TEST REPORT · INSTRUMENT VALIDATION

Static linearity of the PaddleMate Pro strain-gauge paddle-shaft sensor on a carbon dragon-boat paddle, 5–20 kg

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Report number	PM-TR-2026-03
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Device under test	PaddleMate Pro, single strain gauge, offset zeroing before each reading, BLE data transfer
Software	In-house PaddleMate calibration tool; two-point (unloaded → loaded) slope per loading
Specimen	Production carbon dragon-boat paddle, blade ≈ 580 mm; T-grip clamped to the table, shaft on a support 180 mm from the shaft–blade junction; Pro 100 mm from the support towards the grip
Loading	Dead weights hung at mid-blade (lever arm 470 mm from the support); 4.944, 9.880, 14.594 and 19.410 kg; 32 independent loadings, 23 evaluated after sensor warm-up
Reference	Masses weighed on a calibrated, verified scale, 1 g resolution, ±2 g maximum error
Ambient	18 °C laboratory
Measurand	Linearity of the sensitivity (counts per kg) over 4.9–19.4 kg; re-hang scatter

ABSTRACT

Background. A shaft-mounted force sensor is usually calibrated at one known load and then used over a wide force range. This is valid only if the sensor output is proportional to load, so linearity has to be shown on the real paddle, in the geometry where the calibration slope is produced [3, 4].

Methods. A PaddleMate Pro was mounted on a production carbon dragon-boat paddle. The T-grip was clamped to a table, the shaft rested on a support 180 mm from the shaft–blade junction, and the sensor sat 100 mm from the support towards the grip. Dead weights were hung at mid-blade, 470 mm from the support. Four cumulative loads of 4.944, 9.880, 14.594 and 19.410 kg were built from masses weighed on a verified scale (±2 g). Each loading was an independent two-point calibration: unloaded reading, mass hung, loaded reading, slope in counts per kg. Masses were removed and re-hung between loadings. The sensor was switched on immediately before the session, so the first nine loadings, taken during warm-up, were excluded; 23 loadings (5, 8, 6 and 4 per level) were evaluated. Level means were compared with a straight line through zero.

Results. The line through zero had a slope of 33.68 counts/kg ($R^2 = 0.99999$). The level means deviated from it by −0.90%, −0.60%, +0.21% and +0.10% of reading, equal to −0.05, −0.06, +0.03 and +0.02 kg. The largest deviation was 0.31% of full scale. A best-fit line with intercept left a non-linearity of 0.16% of full scale. Re-hang scatter of a single loading was 0.03–0.08 kg (CV 0.3–0.5% at 9.9–19.4 kg, 1.2% at 4.9 kg). Loadings taken during warm-up read 2.8% low.

Conclusion. On a real paddle the warmed-up Pro is linear within ±0.9% of reading and 0.06 kg (0.6 N) over 4.9–19.4 kg, and within ±0.6% of reading from 9.9 kg upward. A single slope from a two-point calibration is therefore valid across this range. Because the scatter of one re-hang exceeds the non-linearity, the calibration should be made after warm-up, as the mean of several re-hangs with a mass of about 10 kg or more.

KEYWORDS dragon boat; instrumented paddle; strain gauge; static calibration; linearity; two-point calibration

1. Introduction

Force and power on instrumented paddles are the primary measurements in paddle-sport performance research, because the paddle is where the athlete's effort enters the water [1, 2]. A shaft-mounted strain gauge does not measure force directly; it measures shaft bending, which is converted to force by a calibration slope. Practical calibrations, including that of the PaddleMate Pro, determine this slope from one known load and an unloaded reading. The slope is then applied to every stroke, from light paddling to peak race force.

That procedure is only correct if the output is proportional to load. Published validations of instrumented paddles therefore apply several known loads and report the error at each [3, 5]. Goreham and Ladouceur showed that accuracy outside the calibrated range cannot be assumed [4]. Laboratory jigs typically use straight tubes or dedicated fixtures. Dragon-boat paddles, however, have a long, stiff blade and a T-grip, and the user calibrates them on the paddle itself.

This report tests the linearity of the PaddleMate Pro on a production carbon dragon-boat paddle, in the same kind of support geometry used for field calibration. It asks two questions. Does the two-point slope depend on the calibration mass? And how large is the error if one slope is used from 5 to 20 kg?

2. Nomenclature

Table 1. Symbols used in this report.

Symbol	Meaning	Unit
m	reference load, weighed mass	kg
y_i	output change of loading i, loaded minus unloaded reading	counts
S_i	two-point sensitivity of loading i, y_i / m	counts/kg
$\bar{y}$, $\bar{S}$	mean output change and mean sensitivity of one load level	counts, counts/kg
b	slope of the least-squares line through zero	counts/kg
a	lever arm from the support to the load, 470 mm	mm
FS	full scale, output at the largest load (19.410 kg)	counts
CV	coefficient of variation (relative standard deviation), 100 $s/\bar{x}$	%

3. Materials and methods

3.1 Device and software

The PaddleMate Pro is a paddle-shaft force and power sensor with a single strain gauge. It zeroes its offset before each reading and transmits data over Bluetooth Low Energy. Calibration used the in-house PaddleMate calibration tool. For each loading, the tool records an unloaded reading, then a loaded reading after the mass is hung, and computes the two-point sensitivity

$$S_i = (R_{\mathrm{loaded},i} - R_{\mathrm{unloaded},i}) / m = y_i / m \tag{1}$$

The tool's export of the unloaded and loaded readings had already been offset-compensated, so they are not raw ADC levels and are not analysed as such. The sensitivity S_i is a difference divided by mass and does not depend on the offset. It is the quantity analysed in this report, and $y_i = S_i m$ is derived from it.

3.2 Specimen and loading geometry

The specimen was a production carbon dragon-boat paddle with a blade of about 580 mm (Figure 1). The T-grip end of the shaft was clamped to a table. The shaft rested on a support 180 mm from the shaft–blade junction, and the blade overhung the table edge. The Pro was mounted 100 mm from the support towards

the grip, so the grip clamp was 500 mm beyond the sensor. Loads were hung from the blade at mid-length, 290 mm from the junction, giving a lever arm of a = 470 mm from the support.

The hanging load tips the paddle over the support, and the grip clamp holds the shaft down. The bending moment is largest at the support, $F\,a$, and falls to zero at the grip. If the grip is idealised as a hold-down pin, the moment at the sensor is 500/600 of the support moment, about 0.39 m × F. A rigid clamp would lower this value slightly. In either case the moment at the sensor is proportional to the load, which is the property tested here. Because each slope is determined in this same geometry, the exact clamp stiffness does not enter the result.

Over the test range the force at the blade was 48.5–190.3 N (with g_0 = 9.80665 m s^{-2}), and the moment at the support was 22.8–89.5 N m. A 10 mm error in the hanging position changes the lever arm by 2.1%.

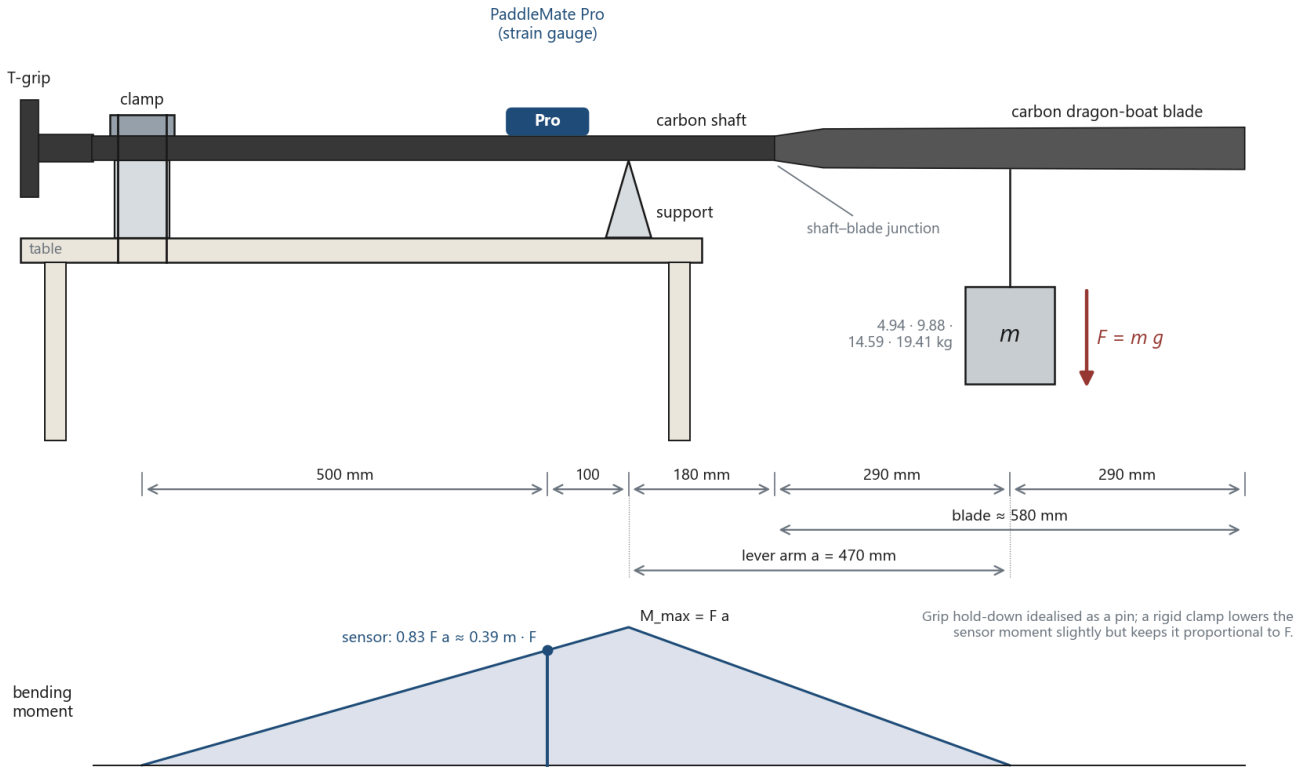


Figure 1. Test set-up, side view (schematic, not to scale vertically). The T-grip is clamped to the table, the shaft rests on a support 180 mm from the shaft–blade junction, and the PaddleMate Pro sits 100 mm from the support towards the grip. Dead weights hang at mid-blade, 470 mm from the support. Bottom: bending moment along the paddle with the grip idealised as a hold-down pin. The sensor sees about 0.83 of the support moment.

3.3 Reference loads

Four masses were weighed on a calibrated, verified scale with 1 g resolution and a maximum permissible error of ±2 g: 4944, 4936, 4714 and 4816 g. They were combined cumulatively into the nominal 5, 10, 15 and 20 kg levels, giving actual loads of 4.944, 9.880, 14.594 and 19.410 kg. Treating the ±2 g limit as a rectangular distribution gives a standard uncertainty of 1.15 g per mass [7]. The combined standard uncertainty of the largest load is 2.3 g, or 0.012%, and is at most 0.023% at the smallest load. This is two orders of magnitude below the effects reported here and is neglected.

3.4 Procedure

Measurements were made at 18 °C on 14 November 2026 between 13:51 and 14:06 (tool time stamps). For each loading the unloaded reading was taken, the mass was hung at mid-blade, the loaded reading was

taken, and the mass was removed. Each loading was therefore a complete, independent two-point calibration, including re-placement of the mass. The order was 4.944 kg (9 loadings), 9.880 kg (8), 4.944 kg again (5), 14.594 kg (6) and 19.410 kg (4), 32 loadings in total.

Warm-up. The Pro was switched on immediately before the first loading. The first block of nine 4.944 kg loadings (13:51–13:55, the first four minutes after switch-on) was therefore recorded while the sensor was warming up. These loadings are excluded from the linearity evaluation, which characterises the warmed-up sensor. They are shown in Figure 3 and summarised in Section 4.3, and the result with all 32 loadings is given in Table 3. The 4.944 kg level is represented by the second block (13:59–14:00), recorded after the 9.880 kg block.

Correction of one data-entry error. In one loading (14:01:59) the mass was typed into the tool as 1.46 kg instead of 14.59 kg; the trailing digit was omitted. The tool therefore reported 336.05 counts/kg. The output change stored with it, 336.05 × 1.46 = 490.6 counts, matches the other 14.594 kg loadings (482–497 counts). The loading was recomputed with the actual mass, giving 33.61 counts/kg. The cause is documented and the correction does not change the measurement, so the loading was retained. It is marked in Figure 3.

3.5 Evaluation

For each level, the mean, standard deviation and CV of S_i and y_i were computed. The scatter between loadings at one level, obtained under repeatability conditions [6], is the re-hang scatter. It contains sensor repeatability, the position of the hanger on the blade and the seating of the paddle on its supports. The level means average this scatter out and are the basis of the linearity evaluation, following the step-wise approach used for force-measuring instruments [8].

Two reference lines were fitted:

- **Line through zero**, $\bar{y} = b\,m$, fitted by least squares to the four level means. This is the model the device actually uses: offset zeroed, one slope. The deviation of each level mean from this line is the error a user would see with a single calibration slope. It is reported as a percentage of reading and of full scale.
- **Best-fit line with intercept**, fitted to all evaluated loadings. Its residuals give the independent non-linearity, i.e. curvature alone. The intercept indicates any constant offset in the loaded-minus-unloaded difference.

Apart from the warm-up block described in Section 3.4, no loading was excluded.

4. Results

4.1 Sensitivity and re-hang scatter per level

Table 2. Two-point sensitivity and output change per load level, warmed-up sensor (23 loadings). *s*: standard deviation of single loadings. Deviation: level mean relative to the line through zero, b = 33.68 counts/kg.

Load, kg	*n*	$\bar{S}$, counts/kg	*s*(*S*), counts/kg	CV	$\bar{y}$, counts	*s*(*y*), kg equiv.	Deviation, % reading	Deviation, % FS	Deviation, kg
4.944	5	33.37	0.41	1.22%	165.0	0.060	−0.90	−0.23	−0.045
9.880	8	33.47	0.10	0.29%	330.7	0.029	−0.60	−0.31	−0.060
14.594	6	33.75	0.16	0.49%	492.5	0.071	+0.21	+0.16	+0.030
19.410	4	33.71	0.14	0.42%	654.3	0.081	+0.10	+0.10	+0.019

FS = 653.7 counts (b × 19.410 kg). kg equivalent = counts / b. 1 kg ≙ 9.81 N.

The mean two-point sensitivities of the four levels lay between 33.37 and 33.75 counts/kg, and from 9.9 to 19.4 kg within 0.82% of each other (Table 2). At 4.9 kg the mean was 0.9% below the fitted slope and the

relative scatter was larger (CV 1.2%).

In absolute terms the re-hang scatter was similar at all levels, 0.03–0.08 kg (0.3–0.8 N) per loading. It did not grow in proportion to the load. A constant absolute scatter becomes a larger percentage at a smaller load, which is why the CV at 4.9 kg is several times the CV at the higher loads. At 9.9–19.4 kg a CV of 0.3–0.5% corresponds to a hanger position error of about 1.4–2.3 mm on the 470 mm lever arm.

4.2 Linearity

Table 3. Linearity summary. First two rows: warmed-up sensor. Last row: all loadings, for completeness.

Model	Slope, counts/kg	Intercept, counts	R^2	Max. |dev.|, % FS	Max. |dev.|, % reading
Line through zero, level means (device model)	33.68	0 (fixed)	0.99999	0.31	0.90 (4.9 kg)
Best-fit line, 23 loadings	33.89 ± 0.09	−3.2 ± 1.1	0.99986	0.16	–
Line through zero, all 32 loadings incl. warm-up	33.66	0 (fixed)	0.99998	0.53	2.08 (4.9 kg)

± values are standard errors. R^2 for the line through zero is computed about zero. 33.68 counts/kg = 3.434 counts/N. An intercept of −3.2 counts corresponds to about −0.09 kg.

The output was proportional to load across the range (Figure 2). With the device model, a single slope through zero, the largest deviation was 0.31% of full scale, at 9.9 kg. All level means were within ±0.9% of reading of the same line, and from 9.9 kg upward within ±0.6%. In absolute terms no level mean was more than 0.06 kg (0.6 N) from the line. 21 of the 23 single loadings were within ±1% of the fitted slope.

The best-fit line with intercept left a non-linearity of 0.16% FS, so the response itself has little curvature. Its intercept, −3.2 ± 1.1 counts (about −0.09 kg), is small; what remains of the deviation from the line through zero behaves like a small constant shortfall in the loaded-minus-unloaded difference, which is relatively largest at the smallest load.

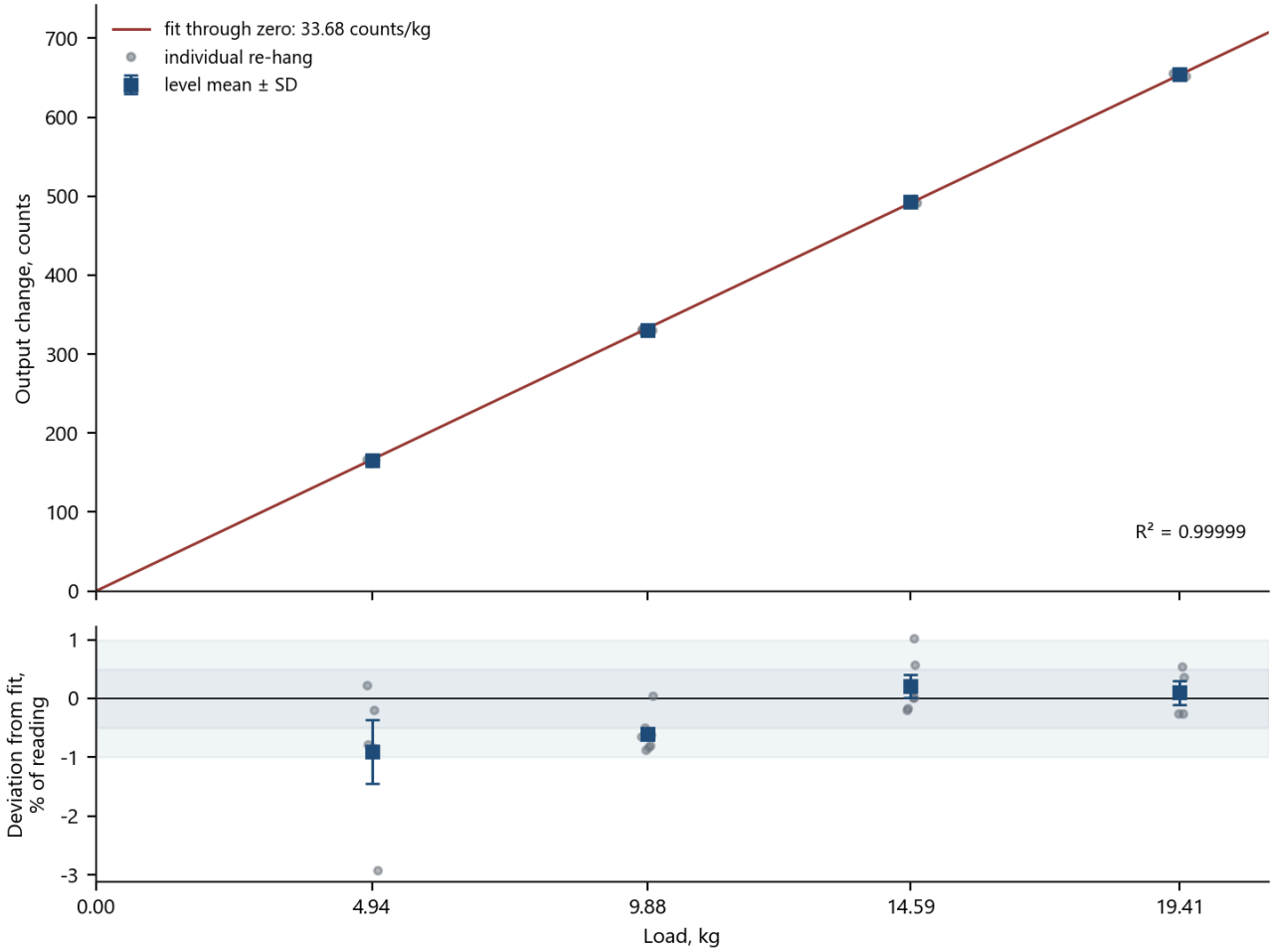


Figure 2. Warmed-up sensor, 23 loadings. Top: output change against reference load. Grey: individual loadings (slightly jittered horizontally). Blue squares: level means ± *s*; the error bars are smaller than the markers. Red line: least-squares line through zero, 33.68 counts/kg. Bottom: deviation from that line in % of reading. Grey: individual loadings. Blue: level means ± standard error. Shaded bands: ±0.5% and ±1%.

4.3 Time course and warm-up

Figure 3 shows all 32 loadings in time order. The nine loadings recorded in the first four minutes after switch-on had a mean sensitivity of 32.73 counts/kg, 2.8% below the slope of the warmed-up sensor, and a CV of 1.7%. When the same 4.944 kg mass was re-hung after the 9.880 kg block, it gave 33.37 counts/kg with a CV of 1.2%. If the warm-up loadings were included, the largest deviation from the line through zero would rise from 0.31% to 0.53% FS (Table 3). The warm-up effect is therefore larger than the non-linearity of the sensor and has to be avoided in calibration and use.

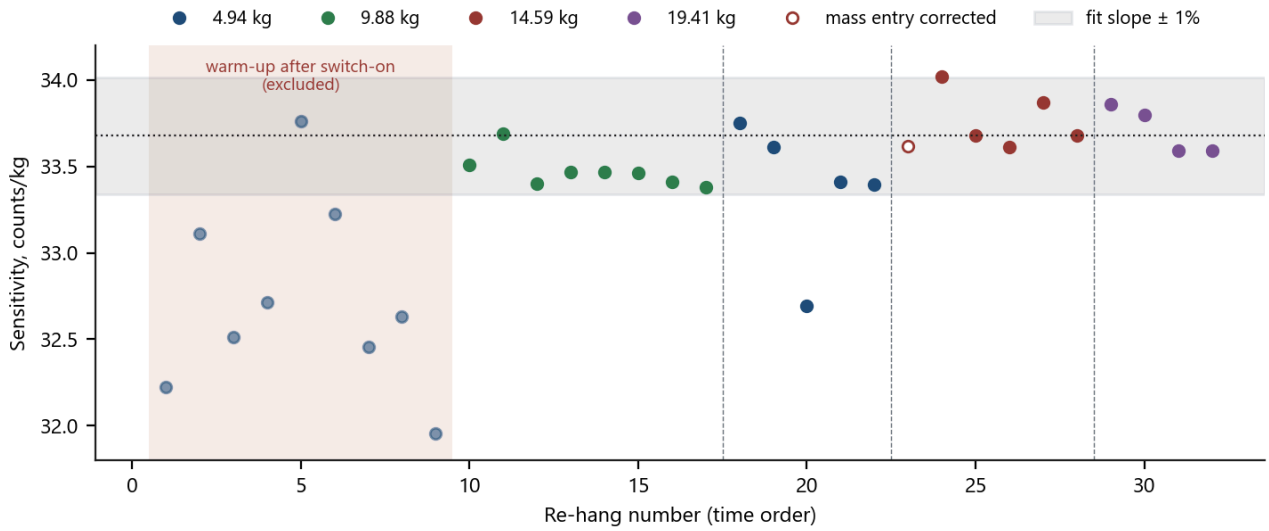


Figure 3. Two-point sensitivity S_i of all 32 loadings, in time order. Colour: load level. Shaded: first four minutes after switch-on (warm-up, excluded from the linearity evaluation). Dashed vertical lines: changes of level. Dotted line: slope of the line through zero; shaded band: ±1%. Open marker: loading with the corrected mass entry (Section 3.4).

5. Discussion

On a production dragon-boat paddle, the warmed-up PaddleMate Pro produced a two-point sensitivity that was essentially independent of the calibration mass: the level means differed by at most 1.1% between 4.9 and 19.4 kg and by 0.82% between 9.9 and 19.4 kg. Used with a single slope through zero, its error was at most 0.06 kg (0.6 N), or 0.31% of full scale. Above 9.9 kg the error was within ±0.6% of reading. For comparison, Rosdahl et al. reported static errors of −3.4 to +3.0% for a commercial instrumented kayak shaft between 98 and 590 N [3].

Warm-up. Loadings in the first minutes after switch-on read 2.8% low, more than the non-linearity of the warmed-up sensor. Seating of the paddle on the support and in the grip clamp during the first loadings may have contributed, and this test cannot fully separate the two. In either case, readings taken directly after switch-on should not be used for calibration.

Low-load deviation. The remaining shortfall at 4.9 kg, −0.9% of reading, behaves like a small constant offset of about −0.05 to −0.09 kg rather than a curve. The absolute re-hang scatter was about the same at every load. Friction or play at the support, the clamp or the hanger would act as a nearly constant force and would affect the light load most in relative terms. The planned loading–unloading (hysteresis) test will address this.

Consequence for calibration. The re-hang scatter of a single loading, 0.3–0.5% at 10–20 kg and 1.2% at 5 kg, is larger than the non-linearity above 10 kg. The accuracy of a two-point calibration is therefore limited mainly by warm-up and by how the mass is placed, not by linearity. Three practical rules follow:

- Switch the sensor on and let it warm up before calibrating.
- Calibrate with a mass of about 10 kg or more. At 4.9 kg, single loadings of the warmed-up sensor ranged from −2.9% to +0.2% of the fitted slope.
- Use the mean of several independent re-hangs, for example five. With a single-loading CV of 0.3–0.5%, the mean of five has a standard error of about 0.13–0.22%.

Relation to the dynamic results. The stroke-to-stroke repeatability of the PaddleMate Nano under a pneumatic load was 0.99% CV [12]. That result applies to the Nano. The dynamic repeatability of the Pro has not yet been measured and will be reported separately. The present report addresses the static side: a calibration slope taken at one load applies to the other loads in the range to within a fraction of a per cent.

Training equipment with displayed power is classified by accuracy in ISO 20957; for rowing machines, class A requires ±10% above 50 W [10, 11]. The static non-linearity found here is more than an order of magnitude below that tolerance.

Limitations.

- One device, one paddle, one temperature (18 °C) and one session were tested.
- Only static loading was tested. Stroke-to-stroke repeatability of the Pro under dynamic load was not measured.
- The sensor was switched on immediately before the session; the first nine loadings were recorded during warm-up and excluded. The warm-up time needed was not determined.
- Loads were applied in increasing order. Loading–unloading hysteresis was not tested.
- The number of evaluated loadings differed between levels (5, 8, 6 and 4). The highest level, with n = 4, has the least precise mean.
- The load acted at a fixed point at mid-blade. On water the centre of pressure moves during the stroke, which changes the lever arm [9]. This affects the conversion from shaft moment to blade force, not the linearity of the sensor.
- The highest load, 190 N at the blade, is below race peak forces. Linearity beyond 19.4 kg was not tested [4].
- The exported unloaded and loaded readings were offset-compensated by the software. Absolute ADC levels, and therefore zero drift during the session, could not be evaluated.

6. Conclusion

On a production carbon dragon-boat paddle at 18 °C, the warmed-up PaddleMate Pro was linear over 4.9–19.4 kg (48–190 N at mid-blade). With a single slope through zero, as the device uses it, the largest deviation of a level mean was 0.31% of full scale and 0.06 kg (0.6 N); all level means were within ±0.9% of reading, and within ±0.6% from 9.9 kg upward. A best-fit line left a non-linearity of only 0.16% of full scale. The re-hang scatter of a single loading, 0.03–0.08 kg, exceeded the non-linearity above 10 kg.

A two-point calibration slope is therefore valid across the tested range. It should be determined after warm-up, with a mass of about 10 kg or more, as the mean of several independent re-hangs.

Conflict of interest

The author is the CEO of PaddleMate, which develops and sells the device under test and the in-house calibration software. The measurements were made by the manufacturer and have not been independently verified.

Data availability

The per-loading CSV file and the analysis script are available on request from contact@thepaddlemate.com.

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