TEST REPORT · INSTRUMENT VALIDATION

Stroke-to-stroke repeatability of the PaddleMate Nano strain-gauge paddle-shaft sensor under pneumatic square-wave bending

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Report number	PM-TR-2026-02
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Device under test	PaddleMate Nano, single strain gauge, firmware offset zeroing, BLE data transfer
Software	In-house PaddleMate tools; raw ADC and processed force export
Specimen	Carbon-fibre tube, OD 30 × 1 mm wall, 1.2 m; Nano at mid-length; ends held down, rotation free
Loading	Pneumatic cylinder under the shaft at ≈ L/3, upward push; 10 bar supply via regulator; 101 strokes, 1.44 s period
Ambient	18 °C laboratory; device powered for 10 min before recording
Calibration	In situ: same rig inverted, 10 kg calibrated mass (98.07 N) hung at the cylinder position
Measurand	Stroke-to-stroke repeatability; no in-line load cell during the runs

ABSTRACT

Background. Most kayak and canoe performance research measures force or power on instrumented paddles, because the paddle is where the athlete delivers propulsion [1–3]. Static validation of such sensors is common [4, 5], but it does not show how consistently a sensor reports a repeated dynamic load.

Methods. A 1.2 m carbon tube (OD 30 mm, 1 mm wall) was held down at both ends; the clamps prevented uplift but let the tube rotate and bend. A PaddleMate Nano sat at mid-length. It had been calibrated in the same rig, inverted, with a 10 kg calibrated mass hung at the cylinder position. A pneumatic cylinder under the tube at about one-third of the span pushed upward. The 10 bar supply was reduced with a pressure regulator and air-preparation unit until the Nano indicated about 200 N. The device was powered for 10 min at 18 °C before recording. In-house software recorded both the raw ADC stream and the processed force output. For each stroke of a 1.44 s square-wave cycle, the trimmed means of the unloaded and loaded plateaus were subtracted to give Δ. Two consecutive runs of 101 strokes were recorded. All strokes were analysed; no data were excluded.

Results. The force output had a mean Δ of 201.19 N (95% CI ±0.39 N), a standard deviation of 1.98 N (95% CI 1.74–2.30 N) and a coefficient of variation of 0.99%. 70% of strokes were within ±1% of the mean and 95% within ±2%. The raw ADC Δ had a CV of 0.88%. Both distributions were consistent with a normal distribution, showed no drift over 100 strokes, and contained no outliers by Grubbs' test ($\alpha = 0.05$).

Conclusion. The scatter includes the variability of the pneumatic actuator, so 0.99% is an upper bound for the stroke-to-stroke repeatability of the sensor. This is an order of magnitude below the ±10% class A tolerance of ISO 20957 for rowing training equipment and comparable to laboratory-grade cycling power meters, so the Nano's repeatability is suitable for measuring athletes. Absolute accuracy is reported separately.

KEYWORDS kayak; canoe; instrumented paddle; strain gauge; repeatability; coefficient of variation; dynamic loading

1. Introduction

In flat-water kayaking and canoeing, the force and power that move the boat are applied through the paddle. Reviews of performance monitoring therefore place instrumented paddles among the principal

tools for measuring what the athlete actually delivers, rather than only boat speed or heart rate [1–3]. That is the professional rationale for developing shaft-mounted force sensors, and for validating them before coaching use. PaddleMate was started on this basis: if the paddle is the measurement point used in the sport-science literature, the sensor on that paddle must be shown to be stable and trustworthy.

Strain-gauge paddle shafts infer stroke force from shaft bending. Published validations use known static loads in a defined geometry [4–6]. Rosdahl et al. reported static errors of −3.4 to +3.0% for a commercial shaft between 98 and 590 N [4]. Goreham and Ladouceur showed that the calibration range must cover the forces seen in use [5]. These tests establish accuracy at a point. They say less about how consistently a sensor reports the same load when the load is applied and removed many times, as it is during paddling.

Sports-science practice expresses this consistency as a typical error or a coefficient of variation [7, 8]. Metrology calls it repeatability: the closeness of results obtained with the same procedure, operator, instrument and conditions over a short time [9].

This report measures the stroke-to-stroke repeatability of the PaddleMate Nano under a repeated pneumatic square-wave load. It asks how large the scatter of the reported stroke force is, and whether that scatter is random or drifts over a short run. The test was not designed to measure accuracy. The Nano had been calibrated in the same rig with a calibrated mass, but the pneumatic actuator was then driven at a fixed supply pressure without an in-line load cell, so the actuator force in each stroke was not measured independently.

2. Nomenclature

Table 1. Symbols used in this report.

Symbol	Meaning	Unit
L_k, H_k	trimmed mean of the unloaded (low) and loaded (high) plateau of stroke k	N or counts
Δ_k	stroke result, $H_k - L_k$	N or counts
n	number of strokes, 101	–
$\bar{x}$, s	sample mean; sample standard deviation	N or counts
CV	coefficient of variation (relative standard deviation), 100 $s/\bar{x}$	%
r_1	lag-1 autocorrelation between consecutive strokes	–
G	Grubbs statistic, max $\lvert x_k - \bar{x} \rvert / s$	–

3. Materials and methods

3.1 Device under test and software

The PaddleMate Nano is a paddle-shaft force sensor with a single strain gauge. It streams data over Bluetooth Low Energy. Recording and export used in-house PaddleMate software written for this sensor family. The same tools can pull both the unprocessed ADC stream and the processed force output from the device, and they wrote the per-stroke CSV files analysed here. Two output modes were recorded:

- **Force output.** The calibrated force in newtons, as reported by the firmware and the application. In this mode the firmware zeroes the offset, so the unloaded level is defined as zero. The output samples have 1 N resolution. No additional client filter was applied.
- **Raw output.** The uncalibrated ADC value, without offset zeroing. A client-side moving filter of 20 samples in the in-house software was active during the raw run.

3.2 Specimen and loading

The specimen was a 1.2 m carbon-fibre tube with an outer diameter of 30 mm and a 1 mm wall, carrying the PaddleMate Nano at mid-length. The clamps at both ends were not rigid fixtures. They only held the tube down against the upward load, so the tube could rotate at the clamps and bend freely between them (Figure 1). Mechanically, this is a simply supported span with hold-down supports. A pneumatic working cylinder sat under the tube at about one-third of the span and pushed it upward. The contact was therefore about 200 mm from the sensor. In the retracted position the cylinder rested just clear of the shaft, with a small gap and no preload, so the unloaded plateau carried no actuator force.

The air supply was 10 bar. A pressure regulator and an air-preparation unit reduced this pressure until the calibrated Nano indicated about 200 N, and a valve cycled the cylinder. The pressure setting was then left unchanged for both runs.

The Nano was calibrated in this same rig before the runs. The rig was turned upside down, and a 10 kg calibrated static mass (98.07 N with $g_0 = 9.80665$ m s^{-2}) was hung at the cylinder position ($L/3$), so that the load acted on the tube in the same direction relative to the clamps and the gauge as the cylinder later did. The calibration geometry and the test geometry were therefore identical. The force output thus estimates the force at the loading point, traceable to the calibration mass, and the ≈ 200 N reading estimates the cylinder force. During the dynamic runs, however, no in-line load cell measured that force stroke by stroke.

The laboratory temperature was 18 °C. The Nano was powered for 10 min before recording so that the electronics and the gauge could settle. No water conditioning of the shaft was used. The actuator cycled at a period of 1.437 ± 0.015 s (mean ± s, from the stroke time stamps).

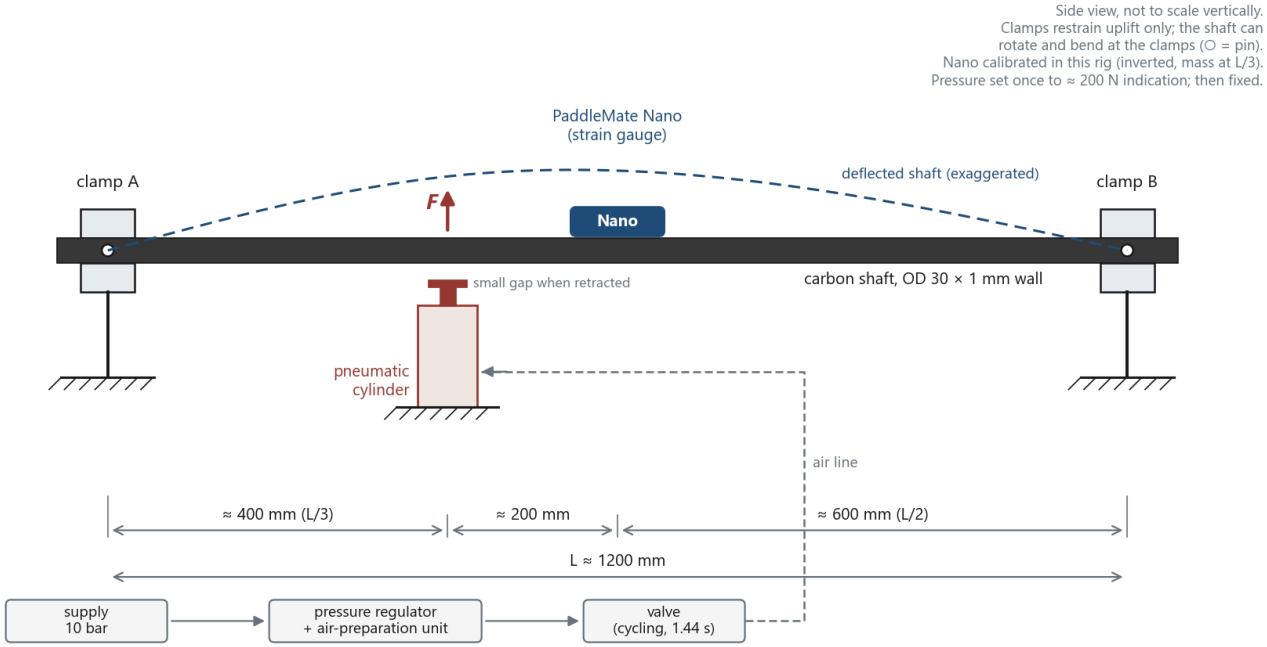


Figure 1. Loading rig, side view (schematic). Carbon tube, OD 30 × 1 mm wall. The clamps restrain uplift only, so the tube can rotate at the clamps (○); the dashed line shows the deflected shape, exaggerated. The PaddleMate Nano sits at mid-length ($L/2$). The pneumatic cylinder acts upward at $L/3$, about 200 mm from the gauge, and clears the shaft when retracted. Supply: 10 bar through a pressure regulator and air-preparation unit; a valve cycles the cylinder at 1.44 s. For calibration the same rig was inverted and a calibrated mass hung at $L/3$. The pressure was then set once so that the Nano indicated ≈ 200 N.

3.3 Stroke detection and per-stroke result

The square wave was segmented by hysteresis thresholds at 30% and 70% of the step height (Figure 2). For each plateau, a window of up to 200 samples was taken and 30% of it was trimmed to remove the

transitions. The remaining samples were averaged: 31–32 samples on the low plateau and 27–28 on the high plateau. The stroke result was

$$\Delta_k = H_k - L_k \tag{1}$$

The stroke result Δ_k is the quantity analysed below. It matches the stroke-level force metric used in training, after plateau averaging.

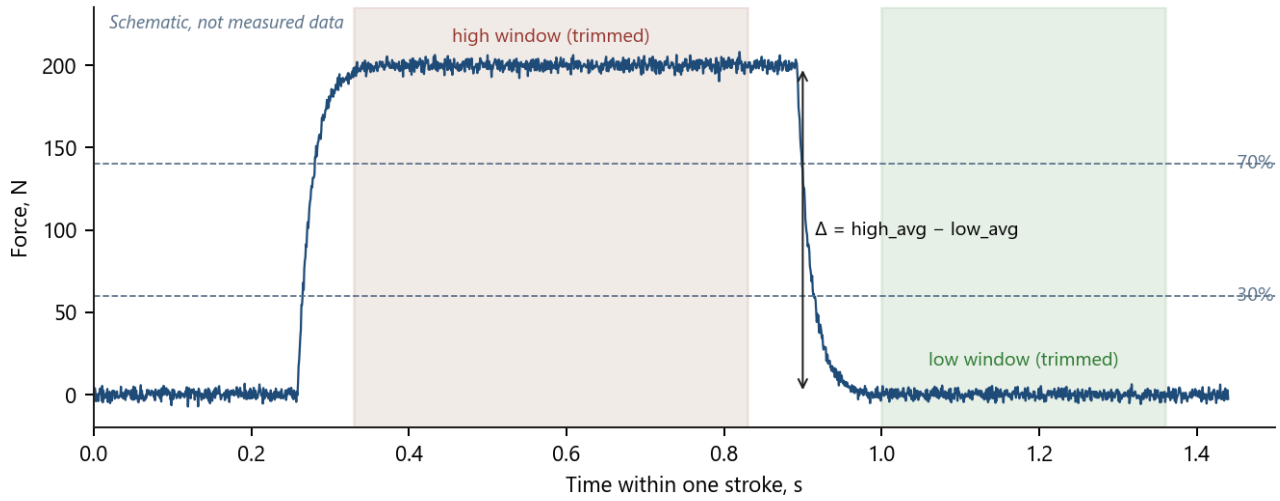


Figure 2. Per-stroke evaluation, schematic. Hysteresis thresholds at 30% and 70% detect the transitions. Trimmed windows on the loaded (high) and unloaded (low) plateau give H_k and L_k, and their difference is the stroke result Δ_k. Illustrative signal, not measured data.

3.4 Runs

Table 2. Recorded runs. Times are UTC, 14 November 2026.

Run	Output	Filter	Start	End	Strokes
1	Raw ADC	in-house SW, 20-sample filter	14:03:07	14:05:31	101
2	Force, N	in-house SW, filter off	14:06:05	14:08:29	101

The two runs were consecutive, not simultaneous. Raw and force values therefore cannot be paired stroke by stroke. Because the filters also differed, comparing the CVs of the two runs is only indicative.

3.5 Statistical analysis

For each series the following were computed, with the scatter treated as a Type A evaluation [13]:

- mean, with a 95% confidence interval based on the *t*-distribution;
- standard deviation, with a 95% confidence interval based on the χ^2-distribution, df = 100;
- CV, range and 2.5th, 50th and 97.5th percentiles;
- skewness and excess kurtosis.

Two tests checked independence. The lag-1 autocorrelation r_1 tested whether consecutive strokes were related. A least-squares trend against stroke number tested for drift, using the *t*-statistic of the slope.

Normality was examined with a normal quantile–quantile plot. The normal curve in Figure 4 has the sample mean and SD. It describes the data; it is not a fitted model used for inference.

The outlier criterion was fixed before evaluation. Grubbs' test was applied two-sided at $\alpha = 0.05$ to the most extreme stroke [10, 11]. For $n = 101$ the critical value is $G_{crit} = 3.39$. A stroke would be excluded only if it exceeded G_{crit}, or if a documented physical cause was found, such as an actuator fault or a pressure

drop. Results would then be reported both with and without the stroke. No stroke met either condition (Section 4.3), so all 101 strokes were analysed.

4. Results

4.1 Force output

Table 3. Descriptive statistics of the stroke result Δ, n = 101 strokes per run.

Statistic	Force output, N	Raw output, counts
Mean (95% CI half-width)	201.19 (±0.39)	77.95 (±0.13)
Standard deviation s (95% CI)	1.98 (1.74–2.30)	0.683 (0.600–0.793)
Coefficient of variation	0.99%	0.88%
Minimum / maximum	195.31 / 206.07	75.74 / 79.23
Range	10.76	3.49
Percentiles 2.5 / 50 / 97.5	197.23 / 201.59 / 205.14	76.69 / 77.97 / 79.10
Skewness / excess kurtosis	−0.30 / 0.09	−0.35 / −0.04
Lag-1 autocorrelation r_1	0.02	−0.03
Trend per 100 strokes (t)	+0.58 (0.85)	+0.23 (1.00)
Grubbs G (stroke) vs G_{crit} = 3.39	2.96 (no. 9)	3.25 (no. 47)

$|t|$ < 1.98 means the trend is not significant at the 5% level.

The force-output Δ averaged 201.19 N with a standard deviation of 1.98 N, giving a CV of 0.99% (Table 3, Figure 3). Consecutive strokes were uncorrelated (r_1 = 0.02). The trend over 100 strokes was +0.58 N and not significant (t = 0.85). The series therefore behaves as independent random scatter around a stable mean.

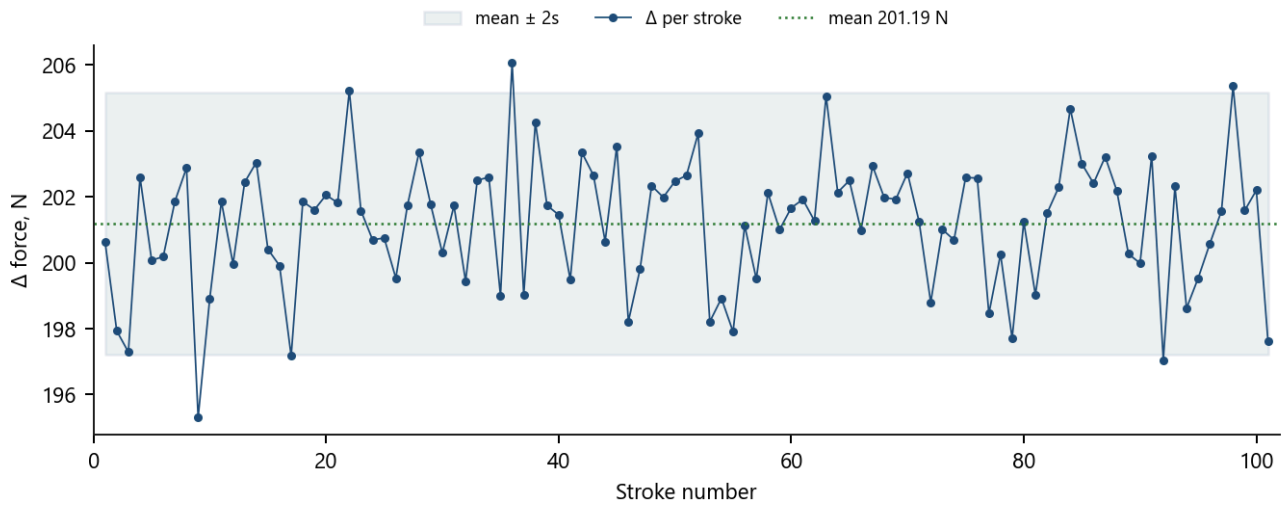


Figure 3. Force-output stroke result Δ_k for 101 consecutive strokes. Dotted line: mean. Shaded band: mean ± 2s.

4.2 Distribution and tolerance bands

Figure 4 shows the deviations from the series mean in 1 N bins. Figure 5 shows the cumulative fraction of strokes within a given deviation. Skewness was −0.30 and excess kurtosis 0.09, and the quantile–quantile plot (Figure 6) follows the identity line. The distribution is therefore close to normal. The tallest bin, at +1 N, reflects the 1 N resolution of the force output, which concentrates the plateau means on a few values.

Table 4. Fraction of strokes within a deviation band around the series mean, force output, *n* = 101.

Band, % of mean	±0.5%	±1.0%	±1.5%	±2.0%	±2.5%	±3.0%
Band, N	±1.01	±2.01	±3.02	±4.02	±5.03	±6.04
Strokes	41	71	87	96	100	101
Fraction	41%	70%	86%	95%	99%	100%

Mean absolute deviation 1.57 N (0.78%). Largest absolute deviation 5.88 N (2.92%), stroke 9.

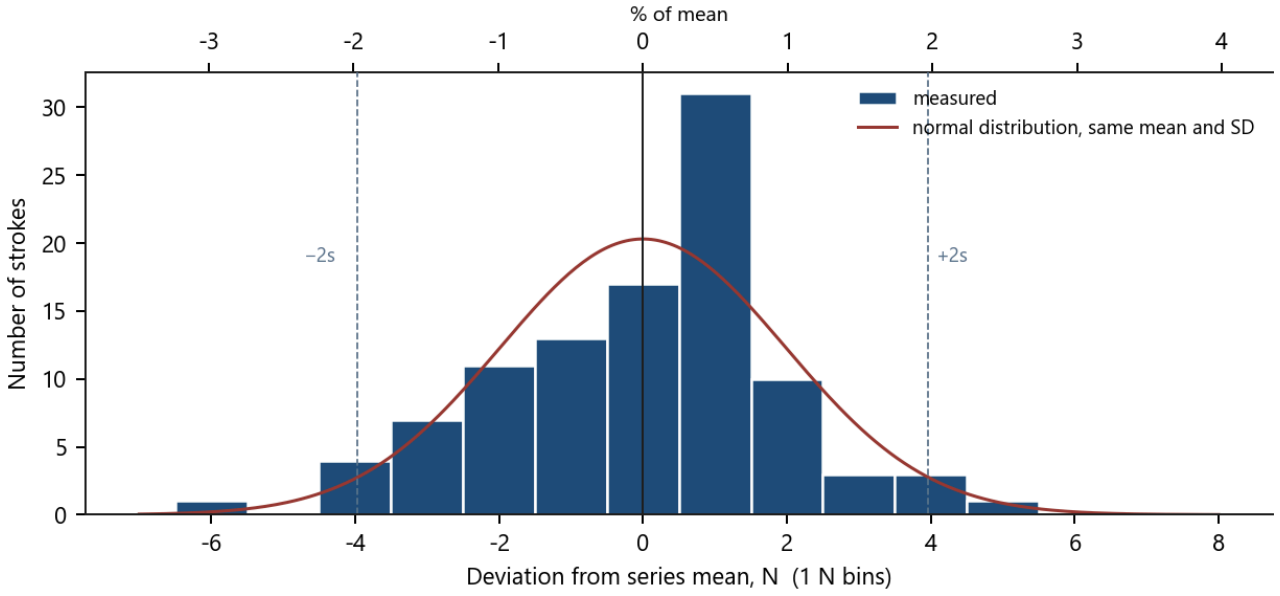


Figure 4. Deviation of the force-output Δ from the series mean, in 1 N bins. Red curve: normal distribution with the sample mean and standard deviation, scaled to *n*. Dashed lines: ±2*s*. Top axis: deviation as a percentage of the mean.

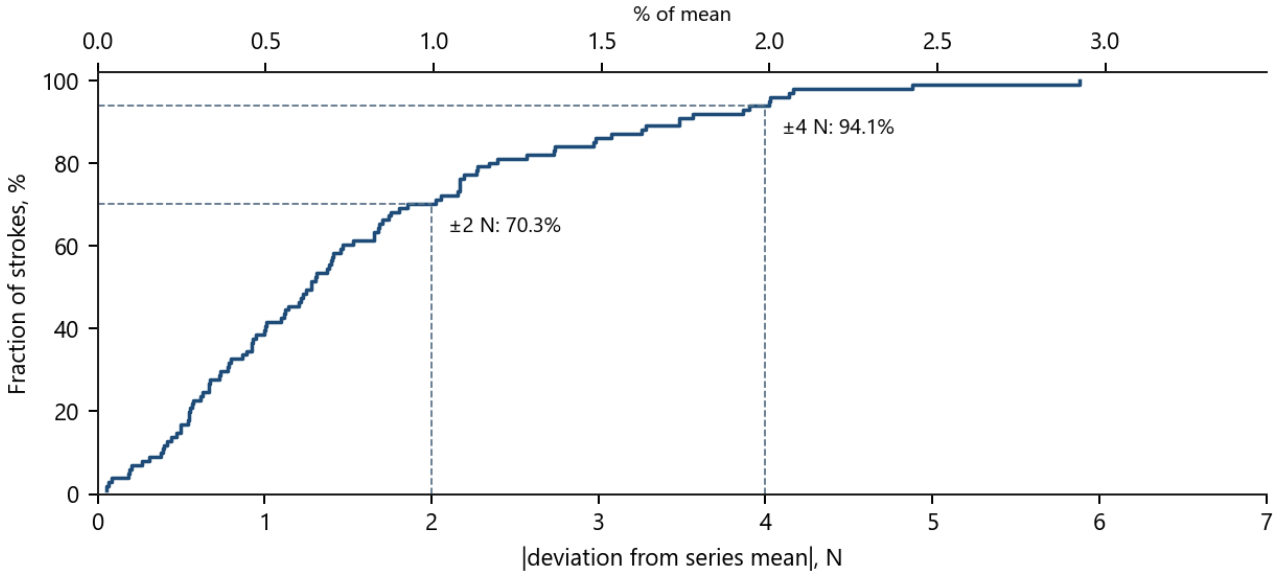


Figure 5. Cumulative fraction of strokes whose absolute deviation from the mean is at most the abscissa value. Top axis: the same deviation as a percentage of the mean.

4.3 Outliers

The most extreme force-output stroke (no. 9, 195.31 N) gave G = 2.96, below G_{crit} = 3.39. No stroke exceeded 3*s*. Six strokes fell outside ±2*s*, compared with 4.6 expected for a normal sample of 101, so they belong to the distribution and are not outliers. In the raw run, the most extreme stroke (no. 47) gave G =

3.25. This was the only stroke beyond 3s, and it was also below the critical value. No physical anomaly was observed during either run. All strokes were retained.

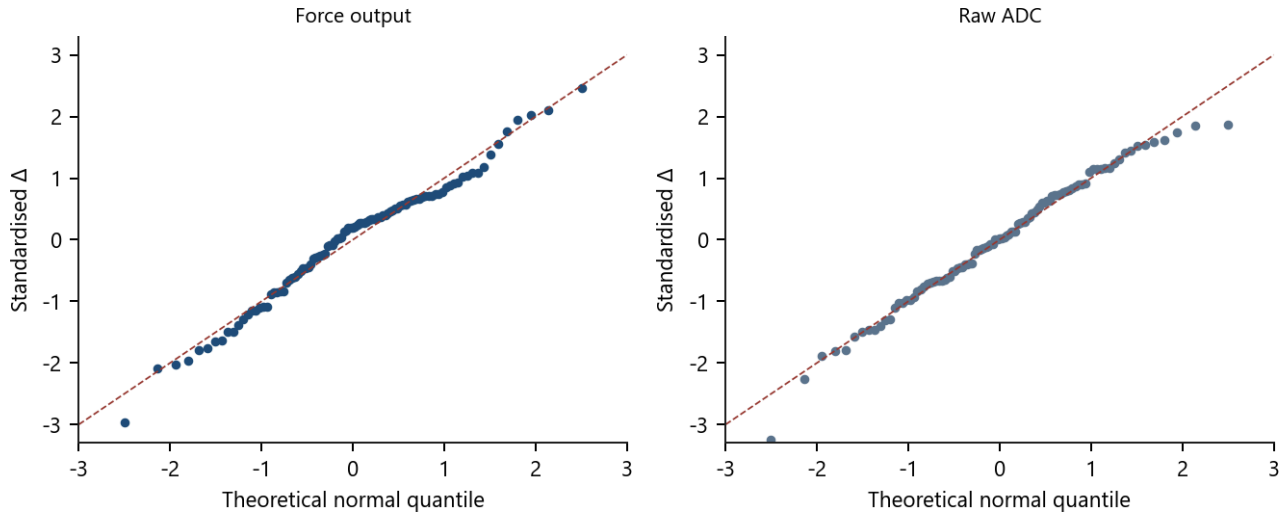


Figure 6. Normal quantile–quantile plots of the standardised stroke result. Left: force output. Right: raw ADC. Dashed line: identity, i.e. perfect normality.

4.4 Raw output

The raw Δ averaged 77.95 counts with s = 0.683 counts, a CV of 0.88% (Table 3, Figure 7). An indicative scale of 201.19 N / 77.95 counts = 2.58 N per count follows from the means of the two runs. On that scale the raw scatter corresponds to about 1.76 N. The difference from the 1.98 N of the force run is within the confidence intervals and is consistent with the different filter settings. Because the runs were not simultaneous, this comparison is indicative only.

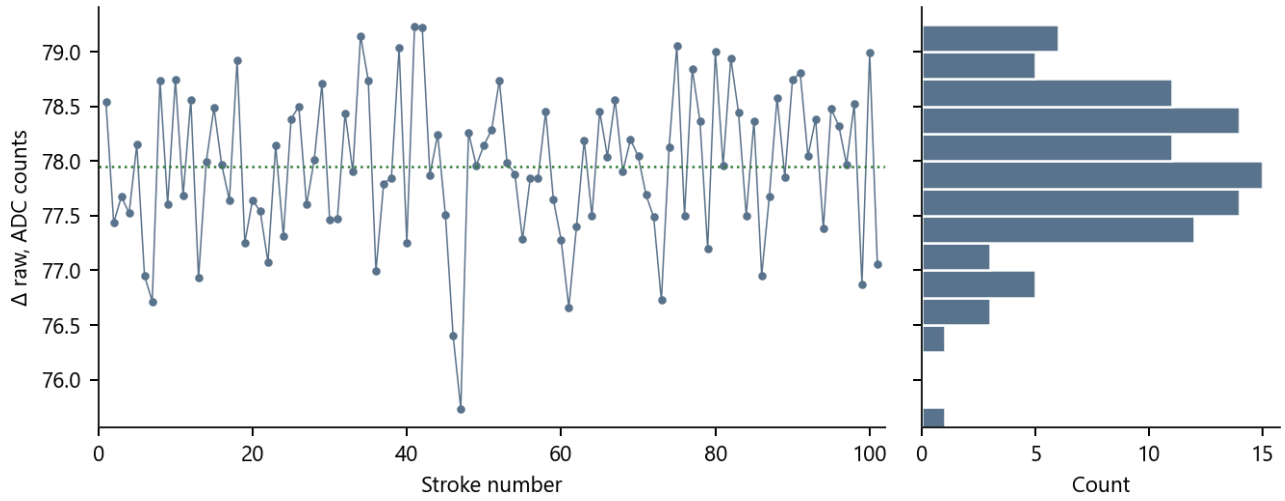


Figure 7. Raw-output stroke result Δ_k in ADC counts, for 101 consecutive strokes, with its distribution on the right. Dotted line: mean.

5. Discussion

Under a repeated pneumatic load, the PaddleMate Nano reported the stroke result with a CV of 0.99% in force mode and 0.88% in raw mode. The scatter was random: consecutive strokes were uncorrelated, there was no drift over 100 strokes, the distribution was close to normal, and the pre-defined outlier test flagged no stroke. In sports-science terms, the typical error of a single stroke is about 2 N at a 200 N load [7, 8]. Averaging over N strokes reduces this error by $\sqrt{N}$, so over ten strokes it is about 0.6 N. That level of

instrument scatter is small compared with the stroke-to-stroke and session-to-session variation usually seen in athletes, which is why a ~1% CV is useful for coaching metrics derived from the paddle.

What the scatter contains. The observed standard deviation combines three sources:

- the stroke-to-stroke variation of the actuator force, from supply pressure, valve timing and friction;
- the sensor noise after averaging;
- the quantisation of the force output.

The test cannot separate them, so 1.98 N (0.99%) is an upper bound for the repeatability of the sensor itself. A load cell in series with the actuator would isolate the actuator contribution. It would also allow the dynamic force to be compared stroke by stroke with an independent reference, which this test does not provide.

Comparison with sport-specific equipment. Stationary training equipment that displays training data is classified by accuracy in ISO 20957; class A is the highest class [14]. For rowing machines, the closest standardised equipment to paddling, class A requires the displayed power to be within ±10% above 50 W [15]. Mobile cycling power meters, the reference instruments of endurance sport, showed a mean precision of 1.2 ± 0.9% CV in a calibration study of 54 units, and about 0.8% for the SRM and PowerTap brands [16]. The best performance tests in sport science reach a CV of about 1–2% [7]. With a CV of ≤ 0.99%, including the actuator, the stroke-to-stroke scatter of the Nano is an order of magnitude below the class A tolerance and in the same range as laboratory-grade cycling power meters. In terms of repeatability, the Nano is therefore suitable for measuring athletes in training and testing.

Relation to accuracy claims. Repeatability and accuracy are separate properties [9]. A sensor can repeat to 1% and still read 5% high if its calibration slope is wrong. Static accuracy and linearity against traceable masses are the subject of the static calibration reports in this series. The present result shows only that the stroke-to-stroke scatter of the Nano is small compared with the ±2% bands reported for static validation of instrumented paddles [4].

Limitations.

- One device, one shaft, one load level and one temperature were tested.
- The force and raw runs were consecutive, not simultaneous, and used different filter settings in the in-house software.
- The force output has 1 N resolution.
- The load waveform was a square wave, not an on-water force profile, and the loading point was fixed. On water, the centre of pressure of the blade moves during the stroke [12].
- The Nano was calibrated in situ with a 10 kg mass, but no in-line load cell measured the actuator force during the runs. The actuator's own stroke-to-stroke variation therefore remains part of the scatter.
- The calibration point (98 N) was about half the test level (201 N). The mean value therefore also depends on the linearity of the sensor, which is reported separately; the repeatability result does not.

6. Conclusion

Over 101 consecutive pneumatic strokes at about 200 N, the PaddleMate Nano force output repeated with a standard deviation of 1.98 N (95% CI 1.74–2.30 N), a CV of 0.99%. 96 of 101 strokes (95%) were within ±2% of the mean. The raw ADC difference repeated with a CV of 0.88%. The scatter was random and normally distributed, with no drift and no outliers, and all strokes were retained. Because the scatter includes the actuator, these figures are upper bounds for sensor repeatability.

This repeatability is well within the ±10% class A tolerance of ISO 20957 for rowing training equipment [15] and matches the precision of laboratory-grade cycling power meters [16]. The PaddleMate Nano therefore measures stroke force with the repeatability required for monitoring athletes in training and testing. Absolute accuracy is addressed by the static calibration reports of this series.

Conflict of interest

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

Data availability

The per-stroke CSV files of both runs and the analysis script are available on request from contact@thepaddlemate.com.

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