

Article

Explanatory Model for Elite Canoeists' Performance Using a Functional Electromechanical Dynamometer Based on Detected Lateral Asymmetry

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Abstract: Canoe modality in flatwater canoeing has a clear asymmetrical nature. This study aimed (1) to determine the magnitude and direction of neuromuscular properties, range of motion (ROM) and lower-limb strength asymmetries in female and male canoeists; (2) to establish sex-individualized asymmetry thresholds for canoeists' neuromuscular properties, ROM and lower-limb strength; and (3) to determine the relationship of canoeists' neuromuscular properties, ROM and lower-limb strength asymmetries with a specific canoe–dynamometer performance test. Twenty-one international canoeists were assessed through tensiomyography (TMG), ROM, lower-limb explosive strength, and a specific canoe incremental dynamometric test. The magnitude of asymmetry assessed through TMG and ROM was not modulated either by sex or performance level (international medal vs. non-medal). Females showed greater asymmetry than males on muscle tone of the erector spinae towards non-stroke side (22.75% vs. 9.72%) and the tibialis anterior (30.97% vs. 16.29%), and Fmax in explosive leg press (2.41% vs. 0.63%) towards the stroke side. International medalists showed greater asymmetry in semitendinosus contraction time towards non-stroke side (20.51% vs. 9.43%) and reached Vmax earlier in explosive leg press towards stroke side leg (19.20% vs. 9.40%). A greater asymmetry in Fmax and in Vm, and a smaller asymmetry in Tvmax and in leg press showed a small predictive capacity for canoeists' performance on a specific canoe incremental dynamometry test. Reporting reference data from world-class canoeists' asymmetries can be of great importance for coaches to periodically control lateral asymmetry.

Keywords: canoe; inter-limb differences; lateral dominance; sex differences



Citation: Álvarez-Yates, T.; Iglesias-Caamaño, M.; Cuba-Dorado, A.; Serrano-Gómez, V.; Ferreira-Lima, V.; Nakamura, F.Y.; García-García, O. Explanatory Model for Elite Canoeists' Performance Using a Functional Electromechanical Dynamometer Based on Detected Lateral Asymmetry. *Symmetry* **2024**, *16*, 347. <https://doi.org/10.3390/sym16030347>

Academic Editor: John H. Graham

Received: 2 February 2024

Revised: 8 March 2024

Accepted: 13 March 2024

Published: 14 March 2024



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1. Introduction

Canoe modality in flatwater canoeing has a clear asymmetrical nature. Canoeists paddle only on one side of the boat, with a single blade paddle, and are always kneeled on the same knee, while the other leg is bent forward in the front area of the canoe. In fact, this asymmetrical feature has already been highlighted by bilateral differences between neuromuscular properties related to upper and lower limbs' strength and mobility [1–4]. Moreover, with high volumes of training and its specialization, the modality can favor the development of asymmetries in muscle mass distribution and tone [4].

However, despite the importance of preventing muscle and postural imbalances, and maintaining symmetrical range of motion (ROM) between bilateral joints for optimal musculoskeletal function, there is no consensus on whether the athlete's performance is related to greater or lesser asymmetry [5]. In reality, at a high-level performance, asymmetries

have been associated with higher-level canoeists. For example, trunk flexion asymmetry has been related to higher racing speeds [4]. In point of fact, these asymmetries can already be seen for lower limbs in the junior category [1].

The importance of muscle strength and power for flatwater paddlers' performance, especially applied at specific joint angles of canoeing movement, has already been pointed out [6]. Large associations have been reported between maximum strength tests that were kinematically similar to the kayak stroke and on-water performance [7,8]. Therefore, it seems interesting to explore an innovative technology for specific strength assessment through functional electromechanical dynamometers, which allows for simultaneous measures of force, acceleration, and controlling different variables (i.e., load, magnitude of resistance, type of muscle contraction, etc.) simulating a specific sport movement pattern [9].

Sex differences in canoeing have already been reported regarding aerobic and anaerobic performance [10,11], upper-body strength [12] and also trapezius neuromuscular properties [13], although all these authors focused on non-canoeist kayakers. Thus, it seems appropriate to deepen the understanding of canoeist's lateral asymmetry to distinguish between females and males, since, to our knowledge, gender differences for canoeists have not been addressed yet. In fact, to date, we have not found scientific evidence that reports or focuses on the canoe woman.

Therefore, based on the importance that lateral asymmetry seems to have on canoeists' performance, and also on its role for preventing muscle and postural imbalances, we consider it important to explore lateral asymmetries to establish individualized reference values for canoeing athletes. Thus, the aim of this study was threefold: (1) to determine the magnitude and direction of eventual differences in neuromuscular properties, range of motion in upper and lower limbs, and explosive strength asymmetries in female and male high-level canoeists with the international performance level (medalists vs. non-medalists in an official international event); (2) to establish test-specific asymmetry thresholds for neuromuscular properties, range of motion and explosive strength for female and male canoeists; and (3) to determine the relationship of canoeists' asymmetries in neuromuscular properties, range of motion in upper and lower limbs, and explosive-strength test with the level of performance assessed through a specific dynamic test using an electromechanical dynamometer.

2. Materials and Methods

2.1. Study Design

Firstly, an exploratory cross-sectional comparative design was carried out to determine the magnitude and direction of the lateral asymmetry of female and male elite canoe athletes, based on their international performance level (medal winner at an official international event). Then, a predictive design was used to explore the influence of ROM, strength, and contractile properties of lateral asymmetry on the likelihood of a specific canoe dynamometry performance. Canoeists' neuromuscular properties were assessed through tensiomyography (TMG), range of motion (ROM), explosive strength and functional dynamometry (see Figure 1).

2.2. Participants

Twenty-one canoeists (see Table 1) from the Royal Spanish and Portuguese Canoe Federation's national teams agreed to participate in the study. Following MacKay et al.'s [14] classification framework based on training volume and performance metrics, 14 canoeists from our study (6 females and 8 males) were considered as tier 4 (elite/international level) while 3 females and 4 males as tier 5 (word class canoeists).

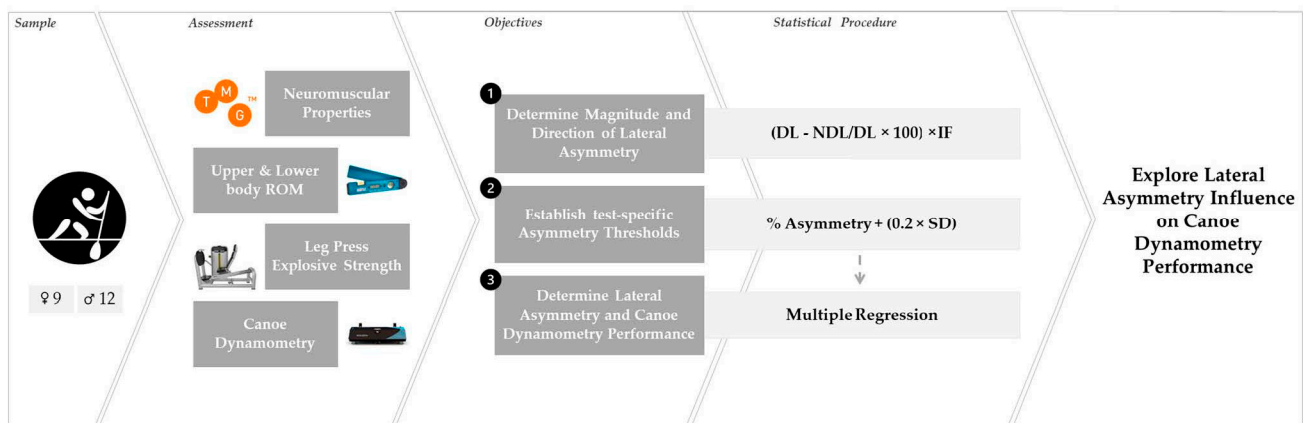


Figure 1. Study framework.

Table 1. Descriptive statistics of canoeists' body composition.

	Men (n = 12)				Women (n = 9)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Age (years)	16	36	21.45	5.279	15	21	17.78	1.986
Height (cm)	170.0	190.0	178.06	6.694	153.0	176.5	161.83	7.416
Weight (kg)	65.40	87.30	76.96	7.813	55.10	74.90	62.06	7.075
Body Fat (%)	7.30	14.70	12.10	2.334	16.00	23.60	20.49	2.347
Muscle mass (kg)	55.10	71.50	64.29	6.091	41.10	57.90	46.61	5.347
Bone mass (kg)	2.90	3.70	3.36	0.299	2.20	3.10	2.50	0.278
BMI ¹	21.70	26.40	24.12	1.424	20.90	26.20	23.60	1.643
Water (%)	60.70	68.20	63.63	2.124	58.20	65.20	60.92	1.946

¹ BMI (Body Mass Index).

All participants, and their parents or legal guardians for juniors, were informed of the project's background, the procedures to be followed and their purpose, and received a description of the expected benefits. An informed consent form was signed by each athlete. The study protocol was conducted in accordance with the Declaration of Helsinki for Biomedical Research in Humans (64th World Medical Assembly 2013) and was previously approved by the Ethical Research Committee of the University of Vigo.

2.3. Procedure

All participants were evaluated in recovery microcycles and in a pre-competitive period to avoid the effects of accumulated fatigue on the assessments. Due to the sample size and the different training groups (6 groups: Spanish senior men's sprint national training group, Spanish senior women's sprint national training group, Spanish junior women's sprint training group, Spanish senior men's marathon training group, Portuguese senior men's and women's sprint national training group, Portuguese junior men's and women's sprint training group), data collection was carried out at different times depending on the planning of each training group.

All tests were carried out by the same experienced researchers in the use of TMG, ROM and strength assessments. Two attempts were made for each limb, with the mean value being used for further analysis. Lateral dominance was determined based on the canoeist's stroke side (stroke vs. non-stroke). To determine inter-limb asymmetries, the formula proposed by Bishop et al. [15] was used: $[DL - NDL/DL \times 100] \times IF$ ($DL < NDL$, 1, -1). To use this formula with canoeists, the stroke side was considered as the DL (dominant limb) side, while the non-stroke side as NDL (non-dominant limb) side. This formula implements the excel IF function that allows to monitor the magnitude and direction of lateral asymmetry without absolute magnitude of variation issues (valued

in %). To assess data reliability, two measurements were taken for all tests, for 15 randomly chosen canoeists, with a 15 min interval between attempts.

2.3.1. Neuromuscular Properties Assessment

TMG was used to measure the radial muscle belly displacement of the main muscles involved in paddling: biceps femoris, deltoid, erector spinae, latissimus dorsi, pectoralis mayors, rectus femoris, semitendinosus, tibialis anterior and trapezius from both sides of the body. Canoeists were assessed on an examination table following the protocol described by García-García et al. [13,16,17].

Measures of radial muscle belly displacement were taken through a digital displacement transducer (GK 30, Panoptik d.o.o., Ljubljana, Slovenia), with the sensor set perpendicularly to the thickest part of the muscle belly, in accordance with the protocol suggested by Perotto et al. [18] and using palpation and visualization for individualization. The self-adhesive electrodes (5 cm × 5 cm, Cefar-Compex Medical AB Co., Ltd., Malmö, Sweden) were symmetrically placed 5 cm away from the sensor. Electrical stimulation was applied with a pulse duration of 1 ms and an initial current amplitude of 30 mA, which was progressively increased in 10 mA steps until reaching 110 mA (maximal stimulator output). The electrical stimulus was produced by a TMG-S2 (EMF-FURLAN & Co. d.o.o., Ljubljana, Slovenia) stimulator. Each measurement was recorded using the following parameters: maximum radial muscle belly displacement (D_m) in mm, contraction time (T_c) as the time in ms from 10% to 90% of D_m and radial displacement velocity (V_{rd}) obtained as the ratio ($\text{mm} \cdot \text{s}^{-1}$) between the radial displacement occurring during the time period of T_c ($0.8 \times D_m / T_c$) × 1000. The curve with the greater D_m was selected for further analysis.

2.3.2. Upper and Lower Limbs ROM Assessment

Shoulder ROM was assessed through shoulder external (ER) and internal (IR) rotation and shoulder flexion using a digital goniometer (Baseline Absolute Axis 360°, Fabrication Enterprises, Inc., White Plains, NY, USA) following Wilk et al. [19] scapular stabilization technique. For ER and IR rotation, paddlers lay on a stretcher, in the supine position, with the shoulder at 90° of abduction and with a 90° elbow flexion. The shoulder was positioned in the scapular plane rather than the coronal plane to minimize any pre-tension of capsular or muscle soft tissue. The center of rotation of the digital goniometer was placed over the tip of the olecranon while the moving arm was placed along the length of the ulna, aligned with the ulnar styloid process.

The stationary arm was placed underneath, perpendicularly to the ground, using the bubble level to assure proper alignment. Shoulder flexion was measured by asking the paddlers to raise their arm straight overhead, as far as possible, while keeping their elbows straight [20]. The stationary arm of the digital goniometer was placed in parallel to the midline of the thorax while the moving arm was aligned with the shaft of the humerus and the lateral epicondyle. Two measurements were taken for each arm and test. The reliability of these shoulder ROM tests ranged from 0.91 to 0.99 in a previous study [20].

The Y-Balance Upper Quarter test was used to assess the stability and mobility of upper extremity to identify asymmetries with a high degree of reliability (ICC ranging between 0.986–0.990) [21]. The test consisted of moving, with one hand from a barefoot push-up position, the three wooden blocks of the Y-Balance Test Kit (Functional Movement System, Inc., Danville, CA, USA) in the medial, inferolateral and superior–lateral directions as far as possible.

A trial was considered failed when at least one of the fault criteria was observed: failure to maintain a unilateral stance; failure to maintain reach hand contact; using the reach indicator for stance support; failure to return the reach hand to the starting position; or lifting either foot off the floor [21]. The maximum reach distance for each reach direction was normalized by dividing it by the upper-limb length. The upper-limb length was measured, with a tape measure (Seca 203, Hamburg, Germany), from the C7 vertebrae to the end of the third finger of the hand with the shoulder at 90°, elbow extended and wrist

at neutral position [22]. Two measurements were taken for each arm to ensure reliability. To compare both limbs, the measures were normalized through the following formula: (distance obtained on an axis/relative length of the limb) $\times$ 100.

The Active Knee Extension test is a highly reliable test (ICC = 0.99 for both right and left limb) to assess hamstring flexibility and the symmetry between limbs [23]. This test is based on angular measurements, recording canoeists' active knee extension, starting from a 90° hip flexion [23], with a digital goniometer (Baseline Absolute Axis 360°, Fabrication Enterprises, Inc., White Plains, NY, USA). Two expert evaluators conducted this test, one in charge of recording data and the other one ensuring no compensatory movements were made by the canoeists during the measurement.

2.3.3. Leg Press Explosive Strength Test

An explosive strength test in the horizontal leg press (RS-1403 Leg Press ROC-IT line; HOIST, Poway, CA, USA) was performed after an individual warm-up chosen by each subject. A linear Encoder (Chronojump Boscossystem, Barcelona, Spain) and the Chronojump software (version 1.7.0 for Windows; Chronojump Boscossystem) were used to record mean velocity (Vm) and maximum velocity (Vmax) in m/s, time in s until reaching Vmax (Tvmax), mean power (Pm) and maximum power (Pmax) in W and time in s until reaching Pmax (Tpmax), and mean force (Fm) and maximum force (Fmax) in N. A previous study reported the validity and reliability (ICC = 0.95–0.988) of this device to measure the movement speed and to estimate power [24].

The horizontal leg press test was performed with a one-leg support, and with a relative intensity of 50% of the canoeist's body weight. The movement consisted of a full leg extension starting from a hip and knee flexion position. Two isolated repetitions were performed for each leg, with the recovery time between repetitions left to the participant's discretion (~1 to 2 min).

2.3.4. Canoe Incremental Dynamometric Test

Before starting the test, each canoeist individually set up the canoe ergometer (Dansprint PRO Canoe Ergometer, Dansprint ApS, Hvidovre, Denmark) as comfortably as possible and resembling the position adopted in his or her own canoe. The ergometers' shaft was adapted with the Functional Electromechanical Dynamometry cable (Dynasystem Research, SYMOTEC, Granada, Spain) which presents a 3 mm displacement precision, 100 g for the sensed load, and a 1000 Hz sampling frequency [25,26] (Figure 2). The functional electromechanical dynamometer (Dynasystem Research, SYMOTEC, Granada, Spain) was used and set up in the tonic mode so that in each one-sided stroke, the load was increased by 3 kg.



Figure 2. Specific adaptation of the Dansprint Canoe to the Functional Electromechanical Dynamometry cable for the incremental dynamometric test.

The ROM of the pull was individualized to each paddler, simulating their stroke length from the entrance to the exit of the blade in the water. This range (cm of cable) corresponds to the start and the end of each step. Therefore, canoeists were able to freely settle to their most comfortable stroke. The test was complete when the paddler was not able to achieve a complete stroke anymore. The test was performed only on the stroke side, with the maximal number of strokes (N_{reps}) and peak force (F_{peak}) being retained for further analysis.

2.4. Statistical Analysis

Relative reliability was calculated through intraclass correlation coefficient (ICC) analysis using single/rater measurement, two-way mixed effects models, and absolute agreement [27]. The coefficient of variation (CV) was used as a measure of absolute reproducibility.

The influence of the inter-limb asymmetry (stroke side vs. non-stroke side) as a function of the international performance level (medal vs. no medal) and gender factors, were assessed with a two-factor ANOVA (international level and gender factors) after previously assuming multivariate normality and homogeneity of variances and covariances. Application of the univariate Kolmogorov–Smirnov test, together with the Lilliefors test, showed that the sample distribution was normal. Homoscedastic assumption was verified with the Box M test, followed by a post hoc HSD Turkey test. The ANOVA two-way effect sizes were reported as partial eta square (η_p^2) and interpreted as small (0.02), moderate (0.06), or large (0.14) [28].

Kappa coefficients were used to assess the extent of agreement regarding the direction of asymmetry between the different variables (i.e., TMG, ROM, leg press, etc.), considering slight (0.00–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), near perfect (0.81–0.99), and perfect (1.00) [29].

In addition, to classify a canoeist as “asymmetrical” or “symmetrical”, the specific asymmetry thresholds procedure of Dos’Santos et al. [30] was carried out, where the % of Asymmetry and SD are the average percentage and standard deviation of the sample’s asymmetry: % Asymmetry + $(0.2 \times \text{SD})$. This classification was applied individually to each variable of TMG, upper and lower limbs ROM, and leg press.

Multiple linear regression with stepwise variable selection was used to obtain a parsimonious model that allows for predicting canoe dynamometry performance (dependent variables: N_{reps} and F_{peak}) as a function of canoeists’ “asymmetrical” classification through asymmetry thresholds for TMG, ROM and leg press variables (independent variables). Model assumptions were verified with residual analysis and Durbin–Watson statistic ($d = 2.423$). Variation Inflation Factor (VIF) was used to verify multicollinearity, resulting in the need for eliminating the lateral asymmetry parameter of Dm and Tc.

All the analyses were performed with the Statistics Package for the Social Sciences (SPSS version 25.0 for Windows, SPSS Inc., Chicago, IL, USA).

3. Results

Relative and absolute reliability (ICC and CV, respectively) were calculated for each test outcome. TMG values for all assessed muscles ranged between 0.92 and 0.99 for Dm, 0.94 and 0.99 for Tc, 0.91 and 0.98 for Vrd. Coefficients of variation were 2.6, 2.8 and 3.3%, respectively. For the Active Knee Extension test, the lowest values of the leg from the stroke and non-stroke side were 0.94 and 0.92, and 2.8–2.8%, respectively; for ER, 0.94 and 0.92, and 4.5–5.7%, stroke and non-stroke side arm; for IR, 0.92–0.89 and 7.7–9.1%, respectively; for shoulder flexion, 0.97–0.98, and 1.3–1.3%, respectively; for the Y-Balance Upper Quarter test, 0.94–0.93, and 1.3–1.3%; for leg press 0.98–0.98, and 10.3–4.8%.

Regarding the inter-limb asymmetries of the contractile properties of the canoeists’ main muscles involved in their one-sided stroke paddle (see Tables 2 and 3), none of the upper or lower body TMG parameters (biceps femoris, deltoid, latissimus dorsi, pectoralis majors, rectus femoris and trapezius) are shown to be modulated either by sex or perfor-

mance level (international medal vs. non-medal). Only the asymmetry of Dm of the erector spinae muscle is greater in female than in male canoeists (22.75% vs. 9.72%; $F = 7.929$; $p = 0.012$; $\eta_p^2 = 0.318$). This asymmetry is negative for both sexes, i.e., toward the non-stroke side. The magnitude of the asymmetry of Tc in the semitendinosus is greater in medalist than in non-medalist canoeists (20.51% vs. 9.43%; $F = 4.590$; $p = 0.047$; $\eta_p^2 = 0.213$). This asymmetry is also negative in both groups. The asymmetry of Dm in the tibialis anterior is also greater in females than in males (30.97% vs. 16.29%; $F = 5.895$; $p = 0.027$; $\eta_p^2 = 0.257$). This asymmetry is positive in both sexes, i.e., toward the stroke side.

Table 2. Descriptive statistics and magnitude of interlimb asymmetry of TMG parameter of upper limbs muscles.

		Gender	Mean (cm) ± SD		% Asymmetry	Asymmetry	Asymmetry Direction	Threshold
			Stroke Side	Non-Stroke Side	(Mean ± SD)	IC 95%		
Deltoid	Tc	Males	15.77 ±2.056	16.00 ± 1.370	6.11 ± 5.788	−5.349–18.039	NS	7.27
		Females	15.73 ± 3.790	21.39 ± 18.111	14.72 ± 24.720	2.071–25.605	NS	19.66
		Total	15.75 ± 2.841	18.31 ± 11.820	9.80 ± 16.788	1.797–18.386	NS	13.16
	Dm	Males	3.65 ± 1.344	4.02 ± 1.207	30.76 ± 20.566	14.007–38.720	NS	34.87
		Females	3.12 ± 0.729	3.63 ± 1.203	23.31 ± 14.646	10.108–34.974	NS	26.24
		Total	3.42 ± 1.131	3.86 ± 1.191	27.56 ± 18.240	15.688–33.217	NS	31.21
	Vrd	Males	188.55 ± 76.970	200.79 ± 56.431	28.72 ± 20.906	10.415–37.449	NS	32.90
		Females	163.71 ± 47.971	167.10 ± 72.280	21.84 ± 17.797	7.666–34.868	S	25.40
		Total	177.91 ± 65.860	186.35 ± 64.289	27.77 ± 19.474	13.012–32.188	NS	31.66
Erector Spinae	Tc	Males	17.21 ± 4.567	16.30 ± 2.942	8.65 ± 8.546	4.401–15.550	S	10.36
		Females	15.44 ± 2.004	15.09 ± 2.475	5.98 ± 7.012	0.066–11.284	S	7.38
		Total	16.45 ± 3.726	15.78 ± 2.755	7.50 ± 7.853	3.871–11.779	S	9.08
	Dm	Males	6.09 ± 1.934	6.53 ± 2.127	9.72 ± 7.894	3.204–16.914	NS	11.30
		Females	4.43 ± 1.851	5.57 ± 1.579	22.75 ± 11.137	16.140–29.936	NS	24.98
		Total	5.38 ± 2.034	6.12 ± 1.929	15.31 ± 11.293	11.686–21.411	NS	17.57
	Vrd	Males	293.85 ± 96.744	325.00 ± 103.023	12.84 ± 12.834	.591–20.732	NS	15.40
		Females	231.43 ± 96.196	296.89 ± 75.901	24.13 ± 15.230	14.197–34.462	NS	27.19
		Total	267.10 ± 99.252	312.95 ± 91.351	17.68 ± 14.732	10.353–34.462	NS	20.62
Latissimus Dorsi	Tc	Males	35.16 ± 9.589	30.25 ± 8.865	20.19 ± 16.811	12.652–33.572	S	23.56
		Females	23.65 ± 5.031	21.28 ± 7.328	15.92 ± 13.043	4.650–25.700	S	18.53
		Total	30.23 ± 9.737	26.41 ± 9.242	18.36 ± 15.105	11.724–26.563	S	21.38
	Dm	Males	9.53 ± 2.788	9.02 ± 3.531	25.83 ± 12.866	17.376–39.187	S	28.40
		Females	7.40 ± 1.958	8.06 ± 3.603	21.02 ± 18.420	9.476–31.422	NS	24.70
		Total	8.61 ± 2.642	8.61 ± 3.505	23.77 ± 15.255	16.630–32.101	S	26.82
	Vrd	Males	233.76 ± 97.429	251.23 ± 115.771	30.75 ± 14.302	22.036–42.545	NS	33.61
		Females	259.39 ± 89.486	320.96 ± 169.910	20.89 ± 14.307	10.058–30.695	NS	23.75
		Total	244.74 ± 92.697	281.11 ± 142.021	26.52 ± 14.812	19.060–33.607	NS	29.48
Pectoralis Major	Tc	Males	21.67 ± 3.016	22.56 ± 3.405	9.80 ± 8.692	2.827–15.705	NS	11.54
		Females	20.38 ± 2.034	21.49 ± 4.389	11.00 ± 8.848	4.345–17.304	NS	12.77
		Total	21.12 ± 2.661	22.10 ± 3.761	10.31 ± 8.558	5.478–14.613	NS	12.02
	Dm	Males	9.31 ± 3.338	7.74 ± 2.573	21.08 ± 12.063	12.452–32.360	S	23.49
		Females	9.179 ± 2.737	7.97 ± 3.389	26.51 ± 16.336	17.106–37.137	S	29.78
		Total	9.25 ± 3.021	7.84 ± 2.872	23.41 ± 13.942	17.703–31.824	S	26.20
	Vrd	Males	342.18 ± 114.359	277.97 ± 90.299	22.76 ± 12.933	12.660–32.698	S	25.35
		Females	357.85 ± 95.830	294.37 ± 109.526	26.10 ± 14.760	16.448–36.611	S	29.05
		Total	348.90 ± 104.544	284.89 ± 96.707	24.19 ± 13.491	17.498–31.711	S	26.89
Trapezius	Tc	Males	29.56 ± 17.987	37.50 ± 22.026	26.04 ± 25.561	7.837–40.359	NS	31.15
		Females	30.02 ± 15.196	28.51 ± 17.212	16.17 ± 15.797	0.519–32.745	S	19.33
		Total	29.78 ± 16.358	33.65 ± 20.152	21.60 ± 21.779	8.919–31.811	NS	25.95
	Dm	Males	7.34 ± 3.056	8.26 ± 3.170	25.17 ± 14.734	13.797–34.664	NS	28.12
		Females	6.75 ± 1.927	7.05 ± 2.349	13.46 ± 15.089	2.229–22.905	NS	16.48
		Total	7.08 ± 2.564	7.74 ± 20.152	19.90 ± 15.680	11.055–25.743	NS	23.04
	Vrd	Males	212.43 ± 50.016	203.13 ± 85.179	26.42 ± 14.989	17.006–40.562	S	29.42
		Females	199.55 ± 67.631	215.73 ± 68.595	21.00 ± 16.990	9.445–32.786	NS	24.40
		Total	206.63 ± 57.321	208.53 ± 76.899	23.98 ± 15.731	16.659–33.240	S	27.13

Dm (maximum radial muscle belly displacement in mm), IC (interval confidence), NS (non-stroke side), S (stroke side), SD (standard deviation), Tc (contraction time in ms), Vrd (radial displacement velocity in mm·s^{−1}).

Table 3. Descriptive statistics and magnitude of interlimb asymmetry of TMG parameter of lower limb muscles.

		Gender	Mean (cm) $\pm$ SD		% Asymmetry	Asymmetry	Asymmetry Direction	Threshold
			Stroke Side	Non-Stroke Side	(Mean $\pm$ SD)	IC 95%		
Biceps Femoris	Tc	Males	34.55 $\pm$ 10.105	41.57 $\pm$ 12.821	23.64 $\pm$ 17.927	7.683–33.388	NS	27.23
		Females	40.27 $\pm$ 18.390	37.68 $\pm$ 9.555	19.86 $\pm$ 17.842	6.644–32.510	S	23.42
		Total	37.00 $\pm$ 14.136	39.90 $\pm$ 11.437	22.02 $\pm$ 17.543	10.940–29.173	NS	25.53
	Dm	Males	7.71 $\pm$ 2.415	9.34 $\pm$ 2.558	24.08 $\pm$ 15.427	13.741–34.893	NS	27.16
		Females	9.75 $\pm$ 1.846	8.86 $\pm$ 2.765	23.06 $\pm$ 15.281	11.480–32.764	S	26.12
		Total	8.58 $\pm$ 2.375	9.14 $\pm$ 2.592	23.64 $\pm$ 14.985	15.718–30.721	NS	26.64
	Vrd	Males	184.78 $\pm$ 60.215	191.86 $\pm$ 56.166	19.58 $\pm$ 15.399	5.307–29.331	NS	22.66
		Females	211.56 $\pm$ 58.273	191.51 $\pm$ 62.563	16.92 $\pm$ 18.416	4.338–28.513	S	20.60
		Total	196.26 $\pm$ 59.472	191.71 $\pm$ 57.452	18.44 $\pm$ 16.3678	8.352–25.393	S	21.71
Rectus Femoris	Tc	Males	27.43 $\pm$ 6.399	25.56 $\pm$ 3.418	17.89 $\pm$ 13.573	10.141–26.966	S	20.61
		Females	26.56 $\pm$ 5.250	24.85 $\pm$ 3.523	20.21 $\pm$ 7.332	11.638–28.567	S	21.68
		Total	27.06 $\pm$ 5.808	25.25 $\pm$ 3.394	18.89 $\pm$ 11.145	13.361–25.295	S	21.12
	Dm	Males	8.35 $\pm$ 2.487	7.46 $\pm$ 1.842	33.93 $\pm$ 11.712	22.765–42.887	S	36.27
		Females	7.63 $\pm$ 2.419	7.36 $\pm$ 1.794	20.97 $\pm$ 16.245	11.213–31.460	S	24.22
		Total	8.04 $\pm$ 2.422	7.42 $\pm$ 1.777	28.37 $\pm$ 14.973	19.945–34.217	S	31.37
	Vrd	Males	250.15 $\pm$ 79.767	236.79 $\pm$ 66.466	30.58 $\pm$ 16.639	19.872–43.905	S	33.91
		Females	235.58 $\pm$ 83.388	244.22 $\pm$ 77.266	24.10 $\pm$ 15.986	11.707–35.890	NS	27.30
		Total	243.91 $\pm$ 79.596	239.97 $\pm$ 69.512	27.81 $\pm$ 16.288	19.320–36.367	S	31.06
Semitendinosus	Tc	Males	41.12 $\pm$ 5.799	44.50 $\pm$ 7.904	15.30 $\pm$ 8.703	4.297–22.513	NS	17.04
		Females	33.38 $\pm$ 7.058	39.87 $\pm$ 4.311	17.61 $\pm$ 19.106	9.486–27.815	NS	21.44
		Total	37.80 $\pm$ 7.337	42.52 $\pm$ 6.878	16.29 $\pm$ 13.750	9.567–22.488	NS	19.04
	Dm	Males	10.37 $\pm$ 1.701	9.84 $\pm$ 3.126	19.69 $\pm$ 14.587	9.542–32.583	S	22.60
		Females	9.33 $\pm$ 3.052	9.67 $\pm$ 2.734	20.29 $\pm$ 18.005	9.344–32.529	NS	23.89
		Total	9.92 $\pm$ 2.365	9.77 $\pm$ 2.893	19.94 $\pm$ 15.710	12.828–29.171	S	23.09
	Vrd	Males	207.13 $\pm$ 53.580	178.10 $\pm$ 53.138	17.69 $\pm$ 14.120	5.785–28.152	S	20.51
		Females	222.03 $\pm$ 53.551	193.78 $\pm$ 49.768	16.56 $\pm$ 15.947	5.165–27.671	S	19.74
		Total	213.52 $\pm$ 52.755	184.82 $\pm$ 51.059	17.20 $\pm$ 14.727	8.761–24.626	S	20.15
Tibialis Anterior	Tc	Males	34.27 $\pm$ 18.995	30.23 $\pm$ 19.613	16.89 $\pm$ 20.658	2.126–35.960	S	21.02
		Females	27.80 $\pm$ 15.947	38.15 $\pm$ 16.861	37.96 $\pm$ 25.910	20.646–54.692	NS	43.14
		Total	31.50 $\pm$ 17.634	33.63 $\pm$ 18.477	25.92 $\pm$ 24.848	16.356–40.356	NS	30.89
	Dm	Males	4.24 $\pm$ 1.316	3.86 $\pm$ 1.672	16.300 $\pm$ 10.238	6.422–24.012	S	18.34
		Females	4.12 $\pm$ 1.982	4.30 $\pm$ 1.296	30.97 $\pm$ 19.210	20.725–38.424	NS	34.81
		Total	4.19 $\pm$ 1.590	4.05 $\pm$ 1.506	22.59 $\pm$ 16.144	16.157–28.634	S	25.81
	Vrd	Males	114.98 $\pm$ 40.360	114.86 $\pm$ 36.091	15.99 $\pm$ 15.842	4.729–26.416	S	19.15
		Females	125.82 $\pm$ 33.768	102.47 $\pm$ 39.621	30.51 $\pm$ 15.705	20.574–42.396	S	33.65
		Total	119.62 $\pm$ 37.179	109.55 $\pm$ 37.199	22.21 $\pm$ 17.057	15.838–31.220	S	25.62

Dm (maximum radial muscle belly displacement in mm), IC (interval confidence), NS (non-stroke side), S (stroke side), SD (standard deviation), Tc (contraction time in ms), Vrd (radial displacement velocity in mm·s^{−1}).

Finally, only the *sex* $\times$ *medal* interaction showed a significant difference ($F = 6.204$; $p = 0.023$; $\eta_p^2 = 0.267$); specifically, medalist canoeists showed greater asymmetry in the tibialis anterior compared to non-medalists (40.27 vs. 22.69%), with both groups displaying asymmetry toward the paddling side (positive asymmetry). The level of agreement between the inter-limb asymmetries direction for contractile properties of the main muscles involved in their one-sided stroke was mainly slight, with a perfect agreement (1.00) being observed only between biceps femoris and semitendinosus muscles.

Concerning the inter-limb asymmetries of the shoulder and leg–hip ROM, and the Y-Balance Upper Quarter test asymmetry (see Table 4), none of them was modulated either by sex or international performance level (international medal vs. non-medal), neither for the Y-Balance Upper Quarter test. The level of agreement between the inter-limb asymmetries direction for ROM and the Y-Balance Upper Quarter test were mainly slight.

For leg press force production, female canoeists showed a higher lateral asymmetry in their Fmax when compared to male canoeists (2.41% vs. 0.63%; $F = 6.568$; $p = 0.021$; $\eta_p^2 = 0.291$), with female canoeists showing asymmetry toward the stroke side (positive asymmetry), while male canoeists displayed asymmetry toward the non-stroke side (negative asymmetry). On the other hand, lateral asymmetry in the non-medalists was greater in their Tvmax than in the medalists (19.20% vs. 9.40%; $F = 8.111$; $p = 0.012$; $\eta_p^2 = 0.336$). This asymmetry was positive in both groups. The level of agreement between the inter-limb

asymmetries direction for average vs. maximum leg press force production was mainly slight (see Table 5).

Table 4. Descriptive statistics and magnitude of interlimb asymmetry for upper and lower limbs ROM assessment.

	Gender	Mean (cm) $\pm$ SD		% Asymmetry	Asymmetry	Asymmetry Direction	Threshold
		Stroke Side	Non-Stroke Side	(Mean $\pm$ SD)	IC 95%		
Shoulder ER	Males	79.87 $\pm$ 12.285	74.04 $\pm$ 12.767	10.39 $\pm$ 7.066	6.298–15.766	S	11.80
	Females	81.31 $\pm$ 9.319	82.72 $\pm$ 8.304	6.58 $\pm$ 5.524	1.922–11.449	NS	7.68
	Total	80.49 $\pm$ 10.876	77.76 $\pm$ 11.688	8.76 $\pm$ 6.588	5.501–12.217	S	10.07
Shoulder IR	Males	61.44 $\pm$ 11.879	61.05 $\pm$ 13.794	11.16 $\pm$ 6.003	6.827–17.376	S	12.36
	Females	70.86 $\pm$ 14.913	69.05 $\pm$ 13.146	9.91 $\pm$ 8.847	4.388–15.003	S	11.68
	Total	65.48 $\pm$ 13.762	64.48 $\pm$ 13.793	10.63 $\pm$ 7.178	7.157–14.640	S	12.06
Shoulder Flexion	Males	166.41 $\pm$ 8.221	170.39 $\pm$ 8.163	3.01 $\pm$ 3.032	0.354–4.523	NS	3.62
	Females	165.82 $\pm$ 11.188	164.56 $\pm$ 15.035	4.03 $\pm$ 3.210	2.107–6.301	S	4.67
	Total	166.16 $\pm$ 9.346	167.89 $\pm$ 11.654	3.45 $\pm$ 3.073	1.843–4.799	NS	4.06
Active Knee Extension	Males	146.49 $\pm$ 11.794	155.14 $\pm$ 9.074	5.81 $\pm$ 4.139	1.474–7.818	NS	6.64
	Females	156.60 $\pm$ 12.802	162.67 $\pm$ 12.113	4.60 $\pm$ 5.377	1.216–7.600	NS	5.67
	Total	150.82 $\pm$ 12.974	158.37 $\pm$ 10.888	5.29 $\pm$ 4.623	2.277–6.777	NS	6.21
YBT Upper Quarter in Medial direction	Males	102.91 $\pm$ 5.764	99.15 $\pm$ 6.962	6.34 $\pm$ 5.632	4.217–11.001	S	7.47
	Females	96.12 $\pm$ 5.510	96.42 $\pm$ 5.701	6.02 $\pm$ 3.830	2.768–9.491	S	6.78
	Total	99.86 $\pm$ 6.503	97.92 $\pm$ 6.414	6.20 $\pm$ 4.786	4.482–9.257	S	7.15
YBT Upper Quarter in Inferolateral direction	Males	94.62 $\pm$ 9.085	94.38 $\pm$ 7.969	5.77 $\pm$ 4.074	2.897–7.602	S	6.59
	Females	92.74 $\pm$ 9.895	91.84 $\pm$ 12.802	3.08 $\pm$ 1.585	0.689–5.351	NS	3.40
	Total	93.77 $\pm$ 9.251	93.23 $\pm$ 9.845	4.56 $\pm$ 3.417	2.479–5.791	S	5.24
YBT Upper Quarter in Superolateral direction	Males	67.32 $\pm$ 9.245	66.45 $\pm$ 10.395	4.61 $\pm$ 3.671	1.269–7.690	S	5.35
	Females	73.44 $\pm$ 10.196	71.18 $\pm$ 10.894	4.99 $\pm$ 5.357	2.056–8.417	S	6.06
	Total	70.08 $\pm$ 9.925	68.58 $\pm$ 10.614	4.78 $\pm$ 4.383	2.598–1.118	S	5.66

ER (external rotation), IC (interval confidence), IR (internal rotation), NS (non-stroke side), S (stroke side), SD (standard deviation), YBT (Y-Balance Tests)

After applying Dos’Santos et al.’s [30] individualized procedure for classifying athletes as “asymmetrical” based on specific asymmetry thresholds, 38.1% and 28% of the canoeist of our sample were considered “asymmetrical” for Tc and Dm in biceps femoris, while the 28.6% for both Tc and Dm in deltoid; 23.8% and 38.1% for Tc and Dm in erector spinae and 28.6% and 42.9% for Tc and Dm in latissimus dorsi. For pectoralis major muscle, 38.1% for Tc and Dm and 42.9% for Vrd, while for rectus femoris muscle, 33.3% were “asymmetrical” for the three neuromuscular parameters (Tc, Dm and Vrd). For the semitendinosus muscle, 28.6% and 42.9% for Tc and Vrd, for tibialis anterior, 28.6% for Dm and 42.9% for Vrd, while for the trapezius muscle, 28.6% for Tc and 38.1% for Vrd.

Specific asymmetry thresholds for ROM parameters classified as “asymmetrical” were 28.6% of canoeists for ER and 38.1% for IR, while in the Y-Balance Upper Quarter test, 33.3% and 42.9% for the inferolateral and superior–lateral directions. Regarding leg press strength, 23.8% of canoeists were classified as asymmetrical for Vm and 38.1% for Vmax.

Multiple linear regression analysis only showed a significant prediction model for canoe dynamometry performance using N_{reps} as the dependent variable and lateral asymmetry in leg press with Fmax ($\beta = 0.517$; $t = 2.780$; $p = 0.017$), Tvmax ($\beta = -0.608$; $t = -3.185$; $p = 0.008$) and Vm ($\beta = 0.988$; $t = 2.397$; $p = 0.034$) as predictor variables:

$$\text{Number strokes} = 10.083 + 3.603 \text{ Fmax} + 7.580 \text{ Vm} - 4.409 \text{ Tvmax} \quad (1)$$

This model is significant, but it only explains a small proportion of the variability in canoeists’ dynamometry performance ($F = 3.189$; $p < 0.038$; $R^2_a = 0.45$).

Table 5. Descriptive statistics and the magnitude of inter-limb asymmetry for leg press strength test.

	Gender	Mean (cm) $\pm$ SD		% Asymmetry	Asymmetry	Asymmetry Direction	Threshold
		Stroke Side	Non-Stroke Side	(Mean $\pm$ SD)	IC 95%		
Vm (m/s)	Males	0.66 $\pm$ 0.260	0.698 $\pm$ 0.270	8.49 $\pm$ 6.282	3.822–13.710	NS	9.75
	Females	0.73 $\pm$ 0.320	0.767 $\pm$ 0.320	6.88 $\pm$ 7.060	1.777–11.575	NS	8.29
	Total	0.69 $\pm$ 0.283	0.73 $\pm$ 0.287	7.77 $\pm$ 6.514	4.241–11.201	NS	9.07
Vmax (m/s)	Males	1.23 $\pm$ 0.481	1.25 $\pm$ 0.454	7.56 $\pm$ 5.738	3.205–10.432	NS	8.71
	Females	1.42 $\pm$ 0.602	1.41 $\pm$ 0.582	6.98 $\pm$ 3.702	3.181–10.342	NS	7.72
	Total	1.31 $\pm$ 0.532	1.32 $\pm$ 0.509	7.25 $\pm$ 4.819	4.246–9.333	NS	8.22
Tvmax (s)	Males	454.54 $\pm$ 180.939	385.54 $\pm$ 90.40	13.21 $\pm$ 9.916	11.144–22.413	S	15.20
	Females	471.67 $\pm$ 103.277	426.44 $\pm$ 56.549	13.45 $\pm$ 8.732	7.557–18.723	S	15.20
	Total	462.25 $\pm$ 147.782	403.95 $\pm$ 77.997	13.32 $\pm$ 9.158	10.993–18.925	S	15.15
Pm (W)	Males	273.09 $\pm$ 130.092	287.08 $\pm$ 137.013	8.37 $\pm$ 6.428	3.702–13.638	NS	9.65
	Females	253.96 $\pm$ 136.277	253.81 $\pm$ 124.211	6.67 $\pm$ 7.021	1.517–11.362	NS	8.07
	Total	264.48 $\pm$ 129.700	272.11 $\pm$ 129.092	7.60 $\pm$ 6.577	4.058–11.052	NS	8.92
Pmax (W)	Males	618.78 $\pm$ 331.231	642.25 $\pm$ 335.842	10.50 $\pm$ 6.970	5.717–14.709	NS	11.90
	Females	610.48 $\pm$ 329.222	608.744 $\pm$ 320.563	9.01 $\pm$ 6.117	4.358–13.267	NS	10.24
	Total	615.06 $\pm$ 321.557	627.17 $\pm$ 320.816	9.83 $\pm$ 5.947	6.348–12.677	NS	11.02
Tpmax (s)	Males	398.27 $\pm$ 182.305	328.36 $\pm$ 95.115	19.68 $\pm$ 10.805	14.202–28.733	S	21.84
	Females	424.78 $\pm$ 99.230	368.22 $\pm$ 63.190	14.06 $\pm$ 9.303	6.514–20.911	S	15.92
	Total	410.20 $\pm$ 147.720	346.30 $\pm$ 82.805	17.15 $\pm$ 10.302	12.476–22.704	S	19.21
Fm (N)	Males	411.92 $\pm$ 64.239	412.52 $\pm$ 66.517	0.64 $\pm$ 0.5057	−0.645–1.8581	NS	0.74
	Females	344.34 $\pm$ 70.542	335.24 $\pm$ 61.603	2.41 $\pm$ 2.385	1.345–3.650	S	2.89
	Total	381.51 $\pm$ 73.871	377.75 $\pm$ 74.043	1.44 $\pm$ 1.830	0.689–2.327	S	1.80
Fmax (N)	Males	733.37 $\pm$ 210.439	770.30 $\pm$ 211.317	2.94 $\pm$ 3.675	3.299–8.027	NS	3.67
	Females	488.43 $\pm$ 113.613	493.45 $\pm$ 112.780	2.43 $\pm$ 2.288	0.097–4.781	NS	2.89
	Total	623.14 $\pm$ 210.649	645.72 $\pm$ 220.968	4.36 $\pm$ 3.538	2.387–5.715	NS	5.07

Fm (average force), Fmax (maximum force), IC (interval confidence), NS (non-stroke side), Pm (average power), Pmax (maximum power), S (stroke side), SD (standard deviation), Tpmax (time until reaching Pmax), Tvmax (time until reaching Vmax), Vm (average velocity), Vmax (maximum velocity).

4. Discussion

The main outcomes of this study display a very good to excellent relative and absolute reliability, and there is evidence of minimal differences in the magnitude and direction of lateral asymmetry between female and male canoeists. Furthermore, female canoeists showed greater asymmetry in Dm (muscle tone) of erector spinae and tibialis anterior muscles, and in Fmax produced in the leg press, when compared to males. In addition, among the international canoeists in our sample, there were few differences between medalists and non-medalists during an official international event. Medalists had greater asymmetry in the Tc of the semitendinosus when compared to non-medalists; however, they had smaller asymmetry in the Tvmax in the leg press when compared to non-medalists. On the other hand, the direction of the asymmetry turns out to have a high variability in the carried-out tests. The specific asymmetry thresholds classify between 23 and 42% of canoeists of our sample as “asymmetric” depending on the test used. Leg press lateral asymmetry seems to have a certain explanatory capacity of the canoeists’ performance, when the performance is assessed through the maximum number of strokes (N_{reps}) achieved in the specific canoe incremental dynamometry test. Specifically, a greater asymmetry in Fmax and Vm and a lower asymmetry in Tvmax in the leg press showed a small predictive capacity for the canoeists’ performance.

Even though the canoe is supposed to be the asymmetric modality of canoeing, not even elite kayak paddlers are able to exhibit symmetric kinematics, since they perform micro adjustments to their body pose and their stroke technique to minimize out-of-balance forces and to maintain stability [31]. Therefore, understanding that canoeists have a higher center of gravity, a reduced base of support, and a one-sided stroke in their paddling position, we can assume that they are more vulnerable to these body adjustments for maintaining stability.

We are already aware that stroke style asymmetry has effects on body loading, unbalanced muscle forces and implications in left–right asymmetry in muscle growth, which can negatively affect speed, and, therefore, kayak racing performance [31]. However, in canoe paddlers, increased asymmetry on the lumbar spine flexion in the coronal plane was associated with higher racing speeds in the Polish national canoe team athletes [4]. We can understand that this greater spine flexion is due to the canoeists' attempt to increase their stroke amplitude. Significant higher paddling movement amplitude in the sagittal plane (both absolute and relative arm length) has already been found in the Italian national kayak team vs. intermediate and novice paddlers (82 ± 5 cm vs. 75 ± 5 and 69 ± 8 cm) [32]. This reduced stroke amplitude in less skilled athletes has been explained mainly due to their insufficient trunk and pelvis rotation, and elbow flexion. Similar conclusions have been observed in New Zealand paddlers, where more successful paddlers entered their blade well forward and closer to the longitudinal axis of the boat and then moved the blade a larger distance (larger amplitude) [33]. Similarly, in outrigger canoe, where paddlers adopt a very similar one-stroke position to flatwater canoe, it has been highlighted that asymmetries in the multi-joint isokinetic strength of upper extremity muscles may be an important characteristic contributing to performance [34]. Likewise, in canoe Slalom, which is the other Olympic canoeing discipline that is performed in whitewater, a significant segmental fluid distribution was also observed between the upper and lower hand of the canoeist's paddle grip, which has been related to differences in muscle mass [35]. Hence, based on the high-performance level of our sample, trunk rotation and flexion are used primarily to increase paddling amplitude, resulting in the storage of elastic energy in associated tissues which, together with the movements of the lower limbs, help the upper limbs transfer force to the stroke. Nevertheless, in the long-term, this energy stored asymmetrically due to the one-stroke technical movement pattern of the canoe can negatively affect the health of canoeists.

Although lateral asymmetry analysis of the contractile properties of the muscles through TMG has been explored in other sports, very few studies have focused on canoeing. Álvarez-Yates and García-García [1] evaluated biceps femoris and semitendinosus lateral asymmetry in three groups of canoeists (high-level, well-trained, and recreational junior canoeists). These authors showed that higher-level canoeists have a very high initial asymmetry in biceps femoris and semitendinosus (approximately 49% and 16%, respectively). Nonetheless, after performing a supervised specific hamstring flexibility program concurrently with the canoeists' daily training program, they were able to reduce asymmetry to 23% and 12% (symmetry increases). These values are similar to those of our canoeists, which were around 23% for Tc and 24% for Dm of the biceps femoris and 15% for Tc and 19% for Dm of the semitendinosus in male canoeists. Interestingly, in our study, it is evident that the magnitude of the asymmetry of Tc in the semitendinosus is greater in medalist than in non-medalist canoeists (20.51% vs. 9.43%). That is, higher asymmetry in the canoeists' knee flexors could be a characteristic of world-level canoeists.

On the other hand, García-García et al. [13] analyzed sex-related differences in contractile properties in a sample of high-level canoeing athletes, even though they only focused on kayakers. These authors point out that sex does not influence the lateral asymmetry of latissimus dorsi, deltoid and trapezius, which are the same findings that we have found in our canoeists. Furthermore, they point out that high-level kayakers show a greater lateral asymmetry in the trapezius than non-kayaking women. With our sample of canoeists, we have not been able to verify differences in the trapezius between performance levels, mainly because: (1) in our sample, all canoeists were athletes competing in an official world canoe event (with medalists included), which probably greatly limits establishing clear differences in contractile properties; and (2) the distinct sports disciplines associated with canoeing and kayaking, as well as the different technical performance patterns.

Furthermore, it should be highlighted that the previously mentioned studies [1,13] determined lateral asymmetry using the algorithm implemented by the TMG-BMC Tensiomyo-

graphy[®] software itself, while we decided to address lateral asymmetry based on test-specific asymmetry thresholds, a method increasingly used in scientific literature in the study of sports asymmetry [15,30,36,37]. Therefore, the previous discussion should be taken even more cautiously.

Focusing on ROM, no differences have been found in the Active Knee Extension test, shoulder ER, IR and flexion, and the Y-Balance Upper Quarter test between female and male canoeists. Our results are in line with McKean and Burkett [38] who also did not find significant sex differences in shoulder ROM (ER and IR). Although these authors focused on kayakers and reported slightly lower values than our canoeists in shoulder IR (kayakers 42.9° and 51.5° vs. canoeists 61.2° and 69.9° males and females, respectively), this might have been due to the different shoulder movement between kayakers and canoeist. Kayakers' shoulder movement focuses more on a closed forward kinetic movement performing repeated shoulder abduction and adduction movements in the frontal plane, accompanied by a symmetrical trunk rotation in the transverse plane in each stroke, while canoeists perform shoulder flexion and extension movements in the sagittal plane, which are accompanied by a trunk rotation only on the stroke side. Therefore, it can be understood why shoulder injury is so common in canoe-kayak sports [39]. Nonetheless, these reduced shoulder ROM values, a product of long-term specific adaptation of the canoeing sport, should not be overlooked, as they are considered a contributing factor to the increase in injuries [37]. Regarding the Y-Balance Upper Quarter test, it has rarely been used with canoeists; however, we found it interesting to explore asymmetries in upper-limb stability and mobility. Gäbler et al. [40] have also used it to predict performance in young canoeists, although they had not reported data in the three reach indicators of the "Y" to be able to compare them with our data. Nevertheless, they had to exclude this test from their regression analysis due to violations of normality assumptions. Similarly, in our multiple linear regression analysis, it had not turned out to be a variable that had a great predictive power.

The Active Knee Extension test has already been used in other studies to assess lower limb flexibility in male international junior canoeists, obtaining higher ROM values than our male canoeists (right: 158.74° and left: 164.20° vs. S: 146.4° and NS: 155.1°) [1]. These authors made no distinction between the canoeists' stroke side, despite the average age of our sample being higher, so our canoeists may have shown hamstring shortening caused by a longer sporting career. Therefore, this greater hamstring shortening, which is slightly more accentuated on the stroke side limb, in older canoeists, and with greater international performance level, indicates that the canoe-specific kneeling position on one leg forward is the product of years of training and specialization in that asymmetrical position. Unlike Limonta et al. [32], this may explain the slightly higher interlimb asymmetries found in the angular variables of lower limbs rather than upper limbs, which they reported in kayakers.

Nilsson and Rosdahl [41] have already highlighted the importance of leg action to contribute to propulsion in kayakers. Slalom canoeists showed greater fluid volume in lower limbs than kayakers, which has been related to greater muscle mass [35]. Nevertheless, slalom canoeists paddle sitting on their knees, while, in flatwater, canoeists use their legs to propel the boat forward through a pelvic retroversion to minimize velocity loss during the blade extraction. Therefore, despite canoeing being considered a predominantly upper-body sport, lower limbs should not be underestimated. Little attention has been given to lower limb strength in canoeists in scientific literature. To our knowledge, the few authors who addressed lower limb strength in canoeists made it through jump tests [42,43], yet the sample was young and composed of university paddlers (mean age 13.69 and 19.7 years, respectively). A similar sample of canoeists as ours, yet involving the junior category, was assessed by Álvarez-Yates and García-García [1]. These authors also assessed lower-limb strength through the unilateral leg press test but, curiously, their sample achieved greater Vm and Pmax than our international and world-level class canoeists. This could certainly be due to the differences in leg press machines, since there are leg press machines in which the movement is produced by pushing the foot platform forward or upward, while, in

others, by pushing the sitting bench backwards. Therefore, caution should be taken when comparing results from different devices.

Centering on sex differences, female canoeists have shown greater lateral asymmetry in the muscle tone of the erector spinae and tibialis anterior, and when producing Fmax in leg press, compared to male canoeists. A reasonable explanation for this greater asymmetry could be related to the greater muscle mass and type II fiber areas in males [44]. We must not forget that Dm has an inversely proportional relationship with muscle and tendon tone [17]. That is, the lower muscle mass and area of type II fibers in females could heighten the inter-limb differences in maximum strength when compared to male canoeists, although this hypothesis must be proven.

A significant explanatory model for canoeists' performance has been obtained using N_{reps} achieved in a canoe incremental dynamometric test on the detected lateral asymmetry in the leg press variables (Fmax, Tvmax and Vm). However, it only explains a small portion of the variability in canoeists' dynamometry performance ($R^2_a = 0.45$). The relationship between Fmax and N_{reps} seems logical, since the specific canoe dynamometry test followed an incremental protocol, where the resistance was increased by 3 kg with each stroke. Therefore, canoeists with greater specific stroke force are expected to perform a greater number of repetitions. However, our findings show us that the most asymmetrical canoeists in lower-limb strength are those with greater performance in the canoe incremental dynamometric test. This may be because canoeists with greater specific asymmetry adaptations produced by the canoe position itself and the unilateral paddling over years of experience are able to optimize their stroke power production from the kneeling canoe position.

These lateral asymmetry adaptations vary greatly in magnitude and direction. This can be seen in the great variability of the magnitude and direction of asymmetry depending on the performed test. Despite the extensive battery test carried out with our canoeists, which included assessments of different nature (neuromuscular properties of the main muscles involved in the canoe stroke, shoulder and hip-knee ROM, and strength through an explosive and a specific dynamometric test), it is difficult to establish a clear trend as to whether canoeists show lateral asymmetries towards the stroke or non-stroke side. Nevertheless, this could be expected given our specific small sample of canoeists, and such similar performance.

Several limitations can be highlighted in this work. Firstly, our sample size is small because of the high level of performance required to be part of it. However, the sample universe of this population is also very small. On the one hand, this situation allows for the perfect technical execution of the specific tests and gives solidity to our results; although, it makes it difficult to extrapolate our findings to other canoeists who have not reached this high level of performance. Furthermore, our findings are limited to the tests carried out to determine the percentage of asymmetry. Although these tests have shown a joint and muscular movement pattern related to the canoe stroke, it would be interesting to explore it with another battery test to check if these results remain stable. In addition, the exploratory nature of this work is also a limitation, making it necessary to carry out other experimental designs to continue observing the influence of lateral asymmetry on canoeists' performance. Finally, the main limitation of this work lies in not assessing performance directly through a competitive test. However, the variability of the competition conditions (i.e., wind, water temperature, depth, etc.) would make it difficult to homogenize these parameters and compare canoeists' performance in the six different canoe training groups. To overcome this possible limitation, we considered using a reproducible test using a canoe ergometer structure attached to a functional electromechanical dynamometer which would allow us to obtain a reproducible (and reliable) measure of sport performance. In this sense, more studies on the acquisition of performance indicators in canoeing are necessary to avoid the impact of weather conditions.

5. Practical Applications

This work reinforces the importance of lower limb strength in canoeing and the use of a new technological device, such as the Functional Electromechanical Dynamometry, for strength training and assessment; this device allows for simulating the specific joint angles of the canoe movement pattern. In addition, reporting different reference data from world-class canoeists' asymmetries can be of great importance for canoeists' coaches, since they should be aware that some asymmetry is inevitable and it is highly task-, metric-, individual-, and sport-specific [45]. Specifically, lateral asymmetry in lower limbs explosive force (Fmax, Tvmax and Vm), measured through the leg press, should be controlled by trainers periodically. A certain level of lateral asymmetry in the lower limbs force is appropriate for enhanced performance, which fits perfectly with the asymmetrical nature of canoe modality. However, an excess of lateral asymmetry could harm that sporting performance. This hypothesis must be addressed in future works.

6. Conclusions

Female canoeists showed greater asymmetry in the Dm (muscle tone) of erector spinae and tibialis anterior muscles, and a higher Fmax produced in the leg press than male canoeists. Medalist canoeists had greater asymmetry in the Tc of the ST when compared to non-medalist canoeists; however, they had smaller asymmetry in the Tvmax in the leg press when compared to non-medalists. The direction of the asymmetry (stroke side vs. non-stroke side) turns out to have a high variability in the carried-out tests. Greater asymmetry in Fmax and Vm and lower asymmetry in Tvmax in the leg press show a small predictive capacity for canoeists' performance on a specific canoe-incremental dynamometry test.

Author Contributions: Conceptualization, T.Á.-Y. and O.G.-G.; methodology, T.Á.-Y., O.G.-G. and F.Y.N.; formal analysis, O.G.-G., M.I.-C. and V.S.-G.; investigation, T.Á.-Y., A.C.-D. and O.G.-G.; resources, T.Á.-Y., V.S.-G. and F.Y.N.; writing—original draft preparation, T.Á.-Y., M.I.-C. and O.G.-G.; writing—review and editing, T.Á.-Y., A.C.-D., V.S.-G. and V.F.-L.; visualization, A.C.-D., V.S.-G. and V.F.-L.; supervision, O.G.-G. and F.Y.N.; project administration, O.G.-G. and F.Y.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Research Committee of the Faculty of Education and Sports Sciences of the University of Vigo (Protocol code 07-1019).

Informed Consent Statement: Informed consent was obtained from all athletes involved in the study.

Data Availability Statement: The data that support the findings of this study are available from the authors T.Á.-Y. and O.G.-G. upon request.

Acknowledgments: The authors would like to thank all the athletes involved in the study, as well as the coaches of the different training groups of Spain (David Costa Bouzada, Alejandro Conde Ordoñez and José Luís Otero Padín) and Portugal (Jasorlav Radon and Rodrigo Guerra), and the Galician Canoeing Federation for the support.

Conflicts of Interest: The authors declare no conflicts of interest.

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