. Because exactly one owner drives the bus, transactions can never interleave and corrupt each other.
- **Fusion task.** Consumes the queue and performs all mathematics: orientation filtering for each IMU, the elbow angle, an activity level, and the on-device event detectors. Confining the slow software floating-point work here means it can never delay a bus transaction.
- **BLE task.** A pure consumer. It reads prepared results from a mutex-guarded shared state and notifies the phone at fixed rates. It performs no computation of its own.

2.5.2 Orientation and elbow angle

Each IMU runs a complementary filter: the gyroscope is integrated for fast, short-term rotation, and the accelerometer, which senses gravity, slowly corrects the accumulated drift. This gives each IMU a stable orientation estimate at approximately 100 Hz with very little computation — important given the absence of a floating-point unit.

The elbow angle is the relative orientation between the forearm and upper-arm IMUs, projected onto the hinge axis of the elbow. The axis is learned in a short guided calibration: the child holds still for a few seconds to establish gyroscope bias, then bends and straightens the arm a few times to establish the hinge axis and its sign. The result is stored in flash and survives restarts. The bias step has a timeout fallback, so calibration always completes within about eight seconds even if the child keeps moving.

2.5.3 Activity level

The amount of non-gravity acceleration, smoothed over time — a single scalar that separates a resting arm from a moving one and feeds most of the detectors.

2.5.5 Sensor roles on the shared bus

All sensors share one bus but serve distinct purposes, summarised in Figure 7.

Sensor	Quantity measured	Used for
2 × LSM6DSOX (IMU)	Acceleration + angular rate	Elbow angle, activity level, impacts, walking, exercise repetitions
MAX30205	Skin temperature	Fever / low-temperature alerts, cast-removal detection
SHT30	Air temperature, humidity	Comfort inside the cast, wet-cast alert, cast-removal detection
MAX30102	PPG (red / infrared light)	Heart rate and SpO ₂ estimation

Figure 7 — Sensor roles within the system

2.5.6 Data synchronisation and remote access

The phone acts as a store-and-forward gateway between the cast and the family server. It compresses the live streams into one compact record every 5 seconds — plus a record for every alert — appends them to a local journal with an increasing sequence number, and keeps 24 hours of history on the phone. Every 30 seconds it uploads pending records in batches; if the server is unreachable it retries later with increasing intervals.

The server answers four small API calls — ingest, summary, time-series and events — behind a family access key, and serves the parent dashboard: an installable web application (PWA) with live tiles, trend charts from 3 hours to 7 days, the share of calm time and a severity-graded alert log. Time series are bucketed on the server, so even a week of data returns as a few hundred points.

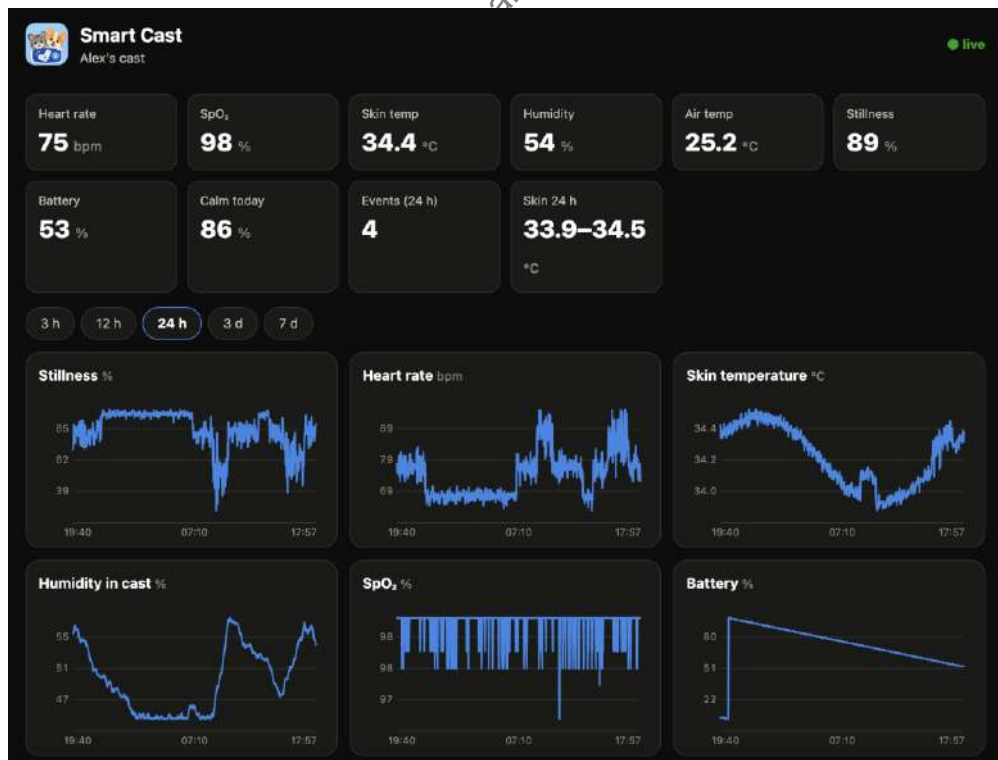


Figure 8 — Parent dashboard (server-side PWA)

2.5.7 Data protection

The system stores health-related data belonging to a minor, and the handling of that data is treated as a design constraint rather than an afterthought. Access to a family's records is gated behind a family access key, and the device itself holds no personally identifying information — records are keyed by device identifier and sequence number only.

2.6 Application Design

The mobile application (Flutter, one codebase for Android and iOS) deliberately has two faces: a playful, game-like mode for the child, and a password-protected area with clinical information for the parent. The same data drives both — the child sees a friendly companion, the parent sees numbers and alerts.

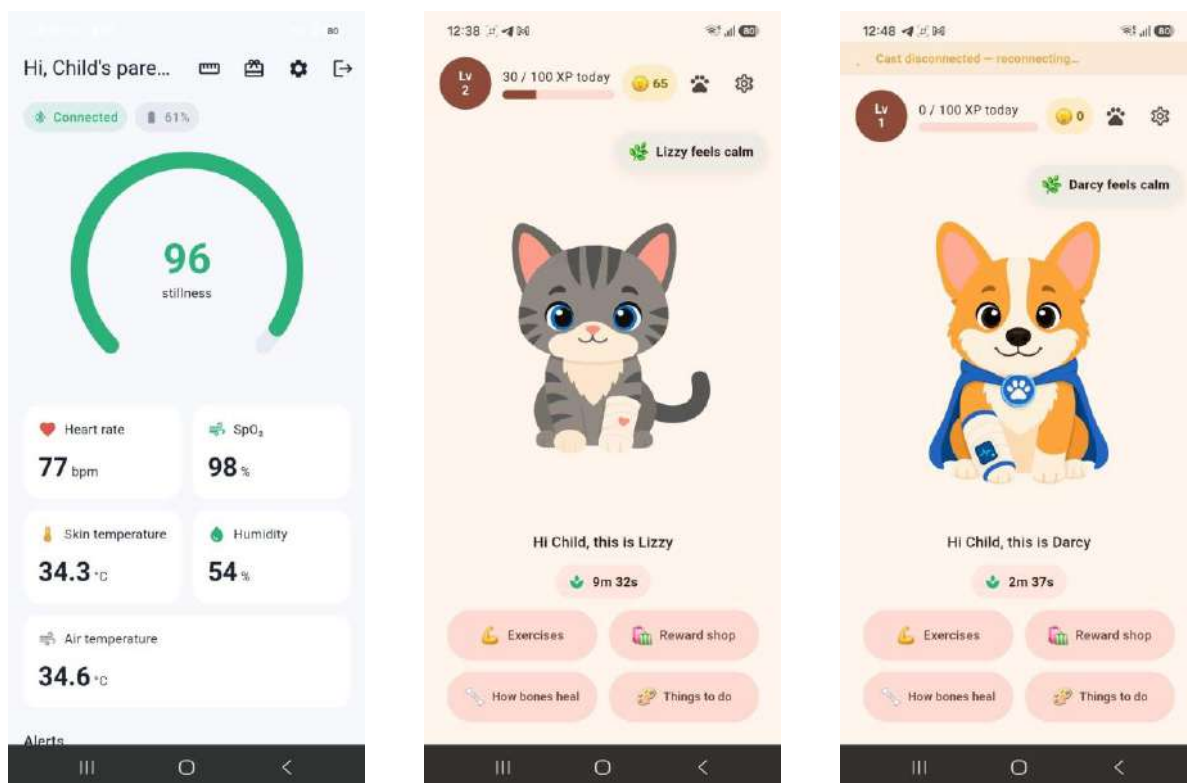


Figure 9 — Application screens

2.6.1 Child mode — the pet coach

The child is greeted by an animated companion: a cat, "Lizzy", or a dog, "Darcy". The pet speaks with a recorded child-friendly voice, reacts to real sensor data, purrs or barks when stroked, and is the channel through which every behavioural nudge is delivered.

Movement coaching is intentionally time-integrated rather than instantaneous. A restlessness value works like a leaky bucket: it rises while the arm moves (2 points/s) and drains while it rests (1 point/s). Sustained motion for roughly 4 seconds enters a visible warning state; continuing for roughly 12 seconds makes the pet sad and costs coins. Leaving the warning state requires the bucket to drain — staying genuinely calm — which prevents the on/off flicker that a naive instantaneous threshold produces. All coaching parameters are adjustable at runtime from a diagnostics screen.

When no cast is connected the pet says so and asks the child to fetch a grown-up. It never praises progress that is not being measured, and points are only earned while real data flows.

Feedback is exclusively positive-framed. The design deliberately avoids scolding, which risks concealment behaviour rather than compliance, and shifts the parent's role from enforcement to reward-granting.

2.6.2 Reward logic

Points are paced and predictable, so parents can reason about them:

Action	Coins	XP
Every 5 minutes of calm	+20	+40
Each exercise repetition	+5	+10
Daily exercise goal (20 repetitions)	+50	+100
Sustained excessive movement	-15	—

Every 100 XP raises the pet's level with a small celebration. Coins are spent in a reward shop whose catalogue the parent defines — a treat, an activity, screen time — and every redemption requires explicit parent approval in the app.

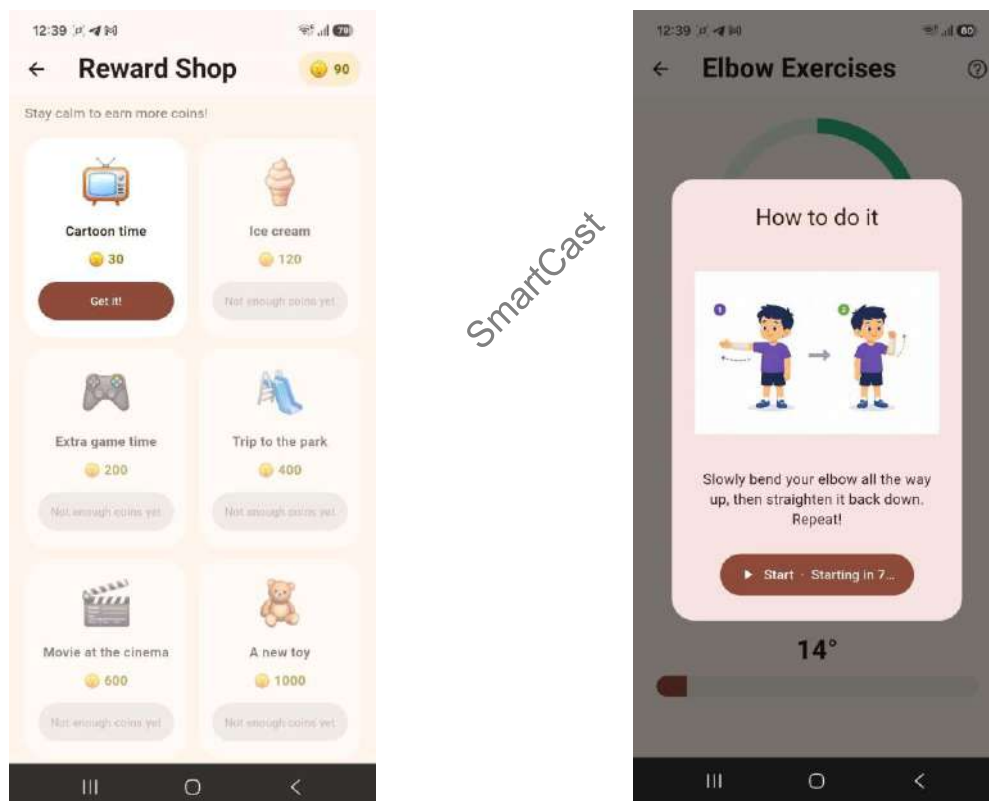


Figure 10 — Reward shop and progression screens

2.6.3 Rehabilitation exercises

The exercise screen counts elbow bends from the real measured angle: a repetition is a flexion beyond 90° followed by a return below 30°. The two thresholds act as hysteresis, so a shaky arm does not double-count. Each session starts with a fresh guided hinge-axis calibration, so the day's cast position never skews the angles. A live bend meter, a progress ring and the pet's encouragement close the loop, and new personal records in range of motion are celebrated.

2.6.4 Parent area

The parent area is password-protected and presents the clinical view of the same data: live values for skin temperature, cast humidity, heart rate and SpO₂; the current arm posture and daily activity summary; a severity-graded alert log; and trend charts from 3 hours to 7 days. The parent configures alert thresholds and movement sensitivity, defines the reward catalogue and its exchange rate, schedules exercise prompts, and reviews completion history. The history is exportable for the follow-up consultation — the objective record identified as missing in Part 1.

2.8 Testing and Validation

The prototype has been assembled and exercised under laboratory (home) conditions, where all subsystems were confirmed to function: the sensors enumerate on the bus, the elbow angle tracks arm movement, the detectors fire, the BLE link is stable, and the application and dashboard receive and display data end to end. No formal quantitative validation has yet been performed. The plan below defines the measurements required to substantiate the design goals.

Test	Method	Acceptance criterion	Result
I ² C bus enumeration	Bus scan; confirm all five devices respond, including both IMUs at distinct addresses	All addresses detected, no NACKs over an extended run	Pass (qualitative)
Tether integrity	Repeated flexion cycling of the 35 cm cable while monitoring for bus errors	No communication faults across the cycle count	Pass (qualitative)
Elbow angle accuracy	Compare computed angle against a goniometer reference across the range of motion	Error within target band across full ROM	Partially pass
Aggressive-movement detection	Scripted safe and unsafe motions; count true and false detections	High true-positive rate, acceptable false-alarm rate	Pass (qualitative)
Skin temperature accuracy	MAX30205 against a reference thermometer at controlled setpoints	Within datasheet accuracy	Pass (qualitative)
Humidity response	SHT31 against a reference in a controlled-humidity environment	Tracks reference within tolerance	Pass (qualitative)
Heart rate and SpO ₂	Compare against a commercial pulse oximeter	Agreement within a clinically acceptable margin	Partially pass
BLE range	Link quality measured at increasing distance, through the enclosure	Reliable link across typical indoor distances	Pass (qualitative)
Wear trial	Extended wear on a mock cast	No pressure points, no discomfort, no sensor displacement	Pass (qualitative)

2.9 Limitations and Future Work

2.9.1 Current limitations

- Gyroscope integration drift accumulates over time. The complementary filter corrects it against gravity, but long-duration angle estimates still require the periodic recalibration described in Section 2.5.2.
- Upper-arm IMU accuracy depends on strap fixation. Slippage relative to the humerus translates directly into angular error in the elbow angle.
- Optical pulse oximetry is sensitive to motion artefact and to variation in skin tone, and requires stable contact pressure to give reliable readings.
- The 35 cm cable crossing the elbow joint is the principal mechanical reliability risk of the design.
- The current build is a hand-wired prototype on perforated board rather than a fabricated PCB, which limits repeatability between units.
- The enclosure is not water-resistant.
- No formal quantitative validation has been completed, and no clinical study has been performed.
- The device is a monitoring and behavioural aid, not a diagnostic instrument, and does not replace clinical assessment.

2.9.2 Future work

- Custom fabricated PCB, reducing height, improving repeatability, and allowing a consolidated pull-up network, a proper antenna keep-out and optical isolation for the MAX30102.
- Replacing the wired tether with a second wireless node, eliminating the dominant mechanical failure mode at the cost of a second battery and time-synchronisation complexity.
- Completion of the quantitative test programme in Section 2.8, followed by a supervised wear trial.
- Extension of the architecture to lower-limb casts, where a hip–knee–ankle chain requires the same relative-orientation reasoning.