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Statistical Analyses of Unidirectional Static Forces on Instrumented Rowing Oarlocks

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Abstract

The PowerLine System includes instrumented rowing oarlocks, which measure athlete-applied forces during on-water rowing. Despite its international popularity, limited research has considered the quality engineering of the PowerLine system. Accordingly, the following research examined the convergent validity and test-retest reliability of the PowerLine force measurements. Unidirectional static forces of up to 431 N were applied to nine sweep and eight scull oarlocks over fifteen days of testing. The differences between the PowerLine force measurements and the known static forces were statistically analyzed. The PowerLine force measurements were consistent over the fifteen days of testing, but were 2.0 % ± 0.8 percentage points less than the quantities of the known applied forces. Although the differences between the experimental measurements and known applied forces corresponded with the manufacturer's specifications, calibration factors for each PowerLine oarlock were generated to correct for the minor discrepancies.

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Keywords: Strain Gauge; Calibration; Rowing Oarlock; Convergent Validity; Test-Retest Reliability

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1. Introduction

The PowerLine (PL) System contains rowing oarlocks instrumented with strain gauge load cells, which quantify athlete-applied forces at 50 Hz. Each load cell consists of three concentric tubes connected in series. The inner tube fits onto the pin of a rowing wing rigger and has a locking mechanism that prevents its rotation around the pin. A swivel fits onto the outer tube of the load cell and can rotate freely, and four strain gauges are attached to the middle tube [1]. Measures of strain from individual strain gauges are temperature sensitive because thermal expansion can affect the volume of the gauge, as well as the object to which the strain gauge is attached. The PL oarlocks minimize their sensitivity to changes in temperature by connecting the individual strain gauges in a Wheatstone bridge circuit [1]. The strain gauges in the PL oarlocks are configured to measure the forces applied in the direction parallel to the boat's main motion (i.e., the x-axis). Therefore, the PL oarlocks are insensitive to the forces applied in the orthogonal (i.e., y-axis) and vertical (i.e., z-axis) directions. The PL force measurements were originally sensitive to the location of the point of force application [1]. The PL oarlocks were then re-engineered to utilize the voltage outputs from two Wheatstone half-bridge circuits to estimate the location of an applied force and automatically calibrate the force measurements [1]. The PL force measurements have a specified tolerance of ± 2 % of the total force measurement [2].

Many Olympic rowing programs use the PL system, including: Canada, Great Britain, Italy, South Africa, Australia, Brazil, France, New Zealand, Lithuania, Croatia, Denmark, Czech Republic, Netherlands, and United States [2]. Despite its international popularity, only one independent study has investigated the validity of the PL force measurements [3]. Forces of up to 554.8 ± 20.4 N were dynamically applied to a loading bar suspended from eight PL oarlocks with a load cell linked in series. The results of a linear regression analysis indicated good agreement between the PL and load cell force measurements.

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Nevertheless, the consistency of the PL force measurements over time has never been documented, and previous research [3] has only tested the accuracy of PL scull oarlocks. Accordingly, the following research examined the convergent validity and test-retest reliability of the force measurements from both sweep and scull PL oarlocks.

2. Methods

Seventeen PL oarlocks (n = 17), nine sweep and eight scull, were stored and tested in a laboratory with a room temperature of 22 ± 2 °C. The oarlock angles are measured using two Hall-effect sensors and an eight-axial pole ring magnet [1]. The angular displacements of the PL swivels are measured relative to the inner tubes, and thus also relative to a rowing boat, since the inner tubes secure to the pin in a fixed direction (i.e., the y-axis). The angle measurements have a specified tolerance of ± 0.5° [2]. The inner tubes of the PL oarlocks were secured to a beam that was supported by two stands (see Fig. 1); the beam represents the pin on a rowing wing rigger. The PL swivels were pointed in the x-direction while the bases of the inner tubes were pointed in the y-direction. Through this perpendicular orientation, any mass suspended from the PL swivels will act in a direction that simulates the direction parallel to the boat's main motion. The PL oarlocks were connected to a programmable data logger, which displayed the real time measurements. The PL force and angle measurements were zeroed through the data logger's local interface.

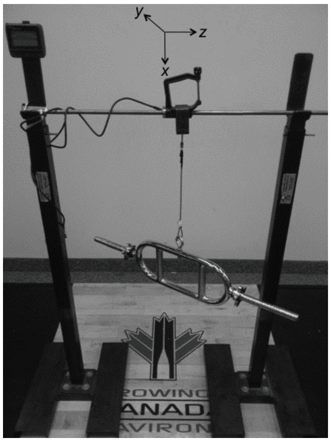

Fig 1. Photograph of the experimental setup. A beam is supported by two stands and a PL oarlock is fixed to the beam. The PL swivel is pointed in the x-direction while the base of the inner tube is pointed in the y-direction. The PL oarlock is connected to a data logger and a custom-made suspension rig is hanging from the PL oarlock.

Static forces of 0, 32.4, 255.1 and 431.6 N were individually applied to the PL oarlocks using a custom-made suspension rig loaded with weight plates. The suspension rig consisted of a box, wire cable and a loading bar linked in series (Fig. 1). The weights of the plates and the suspension rig were verified using a digital bench scale with a ± 0.98 N tolerance (Rice Lake Weighing Systems, USA). 0 N is the theoretical force on the oarlocks while pointing in the vertical direction, 32.4 N is the weight of the suspension rig, and 255.1 and 431.6 N are the weights of the plates, which include the weight of the suspension rig. The PL force measurements slightly oscillated while the oarlocks were statically loaded (i.e., random error). Random error is characterized by unpredictable oscillations and can be minimized by calculating the arithmetic mean over multiple measurements [4]. The PL oarlocks were statically loaded for five seconds and the mean force measurement over that period was calculated and used in the analyses. Data were collected over fifteen consecutive days and statistically analyzed using SPSS Statistics Version 21 (IBM Corp., Canada). The statistical significance (α) was set to 0.05 and the results are presented with 95 % confidence. The uncertainties are expressed as ± standard deviations.

3. Results

3.1. Test-Retest Reliability

Test-retest reliability is the consistency of an instrument to reproduce similar measurements over time [5]. The distributions of the PL force measurements were examined for normality and homogeneity of variance. Normality refers to the magnitude of which a sample distribution correlates with a theoretical Gaussian distribution [4]. A Shapiro–Wilk test [6] was used to analyze the normality of the PL force distributions. The null hypothesis (H_o) was that the PL force measurements are normally distributed as a function of the testing date. The p-values are shown in Table 1. Since the majority of p-values were < 0.05, the H_o was rejected. Considering the results were statistically significant, a non-parametric Levene's F-test [7] was used to investigate the homogeneity of variance of the PL force measurements over the fifteen days of testing. Sample distributions are termed "homoscedastic" when all variables have similar variance; "heteroscedastic" signifies when all variables have different variance

[8]. The H_o was that the PL force distributions are homoscedastic. The p-values for sweep and scull oarlocks were 0.203 and 0.142, respectively. Since the p-values were > 0.05, this indicates homogeneity of variance in the distributions of the PL force measurements as a function of the testing date. Although parametric analyses of variance (ANOVA) can be robust to violations of normality [9], a non-parametric statistical model was selected to provide a more conservative analysis of the test-retest reliability of the PL force measurements. The reduced statistical power associated with non-parametric models was considered.

Table 1. Investigating the normality of the PL force measurements as a function of the testing date using a Shapiro–Wilk test [6]. If the p-value is < 0.05, the results reject the H_o. An asterisk (*) indicates a normal distribution.

Testing Date	Sweep p-values	Scull p-values
1	0.000	0.000
2	0.269*	0.020
3	0.018	0.000
4	0.008	0.000
5	0.001	0.000
6	0.357*	0.002
7	0.045	0.005
8	0.000	0.002
9	0.002	0.037
10	0.000	0.004
11	0.005	0.707*
12	0.008	0.028
13	0.054*	0.000
14	0.020	0.046
15	0.007	0.030

A Kruskal-Wallis One-Way ANOVA was used to evaluate the test-retest reliability of the PL force measurements over the fifteen days of testing. The differences between the PL force measurements and the known static forces were calculated (F_{diff}). The H_o indicated no difference in the F_{diff} over multiple days of testing. The p-values were 0.335 for scull and 0.451 for sweep oarlocks, which suggests that the PL force measurements were statistically consistent from day-to-day. The maximum differences in the PL force measurements over the fifteen days of testing, when loaded with 431.6 N, were 18.8 ± 11.9 N for sweep (i.e., 4.3 % ± 2.6 pp - percentage points) and 16.8 ± 6.2 N for scull oarlocks (i.e., 3.9 % ± 1.4 pp).

3.2. Convergent Validity

Convergent validity is the measured correlation between two independent measures that theoretically correlate [5]. The mean PL force measurements were at least 97.2 % similar to the quantities of the known static forces (Table 2). Excluding the baseline measurements at 0 N, the uncertainties ranged between 1.2 and 5.7 % of the mean PL force measurements. These variations may be attributed to round-off errors and/or limitations in the PL oarlock's sampling rate. Shapiro–Wilk tests [6] were used to analyze for normality in the distributions. The H_o was that the PL force measurements are normally distributed as a function of the known static forces. While the majority of p-values were < 0.05 (Table 2), this suggests that the PL force measurements are not normally distributed as a function of the known static forces. A non-parametric Levene's F-test [7] was used to evaluate the homogeneity of variance of the PL force measurements as a function of the known static forces. The H_o was that the distributions are homoscedastic. The p-values for sweep and scull oarlocks were both 0.100, which indicates homogeneity of variance of the PL force measurements over the range of forces that were investigated.

Table 2. Examining the normality of the PL force measurements (N) as a function of the known static forces (N) using a Shapiro–Wilk test [6]. If the p-value is < 0.05, the results reject the H_o. An asterisk (*) indicates a normal distribution. The PL force measurements for sweep and scull oarlocks were combined over the fifteen days of testing, and are presented as arithmetic means ± standard deviations for each loading condition.

Known Force	Sweep Force	Sweep p-value	Scull Force	Scull p-value
0.0	0.1 ± 0.1	0.000	0.1 ± 0.1	0.000
32.4	31.5 ± 1.8	0.000	31.7 ± 1.6	0.100*
255.1	250.7 ± 3.6	0.016	249.9 ± 4.1	0.000
431.6	425.8 ± 5.5	0.000	425.3 ± 5.1	0.043

Considering the data violated the parametric assumption of normality, a Wilcoxon One Sample Signed Rank Test was used to examine the convergent validity of the PL force measurements. The H_o was that the median PL force measurements equal the magnitudes of the known static forces. Although the median PL force measurements were 98.1 % ± 0.8 pp similar to the quantities of the known static forces (Table 3), the results of the statistical model rejected the H_o since the p-values were <

0.05. This is considered Type I error since the statistical model rejected the H_o when, in actuality, it was true. Excluding the baseline measurements at 0 N, the median PL force measurements were 2.0 % ± 0.8 pp less than the magnitudes of the known static forces. The maximum differences between the PL force measurements and the known static forces were 15 ± 4 N for scull (i.e., 4.5 % ± 1.6 pp) and 14 ± 7 N for sweep oarlocks (i.e., 3.3 % ± 1.5 pp). One scull and sweep oarlock were used to assess whether the convergent validity of the PL force measurements depend upon the point of force application. The box of the suspension rig, while loaded with 255.1 N, was translated along the face of the two PL swivels in the *z*-axis. The results showed that the differences in the PL force measurements as a function of the point of force application were similar in magnitude to the small oscillations in the PL force measurements associated with random error.

Table 3. Evaluating the convergent validity of the PL force measurements (N) using a Wilcoxon One Sample Signed Rank Test. If the *p*-value is < 0.05, the results reject the H_o.

Known Force	Median Sweep Force	Sweep *p*-value	Median Scull Force	Scull *p*-value
0.0	0.1	0.000	0.1	0.000
32.4	31.3	0.000	31.8	0.000
255.1	250.2	0.000	250.2	0.000
431.6	425.6	0.000	426.2	0.000

3.3. Calibration Factors

Although the differences between the PL force measurements and known static forces corresponded with the manufacturer's specified tolerances [2], calibration factors for each PL oarlock were generated to correct for the minor discrepancies. Fig 2 shows an example of the PL force measurements as a function of the known static forces. A linear model was fit to the data using a least squares linear regression analysis (MATLAB, MathWorks Inc., USA). The residuals were randomly scattered about the zero point. Table 4 presents the slope, coefficient of determination (R^2) and *y*-intercept for each PL oarlock as a function of the known static forces. The regression lines accurately fit the data with $R^2 \geq 0.999$. In a calibration experiment, the regression line should pass through the origin [10]. The H_o was that there is no difference between the *y*-intercept and origin. Since the *p*-values were > 0.05, this indicates that the *y*-intercepts all passed through the origin. The slope for each PL oarlock is its calibration factor. For instance, a slope value of 0.982 suggests that, on average, applying a known force of 1 N will correspond to a PL force measurement of 0.982 N. The slopes ranged between 0.976 and 0.993, which indicates that the PL oarlocks underestimated the applied forces.

Table 4. The slope, *y*-intercept and coefficient of determination (R^2) for each PL oarlock as a function of the known static forces. The slopes and *y*-intercepts are expressed as coefficients ± standard deviations. If the *p*-value is > 0.05, the results fail to reject the H_o.

Type	Oarlock ID	Slope	*y*-intercept	*y*-intercept *p*-value	R^2
Sweep	2664	0.989 ± 0.003	-0.18 ± 0.88	0.837	0.999
	2442	0.982 ± 0.002	-0.52 ± 0.47	0.273	1
	2441	0.985 ± 0.001	-0.32 ± 0.38	0.396	1
	2435	0.985 ± 0.003	-1.08 ± 0.76	0.161	0.999
	2443	0.983 ± 0.003	0.39 ± 0.84	0.644	0.999
	3214	0.991 ± 0.002	-0.08 ± 0.53	0.880	1
	3215	0.991 ± 0.002	-0.07 ± 0.41	0.869	1
	2665	0.993 ± 0.002	-0.38 ± 0.40	0.338	1
	2299	0.978 ± 0.002	-0.68 ± 0.47	0.157	1
Scull	2305	0.989 ± 0.001	0.24 ± 0.36	0.511	1
	2444	0.990 ± 0.002	-0.38 ± 0.66	0.570	1
	2445	0.987 ± 0.003	-0.16 ± 0.70	0.818	0.999
	2307	0.982 ± 0.002	0.18 ± 0.55	0.752	0.999
	2447	0.976 ± 0.003	-0.75 ± 0.78	0.343	0.999
	3646	0.980 ± 0.002	0.03 ± 0.60	0.960	1
	2446	0.984 ± 0.002	-0.87 ± 0.44	0.055	1
	2306	0.989 ± 0.002	-0.53 ± 0.53	0.329	1

4. Discussion and Conclusion

Although many Olympic rowing programs use the PL system [2], the day-to-day consistency of the PL force measurements has never been documented. A novel finding of this research was that the PL force measurements were statistically consistent over fifteen days of testing. Inter-day differences in force measurements from strain gauge technology, outside of human error, have been accredited to changes in temperature, pressure and humidity [5]. Considering rowers practice on-water in a variety of weather conditions, future research should analyze the test-retest reliability of the PL force measurements in an outdoor setting. The differences between the PL force measurements and the known static forces were at most 15 ± 4 N for scull and 14 ± 7 N for sweep oarlocks. Previous research [3] reported maximum differences of 15.5 to 45.6 N between PL oarlocks and load cell force measurements. Compared with aforementioned work [3], the increased validity of the PL force measurements established in this research may be attributed to proprietary advancements in the oarlock's technology by the manufacturer.

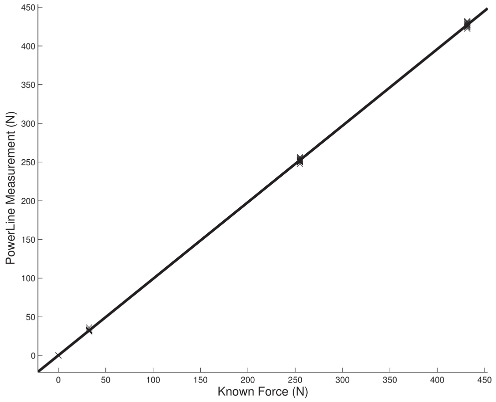

Fig 2. Example of the PL force measurements as a function of the known static forces. The linear fit is a least squares linear regression.

The PL force measurements are supposedly insensitive to the location of the point of force application [1]. This claim was investigated by translating the box of the suspension rig along the face of two PL swivels in the *z*-axis while loaded with a constant force. The differences in the PL force measurements as a function of the point of force application were similar in magnitude to the minor oscillations in the PL force measurements associated with random error. Total error in a measuring instrument consists of both random error and systematic error. Systematic error involves predictable measurement errors that consistently differ from a known quantity [4]. Systematic error can result from "zero error". Zero errors occur when an instrument does not measure zero when the known magnitude is zero; this can offset the *y*-intercept from the origin [4]. Inadequate zeroing is generally the cause of such errors [4]. The *y*-intercepts in this research all passed through the origin, which demonstrates that the PL oarlocks measured approximately 0 N when the known applied force was 0 N. This finding supports the validity of the zeroing protocol used. Calibration factors can be administered to a set of measurements to compensate for bias associated with systematic error [10]. The slope values presented in Table 4 ranged between 0.976 and 0.993, which indicates that i) the PL oarlocks underestimated the applied forces, and ii) the uncertainties associated with systematic errors were relatively small (i.e., 0.7 to 2.4 %). While the differences between the PL force measurements and known applied forces corresponded with the manufacturer's specified tolerances [2], rowing biomechanists and coaching staff can utilize the statistical methods and calibration factors outlined in this research to correct for minor discrepancies in the PL oarlock force measurements.

Acknowledgements

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