

KESTREL PROGRAM

KESTREL R1

A two-body worn scanner for the warehouse picker — the aim at the fingertip, the mass on the wrist. The full front end of an industrial-design program: the form, the human-factors case, the buildable spec, and what it takes to build.

INDUSTRIAL DESIGN · HUMAN FACTORS · HARDWARE & MANUFACTURING ENGINEERING · 28 SEPTEMBER 2026

The aim at the fingertip. The mass on the wrist.

The Kestrel R1 is **a two-body worn scanner**: a near-weightless scan module on the index finger, tethered by a flat flex bridge to a wrist-and-back-of-hand pack that carries every heavy part. The finger carries grams. The wrist carries the battery, the compute, and the radio. *Nothing that weighs anything rides the knuckle.*

That sentence is the whole design. The reference set proves the ceiling of the single-body ring — Zebra's RS5100 is the best in the world and it puts all **70 g** of optics, battery, radio, and trigger on one finger. Seventy grams is weightless for one scan. It is not weightless for eight thousand scans across a twelve-hour shift, cantilevered off the finger joint. ProGlove's MARK 3 answers by aiming from the back of the hand — and trades away the one thing the body does for free: it **points with the fingertip**.

Kestrel refuses the trade. Keep the aim at the fingertip; get the mass off the finger. The only way to have both is to split the body.



FIG. 01 The locked form, off the hand. Finger scan module, wrist pack, and the flat over-molded bridge that connects them — graphite PA66-GF shell, high-vis amber on every interaction and status point, cool-grey elastomer where the device meets skin and floor.

≤22 g	≤124 g	12 hr	IP65	3×
ON THE FINGER (A THIRD OF THE RS5100)	TOTAL WORN MASS DISTRIBUTED, NOT STACKED	SHIFT TARGET · HOT-SWAP ≈8,000 SCANS	SEALED · 1.8 M DROP MIL-STD-810H	FEEDBACK CHANNELS HAPTIC · AUDIBLE · OPTICAL

THE REFERENCE SET — AND WHERE KESTREL SITS

Zebra RS5100

Single body, 70 g — all of it on the finger. The category best, and the ceiling of the single-body approach.

ProGlove MARK 3

~40 g on the back of the hand — aims from the hand, and trades away the fingertip point.

Kestrel R1

≤22 g on the finger, the rest on the wrist. Fingertip aim **and** mass off the finger — the split is the only way to have both.

Four disciplines, one argument.

This dossier binds the full front end of the Kestrel R1 program. Each section is a discipline's case for the same physical object — the form drives the human-factors reasoning, the reasoning holds the form to its numbers, and the spec and cost pass make it buildable. Read it as one continuous argument, not four appendices.

03 – 05
Industrial design
The two-body argument, the form derived from the hand, the material logic, and the colorway defense. Why the finger carries grams and the wrist carries the load.

06 – 09
Human factors
The ergonomics case, reasoned against real anthropometrics and named standards — the mass/moment argument, the reach envelope, thermal limits, and the twelve-hour fatigue synthesis.

10 – 12
Technical specification
The buildable target spec — scan engine, connectivity, battery and runtime math, environmental ratings, materials, feedback, and the competitive-set reality check.

13 – 16
Cost & build path
The BOM by subsystem, tooling and NRE, the assembly and test picture, and the prototype-to-production roadmap — in USD, at a stated 25,000 units/year assumption.

THE SINGLE GOVERNING PRINCIPLE

gloved

ON THE NUMBERS IN THIS DOSSIER

Two registers appear throughout, and each is labeled where it is used. **Standards-bound facts** — IP ratings, MIL-STD-810H, symbologies, radio versions, temperature and contact-heat limits — reference real, checkable standards and real component classes. **Design targets** — masses, dimensions, runtime, cost — are the numbers the program commits to hit, reasoned from the measured data, and labeled as targets.

The cost figures are **program-kickoff estimates**, not quotes: no supplier has been RFQ'd and no unit has been built. Ranges are wide on purpose — that is the honest state of the numbers at kickoff.

Why two bodies.

The split is not styling. It is a moment argument: carry mass where the body carries it best, aim where the body aims naturally, and connect the two with something that disappears.

A — THE SCAN MODULE

FINGER · ≤22 G

Optics, aimer, scan window, the primary trigger, a status LED, a haptic tap. Roughly a third of an RS5100, because the battery and compute are gone. A low finger saddle with an integrated loop, riding the index finger; the smallest possible profile on the aiming digit, clearing bin lips reaching in.

B — THE WRIST PACK

WRIST · ≤78 G

Hot-swap battery, main board, BLE/Wi-Fi radio, the second trigger, and the loud feedback stack. It rides the back of the hand and cuffs the wrist — close to the wrist's rotational axis, off every joint that flexes during a pick.

THE BRIDGE

~4 G

A flat, ribbon-thin over-molded flex cable along the index metacarpal. Power and data. The only thing crossing the knuckle — 2 mm thick, cloth-soft on the skin side; the knuckle bends and the bridge folds with it.



FIG. 02 The architecture, split. The hot-swap cell pulls from the wrist-pack bay; the saddle, bridge, and pack separate at two tool-free connectors so a worn part is replaced at the cart, not sent back.

Form derived from the hand.

The scan saddle

- **Low saddle, integrated loop.** The ambidextrous single-finger form of the reference set. Anti-roll comes from the loop capture and the low center of mass, not from spanning two fingers.
- **Low and forward-raked ~15°.** The aim line follows where a relaxed pointing finger already looks — a label at chest-to-knee height without lifting the wrist. Target ≤ 15 mm above the finger, to clear a bin lip.
- **Recessed, hooded window.** The exit window sits back inside a molded hood; a dropped hand or a box corner strikes the shell, never the glass. The hood doubles as the aim reference.
- **Elastomer floor, hard-shell roof.** Soft where it touches skin, hard where it takes the hit.

The wrist pack

- **Rides the back of the hand, cuffs the wrist.** Dreyfuss applied literally: put the load on the structure built to carry it.
- **Wedge section** — ~8 mm thin at the knuckles so it never fights the hand closing, thickening to ~18 mm at the wrist where the battery lives and thickness costs nothing ergonomically. Mass biased rearward toward the wrist axis to shorten the lever arm.
- **Hot-swap is the shift-length answer.** Twelve hours is not a bigger finger cell — it is a slide-and-latch cell swapped in ~10 s at a cart without removing the wearable. Charging goes off-body entirely.
- **The feedback stack lives here** — the loud piezo and the strong LRA against the back of the hand, where a tap transmits into the wrist through a glove.

MATERIAL STORY

Hard where it must be stiff and take the hit, soft where it touches the human and where it meets the floor.

PART	MATERIAL
Structural shell	PA66-GF30, 30% glass-filled nylon — the enterprise-rugged default; stiff, dimensionally stable freezer-to-dock, takes a matte texture that hides scuffs
Grip & impact	Over-molded TPE/TPU, ~60–70 Shore A — soft, high-friction so the pack does not migrate; the sacrificial impact layer
Bridge	Flat flex circuit in a thin over-molded elastomer ribbon; sealed against sweat and condensation
Window	Hardened optical polycarbonate, recessed in the hood
Sealing	Elastomer gaskets at every sealed seam — the hard/soft split is chosen so the seams that must seal are gasketed

INTERACTION, THREE CHANNELS

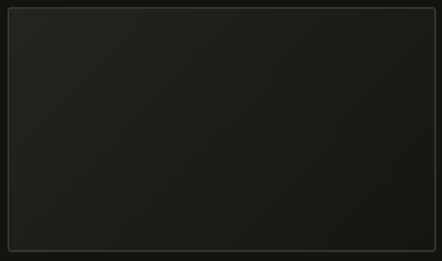
Two mechanical triggers — a proud amber paddle on the saddle flank, a second on the pack edge — either fires. Single press scans; press-and-hold enters continuous aim. Large, proud, edge-defined: a gloved thumb finds them by feel, no flush membrane buttons anywhere on the primary path.

HAPTIC	AUDIBLE	OPTICAL
Strong LRA into the wrist — felt through a glove	≥90 dB piezo — clears warehouse noise	LED in the aim sightline — green good / red error

The warehouse is loud, cold, and gloved — each environment defeats a different channel, so no single one is trusted alone. The human-factors section makes this a specific-failure-mode argument, not belt-and-suspenders caution.

Graphite, amber, grey — and why.

The color does interaction-design work, not decoration. Amber marks exactly the two things the picker touches and the two things they read; the dark body is a maintenance decision; the grey separates what is soft from what is structure at a glance.



BODY

Graphite / near-black

Matte PA66-GF. The enterprise-rugged register. A dark matte shell hides the scuffs, grease, and shelf-dust of a warehouse life, so the device still reads as equipment worth respecting after six months. Matte also kills glare under high-bay lighting.



ACCENT

High-vis safety amber

On the triggers, LED surrounds, strap pull-tabs, and one band on the pack. Found instantly by a gloved thumb; reads as safety equipment on a floor of hi-vis vests and hazard edges; marks precisely what the picker interacts with and reads.



CONTACT

Cool grey elastomer

On the non-accent soft parts — saddle floor, pack underside. Neutral, hides sweat-sheen, and separates the touch/impact material from the structure material so a glance tells you what is soft.

AMBER OVER SAFETY-YELLOW

Yellow-on-yellow disappears against a hi-vis vest. Amber holds contrast against both the black body and the vest — and reads as the warmer, equipment-grade signal, keeping the device in the tool family, not the wearable-toy family.

THE COLORWAY AS WAYFINDING

Three reasons the accent earns its place, none of them taste:

01 **Findability.** An amber trigger against a black body is found by a gloved thumb without looking — and by a supervisor checking a device is worn correctly.

02 **Safety register.** Hi-vis amber is the visual language of the warehouse floor, so the device reads as the safety equipment it is.

03 **Wayfinding.** The accent marks the two triggers and the two LEDs — interaction and status — and nothing else.

The anthropometric envelope.

The device must fit a hand from roughly **165 mm to 206 mm** long and **74 mm to 97 mm** across the knuckles — over a glove, on either hand. That is the fit problem three mount sizes solve.

Values are the design envelope — 5th-percentile female as the small bound, 95th-percentile male as the large bound — from the **2012 Anthropometric Survey of U.S. Army Personnel (ANSUR II)**, with finger-segment and wrist figures carried as the honest working ranges of the Dreyfuss measure-of-man tradition and labeled as such. Design to the span, not to either mean.

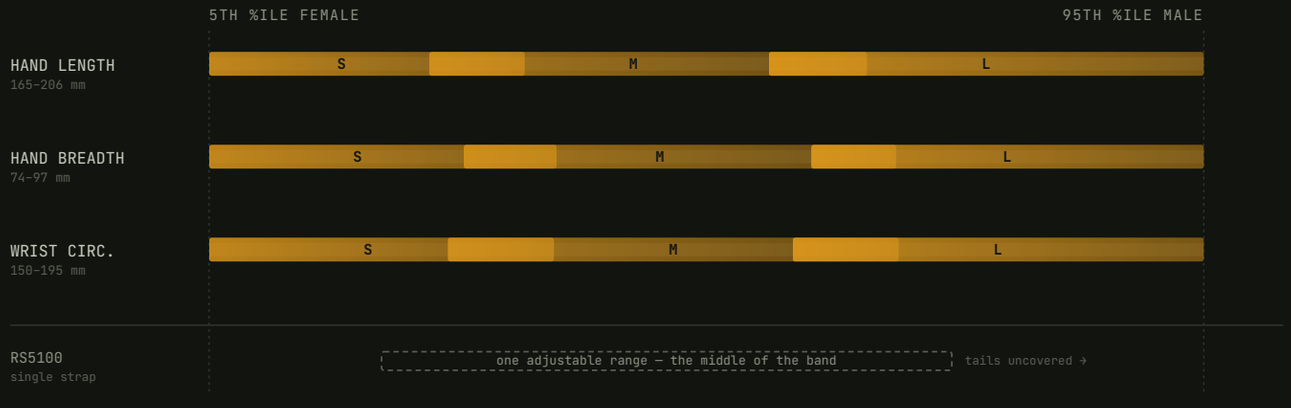
ANSUR II is a military sample — larger and leaner than a civilian warehouse workforce at the mean. Used as a conservative design envelope; every small-end fit call carries deliberate margin below the ANSUR II 5th-percentile female figure.

THE DIMENSIONS THAT DRIVE THE FORM

DIMENSION	5TH %ILE F	95TH %ILE M
Hand length	165 mm	206 mm
Hand breadth (knuckles)	74 mm	97 mm
Index finger length	62 mm	82 mm
Proximal phalanx (seat)	38 mm	52 mm
Wrist circumference	150 mm	195 mm

The saddle seats on the proximal phalanx — the shortest, most consistent zone. Its rigid seat must stay ≤ ~36 mm so it clears the 5th-percentile female first joint; the integrated loop, not the seat length, does the retention.

DIAGRAM 1 — THE PERCENTILE BAND Three sizes tile the whole band, with overlap. No gap left uncovered.



DIA. 01 Three shell sizes (S/M/L) plus cam-strap adjustment tile the 5th-female→95th-male band with ~4 mm overlap at each seam — hand length, breadth, and wrist circumference all covered end to end. A single adjustable strap can move circumference but not the rigid pack footprint or the finger-loop-to-wrist span, which is why the category ships multiple mount sizes.

The twelve-hour case is a moment, not a weight.

The fatigue problem was never the static weight. It is the *repeated moment about the finger joints across a shift* — and a moment is mass times its lever arm to the joint that carries it. The split attacks both terms.

On the finger, cut the mass. The saddle targets ≤ 22 g — a third of the RS5100's 70 g — because the battery, radio, and board have left. The finger-borne moment drops to **~31%** of the single-body case at the same lever arm.

On the wrist, collapse the lever arm. The pack's mass rides the back of the hand and cuffs the wrist, biased rearward toward the radiocarpal axis — a small moment about a joint built to carry load, unlike a finger joint.

THE MASS BUDGET — ONE AUTHORITATIVE TABLE

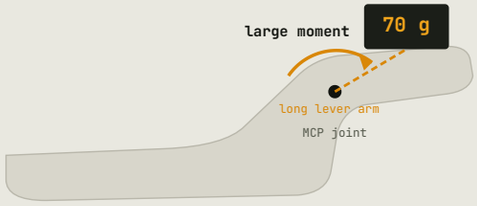
BODY	TARGET	MOMENT LANDS
Scan module `finger`	**≤22 g**	MCP joint — minimized
Wrist pack `wrist`	≤78 g	wrist / forearm — load-bearing
Flex bridge	~4 g	crosses knuckle — negligible
Mount / strap	~20–26 g	distributed skin contact
Total worn (M)	**≤124 g**	**distributed, not stacked**

The HF reasoning carries a ~55–75 g pack / ~80–100 g system range as the electronics-plus-battery envelope before the mount — argument, not a second headline. Total worn mass exceeds the RS5100's 70 g; that is not the fatigue metric and must not be read as one.

DIAGRAM 2 — THE MOMENT, TAKEN OFF THE FINGER

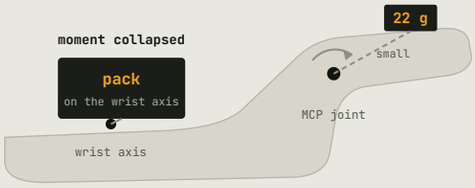
The same job. The load moved from a finger joint to the wrist.

SINGLE-BODY RING



Finger-borne mass: **70 g**

KESTREL R1 — SPLIT



Finger-borne mass: **≤22 g**

DIA. 02 The real comparison is not 80–100 g vs. 70 g. It is ≤22 g on the finger vs. 70 g on the finger — the finger taken from a 70 g cantilever to a ≤22 g one, the remaining mass moved onto the wrist and forearm at a near-zero lever arm. A heavier device that is comfortable all shift beats a lighter one that fatigues the finger by hour eight.

The honest caveat: the split adds a load the single body does not have — the strap contact pressure of the pack on the back of the hand across a shift. It trades a distributed skin-contact pressure, which the body tolerates for long periods, for a concentrated joint moment, which it does not. The trade is correct. It is not free, and it is addressed in the fatigue synthesis.

Sized for the hand that lost its senses.

A warehouse glove enlarges the digit, kills fine proprioception, and dulls light vibration. Every touch target and every feedback channel is designed for that hand — not the bare one.

The controls follow **MIL-STD-1472** gloved criteria, corroborated by ISO 9241-9 (20–25 mm minimum, 25–40 mm ideal for gloved operation). Triggers are large, proud paddles — found by gross feel, not fine feel — with a positive detent that is itself a fourth, mechanical confirmation the picker feels through the glove.

WHY THREE FEEDBACK CHANNELS

Not caution — a specific-failure-mode argument. Each environment defeats a different channel, and no two failures usually coincide.

CHANNEL	WHAT DEFEATS IT
Audible	Ambient noise — a busy DC runs 80–90 dB; ear protection common
Haptic	A thick cold-storage glove on a cold hand dulls light vibration
Optical	A glance away — the picker looks at the shelf, not the device

Good and error states differ on every channel independently — single tap + rising tone + green vs. double-tap + error tone + red — so whichever channel gets through still carries the distinction.

TRIGGER SIZING — MIL-STD-1472, BARE VS. GLOVED

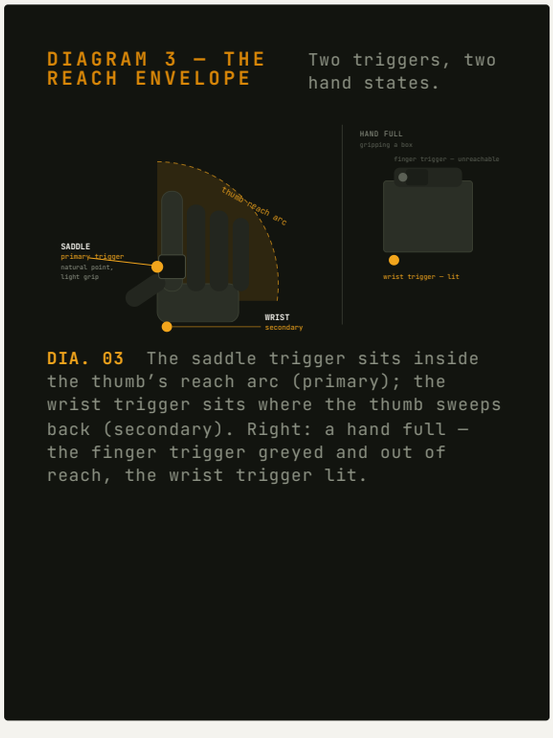
PARAMETER	BARE	GLOVED	TARGET
Thumb pushbutton, min ø	19	25	≥20*
Single-finger separation	13	25	—
Access to first joint	32	38	gloved
Actuation force (N)	2.8	~11	3–6
Felt travel (mm)	—	—	2–4

Dimensions in mm unless noted. *Paddle-style — a raised rim and long edge are findable across a wider search area than a round button. Below the ~2.8 N floor the trigger fires on incidental contact; a detent well above it and well below the ~11 N ceiling gives a felt click through the glove.



FIG. 03 The saddle up close — recessed hooded window at the fingertip end, the amber trigger paddle on the thumb-side flank, edge-defined for a gloved thumb.

Why two triggers. The saddle trigger sits under the naturally-falling thumb — the shortest, most neutral excursion the hand offers, in-envelope for the whole design band. The wrist trigger is for when the fingers are wrapped around a heavy box and the finger cannot extend to aim: the same thumb to the wrist, or the opposite hand. Either fires.



DIA. 03 The saddle trigger sits inside the thumb's reach arc (primary); the wrist trigger sits where the thumb sweeps back (secondary). Right: a hand full — the finger trigger greyed and out of reach, the wrist trigger lit.

Comfortable, all shift — and honest about the cost.

THE THERMAL LIMIT IS A STANDARD, NOT A PREFERENCE

The wrist pack holds the battery, board, and radio against the back of the hand for a full shift. The governing limit is **EN ISO 13732-1** (CENELEC Guide 29): for 8-hour-plus contact over a minor body area, the burn threshold converges to **43 °C** across materials.

43 °C
HARD SAFETY CEILING
EN ISO 13732-1, 8H+

~40 °C
COMFORT TARGET
GOAL ≤38–39 °C

Three levers keep the contact face under the line: dissipate away from the skin (heat-producing parts biased to the outer shell, shedding to moving warehouse air); keep steady-state draw low (a worn scanner draws current only in the sub-second decode window); and — the biggest win — **the hot-swap removes on-body charging entirely**, the worst thermal case for any wearable.

The cold-storage inversion: at 0 °C to −25 °C the device is the warm object and modest waste heat is welcome. The 43 °C ceiling is trivially met; the cold problem is battery chemistry and condensation — solved by the freezer cell and the sealed over-molded bridge.



FIG. 04 The hot-swap, mid-swap. A slide-and-latch cell changed in ~10 s at a cart without removing the wearable; a small buffer holds the BLE pairing across the swap so the host is never dropped. Charging happens off-body in a bay charger — runtime and thermal, solved at once.

THE TWELVE-HOUR SYNTHESIS — FOUR LOAD SURFACES, EACH ALREADY MITIGATED

FATIGUE SURFACE	MITIGATION IN THE LOCKED FORM
Finger-joint moment repetitive	≤22 g on the finger — ~31% of the single-body case. The dominant driver, cut to a third.
Pack contact pressure static	Mass on the flat of the hand and wrist, spread by a broad elastomer cuff; no hard edge on the styloid.
Thermal sustained	≤43 °C hard / ≤~40 °C comfort; on-body charging removed.
Sweat & maceration sustained	Launderable mount; sealing surface separated from a breathing skin-contact surface.



FIG. 05 Glove-over by default — the cam-and-hook-and-loop closure works by a gloved hand with no fine pinch; the amber pull-tab is the findable grab point. The mount is the cheap, launderable, replaceable part.

The scan action is a light, well-detented thumb press in the most neutral posture the hand offers, and the hands stay free to work between scans. On the metric that governs shift fatigue — finger-borne moment — the device is more defensible than the 70 g single body it is measured against, with the honest cost named and mitigated rather than hidden.

The scan engine.

Reference class: **Zebra SE4770-grade compact 1D/2D area imager** — the current-generation engine in best-in-class ring scanners. Production would source the SE4770 itself as an OEM engine, or an equivalent-class compact area imager.

ENGINE — SE4770 CLASS

PARAMETER	TARGET / SPEC
Engine type	Compact 1D/2D area (CMOS) imager, aimer + illumination
Optical resolution	1280 × 960 px
Aiming element	655 nm laser aimer dot
Illumination	Hyper-red 660 nm LED (warm-white option)
Field of view	~48° H × ~30° V
Angular tolerance	Pitch ±60° · Skew ±60° · Roll 360°
Ambient light	to ~107,000 lux
Motion tolerance	Reads on the move — ~4–5 m/s label sweep

The enterprise imaging + decode stack reads poorly-printed, scratched, dirty, low-contrast, and shrink-wrapped labels — what separates this engine class from a phone camera. Scan window: hardened optical polycarbonate, recessed inside the hood so a strike lands on the shell, never the glass.

WORKING RANGE — STANDARD ENGINE, BY DENSITY

SYMBOLOGY / DENSITY	NEAR	FAR
Code 39, 3 mil	7.6 cm	14.7 cm
Code 128, 5 mil	5.8 cm	24.9 cm
PDF417, 6.67 mil	6.4 cm	25.7 cm
DataMatrix, 10 mil	5.3 cm	27.9 cm
UPC-A, 100%	4.1 cm	63.2 cm
Code 39, 20 mil	4.1 cm	91.7 cm
QR, 20 mil	2.8 cm	44.5 cm

Practical envelope: a picker scans from a hand's-width (≈5 cm) to across a bin (≈60–90 cm) with no distance adjustment.

RANGE OPTION — LONG REACH

A long-range variant (Zebra SE55-class, IntelliFocus multi-focus) reads from ~5 cm to ~12.2 m — a top-rack pallet label from the floor. This is a **BOM/SKU option**, not the base engine (larger and pricier). Base SKU on the SE4770-class standard-range engine; offer long-range for cold-chain and high-bay accounts.

SUPPORTED SYMBOLOGIES

1D: Code 39, 128, 93, Codabar/NW7, Code 11, MSI, UPC/EAN, Interleaved 2 of 5, Korean 3 of 5, GS1 DataBar, Base 32.

2D: PDF417, MicroPDF417, Composite, TLC-39, Aztec, DataMatrix, MaxiCode, QR, Micro QR, Han Xin, Postal Codes.

OCR: OCR-A, OCR-B.

TRIGGERS — TWO, EITHER FIRES

A proud amber paddle on the saddle flank (same-hand thumb) and a second on the pack edge (opposite hand, or same thumb when the fingers are full). Single press scans; press-and-hold enters continuous aim. Trigger life rated for millions of actuations.

FEEDBACK & INDICATORS — THREE INDEPENDENT CHANNELS

HAPTIC

Strong LRA, wrist pack

A crisp tap on a good read, a distinct double-tap on a no-read — fired into the wrist, so it transmits through a cold-storage glove. A small saddle tap motor gives a local aim cue.

AUDIBLE

Piezo, ≥90 dB(A)

Distinct good vs. error tones, settable and mutable. A step up from the category's ~85 dB(A) at 10 cm — a deliberate margin for noisy freezer and dock floors, validated on the bench.

OPTICAL

Saddle LED + pack bar

A status LED in the aim sightline (green / red) plus a directional LED bar for left / right / straight pick-path guidance, and charge LEDs. No display — this is a peripheral.

Compute, radio, battery, environment.

COMPUTE & CONNECTIVITY

BLE PERIPHERAL

A cordless BLE/Wi-Fi **peripheral**, not an on-board Android computer — it pairs to a host and streams decoded data. On-board Android means a bigger SoC, a display, a much bigger battery, more heat, and 3–5× the BOM; the category leaders are all peripherals for that reason.

PARAMETER	SPEC
SoC / MCU	Nordic nRF52840-class — 64 MHz Cortex-M4F, 1 MB flash, integrated BLE 5.x + NFC
Primary radio	Bluetooth Low Energy 5.2 — HID + SPP, 90 m Class-1 LoS
Pairing	NFC tap-to-pair + scan-a-barcode fallback
Wi-Fi (option)	802.11ax (Wi-Fi 6) direct-to-network SKU
Storage	On-SoC flash + small QSPI for logs / connection-loss staging

BLE 5.2 as the floor beats the RS5100's 4.0. Base SKU is BLE-only — the right call for battery life and how the category deploys (paired to a wrist computer that carries the WMS client). Wi-Fi is offered where the account has no host device; it raises power and BOM.

BATTERY & THE RUNTIME ARGUMENT

HOT-SWAP

Prismatic Li-ion pouch, slide-and-latch in the wrist wedge. The whole reason the finger is ≤22 g is that the battery is not on it.

CELL	CAPACITY	USE
Standard	~1,300 mAh ~4.8 Wh	12-hr shift
Extended / freezer	~2,000 mAh ~7.4 Wh	Back-to-back / deep cold

The runtime math — 12 hr / ~8,000 scans

Per-scan (imager + decode + BLE), 8,000×	~1.2 Wh
Idle / standby over 12 hr	~1.5–2.0 Wh
Feedback stack, ~8,000 pulses	~0.3–0.5 Wh
Budgeted shift energy	**~3.0–3.7 Wh**

A ~4.8 Wh cell carries it with >25% reserve. Deliberately generous vs. the RS5100's proven 1.7 Wh: cold cuts capacity, and the hot-swap means never stranded.

Honest framing: the 8,000-scan / 12-hr target is an engineering budget, not a bench-measured result — no unit has been built. It descends from the reference device's proven envelope on a smaller cell plus a conservative margin. Bench validation is a named program milestone.

ENVIRONMENTAL RATINGS

IP65
BASE — DUST-TIGHT, WATER JETS. IP67 IMMERSION AS A SEALED-SKU OPTION.

1.8 m
DROP TO CONCRETE, MIL-STD-810H METHOD 516.8; 1,000 TUMBLES AT 0.5 M.

−30 °C
FREEZER SKU (FREEZER CELL + LOW-TEMP FIRMWARE). -20 °C BASE COLD.

MIL-STD-810H defines test methods, not a pass/fail grade — a spec is meaningful only when it names the method, height, surface, and number of drops, which this one does. The cold story is a battery story: the glass-filled nylon shell is dimensionally stable across the whole range; what limits cold operation is the cell. Storage -40 to +60 °C with battery; humidity 5–95% non-condensing; ESD ±15 kV air / ±8 kV contact.

MATERIALS — HARD WHERE IT TAKES THE HIT, SOFT WHERE IT TOUCHES THE HUMAN

Shell: PA66-GF30 glass-filled nylon — matte, hides scuffs, survives the drop canon. **Grip & impact:** over-molded TPE/TPU ~60–70 Shore A. **Window:** hardened optical PC, recessed. **Sealing:** elastomer gaskets at every seam. **Mount:** launderable webbing + metal cam buckle.

DIMENSIONS & MANAGEMENT

Scan module ~45×24×≤15 mm · **wrist pack** 8→18 mm wedge, ~70×50 mm · **bridge** ~2×12 mm. Config by NFC tap + barcodes + host tool; firmware OTA over BLE; PowerPrecision-style state-of-health. Left/right is a strap flip, not a second SKU.

Against the reference set.

Every competitor figure below is that vendor's own published number. Where Kestrel's target beats or trails theirs, the table says so plainly.

	KESTREL R1 (TARGET)	ZEBRA RS5100	ZEBRA RS6100	HONEYWELL 8670	PROGLOVE MARK 3
Architecture	Two-body	Single-body	Single-body	Two-body	Back-of-hand
Aim point	Fingertip	Fingertip	Fingertip	Fingertip	Back of hand
Finger mass	≤22 g	70 g	70 g	small	~40 g on hand
Total worn	≤124 g	70 g	70–76 g	136 g	~39–40 g
Engine	SE4770-class	SE4710 / 4770	SE55 long-range	Adaptus	Multi-range AF
Radio	BLE 5.2 +Wi-Fi6	BLE 4.0	BLE 5.2	BLE 2.1	BLE 5.0
Sealing	IP65 (IP67 opt)	IP65	IP65	IP54	IP65
Drop	1.8 m	1.8 m	1.8 m	1.5 m	2.0 m
Cold	-20 / -30 SKU	-20 °C	-30 °C	-20 °C	-20 °C
Shift / scans	12 hr / ~8,000	12 hr / 14,400	12 hr / swap	10 hr / ~6,500	12,000 / charge
Hot-swap	Yes (wrist)	Yes	Yes	No (fixed)	Yes

WHERE IT WINS

The only entry that keeps **fingertip aim** and gets the mass off the finger — ≤22 g vs. 70 g. The two-body split is the differentiator. Ships BLE 5.2 as a floor (beating the RS5100's 4.0), matches the leader's 1.8 m drop and IP65, and offers the freezer SKU.

WHERE IT MUST EARN ITS CLAIM

The 8,000-scan / 12-hr number is a **target, not yet measured** — the RS5100 proves 12 hr on far less energy and the larger cell has margin, but the program owes a bench measurement. The ≥90 dB piezo is a step up and must be validated. Total worn mass (≤124 g) is heavier than a single-body ring — the trade is deliberate: mass moved onto the wrist, where the body carries it, is worth carrying a little more total.

DECIDED IN THIS SPEC

- Two-body split; ≤22 g finger target
- SE4770-class standard-range imager as base engine
- Cordless BLE 5.2 peripheral (not on-board Android); NFC pairing
- Prismatic Li-ion hot-swap wrist cell; standard + freezer options
- IP65 base; 1.8 m / MIL-STD-810H drop; –20 °C base / –30 °C freezer SKU
- PA66-GF30 shell + TPE/TPU over-mold; three-channel feedback; two triggers; no display

OPEN QUESTIONS FOR THE PROGRAM

- **Wi-Fi SKU demand** — does the account base deploy with a host wrist computer (BLE-only is right) or without one (needs the 802.11ax SKU)? Changes the base BOM.
- **Long-range engine demand** — high-bay / across-aisle accounts justify the pricier SE55-class SKU.
- **IP67 demand** — washdown / immersion accounts justify the extra sealing engineering.
- **Bench validation of the runtime budget** — the 12-hr / 8,000-scan target must be measured on a prototype.

USD · EST. · 25,000 / YR
Program-kickoff estimates, not quotes

The BOM by subsystem.

Every figure is a program-kickoff estimate: no supplier RFQ'd, no tooling quoted, no unit built. Ranges are wide on purpose — that is the honest state at kickoff. Cost per unit is almost entirely a function of volume; the base assumption is **25,000 units/year, a ~3-year program (~75,000 lifetime)**.

SCAN MODULE (FINGER)

LINE ITEM	EST. USD
Imaging engine (SE4770)	$28–45
Window + hood	$0.4–0.8
Primary trigger	$0.6–1.2
Status LED + pipe	$0.2–0.4
Tap haptic	$0.6–1.5
Flex / interconnect	$0.5–1.0
Subtotal	**~$31–50**

The imager is ~90% of it.

WRIST PACK

LINE ITEM	EST. USD
Main board (PCB, assy)	$4–8
SoC (nRF52840-class)	$4–7
Battery cell (~1,300 mAh)	$3–6
Pack: BMS, contacts	$2–4
Hot-swap latch	$1.5–3.5
Strong LRA haptic	$1.5–3.5
Piezo, triggers, LEDs, NFC, buffer	$2.3–5.4
Subtotal	**~$19–34**

The SoC integrates the BLE radio — no separate radio part.

BRIDGE, HOUSINGS & MOUNT

LINE ITEM	EST. USD
Over-molded flex bridge	$2.5–5.0
Sealed connectors (×2)	$1.0–2.5
PA66-GF30 shell parts	$2.0–4.0
TPE/TPU over-mold	$1.5–3.0
Strap / mount soft goods	$2.5–5.0
Fasteners, adhesive, misc.	$2.0–4.0
Subtotal	**~$11.5–23.5**

Tooling amortized separately.

TOTAL BOM · BASE SKU · ~25K/YR

$61–107

Planning midpoint ~$85. The imager alone is 35–55% of the BOM — every cost conversation starts there. Second-tier drivers: the battery/hot-swap system and the quality LRA.

SKU DELTAS (ADDED TO BASE BOM)

OPTION	BOM DELTA	WHY
Long-range engine (SE55)	+$25–50	Bigger multi-focus engine
Wi-Fi 6 direct-to-network	+$8–18	Module + antenna + power; cuts runtime
Extended / freezer battery	+$3–5	Cold-optimized cell; spare packs too
IP67 sealing	+$2–5	Extra gasketing + validation NRE

Why the program needs volume.

BOM MOVES WITH VOLUME

ANNUAL VOLUME	BASE BOM/UNIT	DRIVER
1,000 / yr	~$115–135	No volume pricing; small-lot resin
10,000 / yr	~$95–105	Engine + SoC pricing moves
25,000 / yr	**~$85**	The plan's assumption
50,000 / yr	~$72–80	Best engine pricing; tools earn out

Below ~10k/yr this product is hard to build economically — the enterprise imager does not discount at hobby volume and the tooling has too few units to amortize against. This is a program that wants scale to work.

TOOLING AMORTIZES TO NOTHING AT SCALE

LIFETIME VOLUME	TOOLING $/UNIT
3k (1k/yr × 3)	$58–117 — punishing
30k (10k/yr × 3)	$6–12
75k (25k/yr × 3, base)	**$2.30–4.70**
150k (50k/yr × 3)	$1.20–2.30

At the base 75k lifetime, tooling adds only ~$2–5/unit against an $85 BOM — negligible. At 3k lifetime it adds $58–117 and the program does not pencil. **Tooling is not the cost problem at scale; it is the reason the program needs scale.**

HARD TOOLING NRE

TOOL	EST. NRE
Wrist-pack housing (2-shot)	$60–120k
Saddle + hood (2-shot)	$45–90k
Triggers, caps, small parts	$25–50k
Flex-bridge over-mold	$20–40k
Mount / strap (×3 sizes)	$25–50k
Total hard tooling	**~$175–350k**

Two-shot co-molding and three mount sizes are what make a two-body, two-material, three-size product's tooling expensive — named here so it is not a surprise.

FACTORY-GATE COGS — BASE SKU, ~25K/YR

LAYER	EST. USD/UNIT
BOM (midpoint)	~$85
Assembly labor	$4–9
Test + calibration	$2–5
Tooling amortization	$2–5
Yield reserve + scrap	$3–6
CM margin / overhead	$8–15
Est. factory-gate COGS	**~$105–125**

Operator cells with fixtures in a mid-tier CM line, not a lights-out line — a small, high-mix product with soft goods and over-molds. Every imager is tested and calibrated against a target board: a real station, real cycle time, real yield loss. Sealing verification adds a leak check, heavier for the IP67 SKU.

From concept to a unit you can hold.

THE PROTOTYPE PATH

The program does not go straight to tooling. The standard hardware gate sequence, and roughly what each costs:

PHASE	ROUGH COST
Proof-of-concept / breadboard prove the split, bridge, runtime	$25–75k
EVT — first real PCBs, soft housings	$100–250k
DVT — near-production, the environmental gauntlet	$150–400k
PVT — hard-tooled parts, pilot lot, certify	$150–400k

TO A BUILDABLE EVT PROTOTYPE YOU CAN HOLD AND DEMO

~$150–350k

4–7 months — dominated by the electrical + mechanical engineering and the first real boards. A working unit that scans, pairs, gives three-channel feedback, and holds its shape.

FULL FRONT-END NRE TO PRODUCTION READINESS

BUCKET	EST. USD
Hard tooling	$175–350k
Electrical (schematic, PCB, firmware)	$150–400k
Mechanical / ID engineering	$100–250k
Certification (FCC, CE/RED, BT SIG, laser, UN 38.3, IP, 810H)	$100–250k
Prototyping (EVT/DVT/PVT)	$150–400k
All-in to production readiness	~$675k–1.65M

TARGET UNIT COST & THE MARGIN STORY

BOM	~$85
Factory-gate COGS	~$105–125
Landed cost (+ freight, duty)	~$120–150
Fully-burdened cost basis	~$130–165

Against a ~$1,200–1,500 incumbent kit street price (Zebra RS5100), that is a healthy hardware gross margin — but the incumbents' real return is software, consumable batteries, and support, not the bare hardware. A new entrant prices as a hardware-led challenger in the **$500–1,000** band first and earns the incumbent tier once the ecosystem and the validated ergonomic claim mature.

THE COST PICTURE, IN THREE SENTENCES

01 **The imager is the program** — 35–55% of the BOM; the standard-vs-long-range engine choice is the biggest single lever.

02 **The program needs volume** — at 25k+/yr the tooling amortizes to $2–5/unit and the BOM lands near $85; below ~10k/yr the imager and tooling both refuse to discount.

03 **The margin exists, but the money is in the ecosystem** — a ~$130–165 unit against a $1,200+ kit is a comfortable hardware margin; price as a challenger first, earn the premium tier as the ecosystem and the validated claim mature.

What's decided. What's live.

A real program carries both. The form is locked and defensible on the numbers in this document; what remains is a list of verifications to close on the way from concept to production — each stated concretely enough to close, none of them a defect in the locked form.

DECIDED the locked form & base spec

- Two-body split — aim at the fingertip, mass on the wrist; **≤22 g finger** target.
- Single-finger scan saddle with integrated loop; wedge wrist pack, thin at the knuckles, thick at the wrist; flat over-molded flex bridge.
- SE4770-class standard-range imager as the base engine.
- Cordless BLE 5.2 peripheral (not on-board Android); NFC tap-to-pair.
- Prismatic Li-ion hot-swap wrist cell; standard + extended/freezer options.
- IP65 base; 1.8 m / MIL-STD-810H drop; –20 °C base, –30 °C freezer SKU.
- PA66-GF30 shell + TPE/TPU over-mold; graphite / amber / grey colorway.
- Three-channel feedback; two triggers; ambidextrous S/M/L glove-over mount; no display.

LIVE the next-phase verifications

01 **Runtime budget on hardware** — the 12-hr / ~8,000-scan target is a calculated budget; measure actual per-scan and idle draw on a prototype.

02 **Saddle rigid-body length ≤~36 mm** — the one fit dimension that bites the 5th-percentile female first joint; confirm against the locked geometry.

03 **L wrist strap over a cold-storage glove at the 95th-percentile male wrist** — the one live sizing item; a short strap strands a picker. Add ≥15–20 mm over the bare figure.

04 **Contact-surface temperature ≤43 °C / ≤~40 °C comfort** — verify on a thermal mock-up under a realistic picking duty cycle; the limit is surface temperature at the skin.

05 **Trigger force ~3–6 N with a detented click felt through a glove**; and **haptic strength verified through a cold-storage glove on a cold hand** — the whole three-channel argument rests on it.

06 **≥90 dB piezo** validated on the bench; **ambidextrous LED-bar mapping** confirmed correct when the pack is flipped.

07 **Separate the IP-sealed surface from the breathing skin-contact surface** on the back-of-hand pad — a detail to close in ID.

The finger carries grams. The wrist carries the load. The aim stays where the body aims for free — and every number that claim rests on is named, sourced, and honest about what is still owed.