Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

# Individual Catch-Phase Paddle Configurations in Elite Para-Kayak Athletes: A Reference-Based Kinematic Single-Case Series

**Maria Teresa Benincasa**

Mariateresa.benincasa@univr.it

University of Verona

**Daniele Albano**

University of Sannio

**Silvia Coppola**

University of Salerno

**Claudia Costa**

University of Verona

**Francesco Coiro**

University of Verona

**Ester Celentano**

University of Salerno

**Enrico Serra**

University of Verona

**Rodolfo Vastola**

University of Salerno

**Research Article**

**Keywords:** Paracanoe, Kayak ergometer, Optimal Stroke Profile, Paddling Kinematics, Single-case analysis

**Posted Date:** October 27th, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-10500181/v1

**License:** This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

**Additional Declarations:** No competing interests reported.

# Abstract

Paddling is cyclic and technique determines performance, requiring adaptations to maintain propulsive effectiveness. In Olympic sprint kayaking, a kinematic reference stroke profile has previously been proposed to describe an optimal execution space, whereas its applicability to paracanoe remains unclear. This exploratory study examined how paracanoe athletes deviate from a previously published Olympic reference stroke profile by comparing four variables at the catch: Paddle Advance, Paddle Separation, Frontal Angle and Lateral Angle. Athletes performed two 30-s maximal trials on a kayak ergometer while three-dimensional paddle kinematics were recorded. Deviations from the Olympic reference profile were quantified using z-scores and modified single-case t-tests. All athletes showed deviations. Frontal angle, lateral angle and paddle advance were higher, whereas paddle separation fell within the variability of the reference profile. The Olympic reference profile may represent a useful preliminary benchmark, but individual configurations emerge and may be related to specific functional constraints.


# Introduction

Sprint canoeing is practised on flatwater and involves races over distances ranging from 200 to 5000 metres. In kayaking, the athlete sits on a fixed seat, with the feet placed on a footrest and the legs semi-flexed to facilitate the transmission of propulsive force. Propulsion is generated using an offset double-bladed paddle (International Canoe Federation, 2021). Performance depends on maintaining a high mean speed by maximising propulsive forces and limiting hydrodynamic and aerodynamic resistance (Goreham et al., 2018; McDonnell et al., 2013; Baker, 2012; Michael et al., 2009). The cyclic nature of the movement requires high intersegmental coordination and a continuous exchange of reaction forces, oriented in different directions, whose interaction sustains propulsion (Bjerkefors et al., 2019; Bjerkefors et al., 2018; Ribeiro et al., 2024; Rosén et al., 2021). Maintaining this dynamic balance entails constant mechanical adjustments related to technique, strength capacities and the athlete-boat-environment interaction (Baker, 2012; Michael et al., 2009), making the analysis of kinematics and the forces involved central to performance optimisation (Michael et al., 2009). From this perspective, paddling technique represents a key determinant of performance, as it enables the maximisation of power transfer to the water with lower energy expenditure. In particular, the paddle trajectory has been identified as a key variable for stroke efficiency and speed and, given the high drag and instability of the kayak, requires continual refinement and adjustment (Garnier et al., 2023; Löppönen et al., 2022). Considering the importance of blade trajectory for performance, López López and Ribas Serna (2011) proposed the Optimal Stroke Profile (OSP) as a quantitative reference for describing paddle trajectory in elite Olympic flatwater kayaking. In their study, six Olympic flatwater kayakers from the Spanish national team performed a 60-s maximal sprint in the laboratory on a kayak ergometer, and three-dimensional motion analysis was used to quantify the paddle trajectory during the ergometer-based stroke. The OSP was defined using four kinematic variables: Paddle Advance and Paddle Separation, which describe the antero-posterior and medio-lateral position of the paddle at the catch, and Frontal Angle and Lateral Angle, which describe paddle orientation in frontal and lateral projections. Since no significant differences were observed among the six kayakers for these variables, the authors defined the OSP as the mean profile obtained from the elite kayakers and proposed it as a criterion for describing an ideal stroke in elite kayaking. In the present study, however, the OSP was not treated as a universally validated gold standard, but as a

published Olympic-derived kinematic reference model. Nevertheless, to our knowledge, it remains the only published framework that explicitly attempts to define an optimal paddle trajectory in sprint kayaking through specific spatial and angular kinematic descriptors. More recently, Garnier et al. (2023) also referred to the OSP when interpreting stable paddling profiles in trained kayakers performing maximal sprints of different durations on a kayak ergometer, supporting its continued relevance as a comparative reference, although not as a definitive normative standard. Although elite athletes show a tendency to converge towards consistent profiles regardless of sprint duration and pacing strategy (Garnier et al., 2023), the applicability of the OSP to paracanoe remains to be clarified. Paracanoe is the Paralympic canoeing discipline for athletes with a physical impairment and, in the case of kayak, involves individual races in single-seat boats with a double-bladed paddle (KL) over a distance of 200 metres (International Canoe Federation, 2021). Despite its recent introduction at the Paralympic Games, the literature on paddling technique remains limited, making it relevant to verify the transferability of models developed in Olympic kayaking. The functional classification system currently in use comprises three classes (KL1-KL3), differentiated according to trunk and lower-limb function (International Canoe Federation, 2023; Rosén, 2021). Along this continuum, trunk-pelvis rotation and lower-limb mobility progressively decrease from KL3 to KL1 (International Canoe Federation, 2023), with reduced range of motion (ROM) and power-generating capacity compared with Olympic kayakers (Bjerkefors et al., 2019; Rosén, 2015). These limitations lead athletes in the more impaired classes to adopt compensatory strategies that differ from those of Olympic kayakers. For example, KL1 paracanoeists tend to compensate for limited trunk and pelvic mobility through greater involvement of the shoulder and arm musculature and specific scapulohumeral mechanics, in an attempt to maintain effective propulsion despite limited trunk stability (Rosén, 2015). These functional disparities are also reflected in performance, KL3 athletes tend to achieve higher speeds, higher stroke rates and a wider paddling motion, whereas KL1 and KL2 display slower speeds, lower stroke rates and reduced displacement per stroke (Redwood-Brown et al., 2021; Rosén, 2015; Ribeiro Neto et al., 2024).

Despite advances in understanding the biomechanical differences between Olympic and Paralympic kayakers, a systematic analysis of paddle trajectories in paracanoe relative to the OSP is still lacking. It is therefore unclear whether the OSP, developed from elite kayakers without disabilities, can be regarded as a universal reference model or whether, conversely, it is necessary to acknowledge the existence of optimal profiles specific to different disability classes. In light of this gap, the present exploratory study used the OSP proposed by López López and Ribas Serna (2011) as a published Olympic-derived kinematic reference to describe how elite paracanoe athletes' catch-phase paddle configurations align with, or deviate from, this reference model. The aim was to examine the transferability of this Olympic-derived reference to paracanoe by analysing the four kinematic variables used to define it. It is hypothesised that deviations from the OSP are present and can be graded across the functional KL classes, in relation to differing levels of trunk and lower-limb control. Clarifying the extent to which Paralympic athletes deviate from the Olympic technical model may provide initial indications useful for training-related reflection, helping to understand how to adapt technical goals and instructional strategies to the specific motor and postural capacities of different classes of athletes and, at the same time, stimulating further research into the adaptive mechanisms underpinning performance in paracanoe.

# Methods

# Participants

Four paracanoe athletes from the Italian Canoe Kayak Federation, specialising in the kayak 200 m discipline (KL), participated in the present study (Table 1). All athletes were classified according to the International Canoe Federation (ICF) classification system and competed in official events. Two athletes belonged to the KL1 class (Athletes 1 and 2) and two to the KL3 class (Athletes 3 and 4). The KL1 athletes were characterised by the absence of functional control of the trunk and lower limbs. Athlete 1 required external support to maintain the seated position and presented reduced upper-limb strength, whereas Athlete 2 presented a comparable trunk and lower-limb functional profile without additional upper-limb impairment. The KL3 athletes presented impairments of the lower limbs, with preserved trunk and upper-limb function. Athlete 3 was characterised by a unilateral transtibial amputation, whereas Athlete 4 presented a neurological lower-limb impairment, associated with an absence of voluntary movement distal to the knee.

Table 1
Age, gender, anthropometric, and competitive experience characteristics of the participants

| Athlete | Class | Gender | Age (years) | Height (cm) | Body mass (kg) | Years of competitive experience (years) |
|---|---|---|---|---|---|---|
| Athlete 1 | KL1 | Male | 25 | 150 | 60 | 12 |
| Athlete 2 | KL1 | Male | 41 | 170 | 90 | 8 |
| Athlete 3 | KL3 | Female | 32 | 168 | 60 | 6 |
| Athlete 4 | KL3 | Male | 16 | 167 | 72 | 9 |
| Mean ± SD | - | - | 29 ± 11 | 164 ± 9 | 71 ± 14 | 9 ± 3 |

At the time of assessment, all athletes had a confirmed sport class status in accordance with ICF regulations. Only officially registered para-kayak athletes were included, with medical clearance for competitive sport and at least one year of experience in official competitions at national or international level. Athletes competing at a lower level or presenting injuries likely to compromise typical paddling technique were excluded. All participants followed a structured training programme of 5 ± 1 sessions per week, totalling 14 ± 4 hours of exercise overall, in line with the average training loads reported for international-level Paralympic athletes (Rosén et al., 2021).

# Procedures

All participants received detailed information about the experimental protocol and signed an informed consent form, in the case of underage participants, consent was signed by parents or those holding parental responsibility. The study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Ethics Committee of the Department of Human, Philosophical and Education Sciences of the University of Salerno (Protocol Number: 0125702). The entire experimental protocol was designed and supervised by the staff of the Laboratory for Innovative Teaching and Sports Performance Analysis of the University of Salerno, in collaboration with the Italian Canoe Kayak Federation. Tests were carried out at the

Laboratory under controlled environmental conditions between 09:00 and 14:00. Participants were asked to refrain from intense training in the 24 h preceding the measurements.

## Ergometer set-up and testing protocol

Testing was performed on a flywheel kayak ergometer (Dansprint kayak ergometer, Dansprint ApS, Hvidovre Municipality, Denmark) to maintain consistency with the experimental setting used in the original OSP study and to provide a controlled and repeatable environment for marker-based kinematic analysis. Prior to the trials, athletes were thoroughly familiarised with the experimental procedure. For KL1-class athletes, customised seats or adaptive straps were fitted to the ergometer to closely reproduce race conditions. The KL3 athlete with a left transtibial amputation used her own prosthesis throughout all trials. The distance between the seat and the footrest bar was individually adjusted to match each athlete's usual kayak settings, ensuring maximum postural similarity between the on-water position and the laboratory position. Flywheel resistance was set according to each participant's body mass, following the manufacturer's technical specifications, to approximate the mechanical resistance experienced during on-water paddling (http://www.dansprint.com) (accessed 13 October 2025). After a 10-min warm-up at self-selected intensity, performed under the supervision of their coach and consistent with individual preparation routines (Rosén et al., 2021), participants completed two 30-s maximal trials (Rebensburg et al., 2019), interspersed with 15 min of complete recovery (Garnier et al., 2023; Rebensburg et al., 2019). All participants had prior experience using the kayak ergometer and were instructed to use their habitual paddling technique to preserve the naturalness of the movement.

## Kinematic acquisition

Kinematic data were collected using a passive-marker optoelectronic system (BTS SMART-D, BTS Bioengineering, Milan, Italy). To define the task reference frame and reconstruct the three-dimensional paddle trajectory, four markers were applied: two fixed to the ends of the paddle (Fig. 1) and two on the rear frame of the kayak ergometer.

The paddle markers were used to reconstruct the longitudinal axis of the paddle and to track the spatial trajectory of each paddle end. The ergometer markers were used to define a stable task reference frame, allowing paddle motion to be described relative to the orientation of the kayak ergometer. The trajectories of the spherical reflective markers (12 mm diameter) were recorded by six infrared cameras positioned around the kayak ergometer (Dansprint, Dansprint ApS, Hvidovre, Denmark), so as to fully cover the working volume and minimise shadowed areas. The ergometer was equipped with a fixed flywheel connected to a carbon-fibre shaft via a retractable cable anchored at both ends, a configuration designed to approximate mechanical aspects of paddle traction during ergometer-based paddling. Before each acquisition, the optoelectronic system was calibrated according to the manufacturer's procedures, using a dynamic calibration wand (120 s) and a tri-axial static calibration device (10 s), to ensure the accuracy of the capture volume. Data were sampled at 140 Hz.

# Data analysis

Kinematic data processing was performed using BTS Analyzer software (v. 1.10.470.0) from the three-dimensional coordinates of the passive markers acquired at 140 Hz. The trajectories of the markers applied to the two ends of the paddle were interpolated using cubic splines over the entire trace (software default operator). This step was retained as part of the default preprocessing workflow; however, no missing samples were detected in the paddle-marker trajectories within the analysed central 20-s window. Trajectories were then smoothed using a triangular moving average filter. After filtering and interpolation, marker data were transformed from the laboratory absolute coordinate system to the task coordinate system, fixed to the kayak ergometer, in order to describe movements relative to the structure and orientation of the kayak. In this reference frame, the X-axis is oriented in the antero-posterior direction, with the positive direction pointing towards the bow (the athlete's direction of travel); the Z-axis is oriented to the athlete's right (positive medio-lateral direction), whereas the Y-axis is oriented upwards (positive vertical direction). The origin was set at the midpoint between the two markers positioned at the lateral ends of the rear part of the kayak ergometer, in order to provide a stable and repeatable spatial reference for all acquisitions. Once expressed in the task coordinate system, trajectories were numerically differentiated to obtain the velocity components of the markers. Particular attention was paid to the antero-posterior component of velocity ($v_X$) of the markers positioned at the ends of the paddle, as this variable was used in subsequent steps for the automatic identification of paddle entry and exit events (catch and release).

# Definition of events

The paddling cycle was defined as the interval between paddle entry (catch) and the subsequent entry of the same paddle, considered separately for the right and left sides. Automatic identification of these events was based on analysis of the antero-posterior component of velocity ($v_X$) of the marker positioned at the end of the paddle, obtained as the first time derivative of the marker trajectory using the differentiation operator implemented in BTS Analyzer software (v. 1.10.470.0). Similar cycle-segmentation approaches based on velocity criteria have already been adopted in kinematic analyses of ergometer paddling (Limonta et al., 2010). As the ergometer paddling trials had a total duration of 30 s, the first and last 5 s of the recording were excluded to eliminate the transient phases of initial acceleration and final deceleration. The analysis was therefore conducted on a central 20-s window. Event detection was performed separately for each side in two steps. In the first step, the negative peaks of $v_X$ were identified because they corresponded to the backward movement of the paddle during the pull phase. These negative peaks were used only to define a side-specific velocity threshold, not as catch or release events. Local minima were detected using predefined BTS Analyzer settings, including an 80-ms local search radius, a 2% standard-amplitude criterion and a 100-ms minimum width, in order to exclude small oscillations and noise-related fluctuations. From the retained minima, the mean value and standard deviation were calculated for each side. The side-specific threshold was then defined as mean + 5·SD. In the second step, this threshold was used to identify the temporal limits of each pull phase. The catch event was defined as the sampled time point immediately before the $v_X$ curve crossed from above to below the side-specific threshold, corresponding to the onset of the pull phase. The release event was defined as the sampled time point immediately after the $v_X$ curve crossed back from below to above the same threshold, corresponding to the end of the pull phase. A representative example of the velocity-based event-detection procedure is provided in Supplementary Material (Supplementary Figure S1). The 3% standard-amplitude setting was used only as a software tolerance for accepting threshold crossings and reducing spurious detections. It was not an additional biomechanical criterion, and no zero-crossing or

change-of-sign criterion was used to define the final events. This procedure, applied independently to the two sides, allowed the temporal boundaries of each paddling cycle to be delimited automatically and reproducibly, minimising subjective operator intervention.

## Calculation of kinematic variables

Four reference kinematic variables were calculated, in accordance with the definition proposed by López López and Ribas Serna (2011): two spatial and two angular. The spatial variables included: Paddle Advance (PA), defined as the distance along the antero-posterior axis between the paddle entry point and the origin of the kayak reference frame, corresponding to the projection of the movement in the direction of travel; Paddle Separation (PS), calculated as the distance along the medio-lateral axis between the paddle entry point and the longitudinal axis of the kayak, indicating the lateral distance of the stroke relative to the centreline of the boat. A graphical representation of these four variables is provided in Fig. 2. For each side, the entry point was defined on the marker positioned on the corresponding end of the paddle. The angular variables included: Frontal Angle (FA), i.e. the angle between the longitudinal axis of the paddle and the medio-lateral axis of the kayak reference frame projected onto the frontal plane; Lateral Angle (LA), defined as the angle between the paddle and the antero-posterior axis of the kayak reference frame projected onto the sagittal plane. The longitudinal axis of the paddle was defined as the segment joining the two markers fixed to the ends of the paddle.

**(A)** Paddle Advance (PA), **(B)** Paddle Separation (PS), **(C)** Lateral Angle (LA), and **(D)** Frontal Angle (FA).

## Definition of the paddling cycle

Blade entry (catch) and exit (release) events, identified on the basis of the antero-posterior component of marker velocity, allowed the temporal boundaries of the paddling cycles to be precisely defined. The three-dimensional trajectory of the marker placed on the end of the paddle expressed in the kayak reference frame and used to compute the spatial variables (Paddle Advance, Paddle Separation) and the time series of paddle angles in the frontal and sagittal planes used to compute the angular variables (Frontal Angle, Lateral Angle) were then time-normalised over the cycle. Finally, for each athlete and for each side, one representative cycle for each variable was selected, in line with the methodological approach of López & Serna (2011), which, for defining the optimal profile, involves the use of a single cycle per athlete.

# Trial stability and representative-cycle selection

Within-trial stability was verified using the coefficient of variation (CV%) calculated across cycles; a trial was considered stable if CV% ≤ 10%. For each trial, the mean cycle curve was computed, and similarity across the entire curve between the two trials was assessed using two complementary criteria: (i) Pearson's correlation coefficient (r), with a threshold of $r \geq 0.95$ for shape agreement; (ii) normalised root mean square error (nRMSE) relative to the overall range (max-min calculated across the two mean curves), with a threshold of nRMSE ≤ 10% for point-by-point distance. Trials were deemed similar and suitable for representative-cycle selection when both were stable and satisfied both criteria; otherwise, the representative cycle was derived

from the more stable trial. For each athlete, selection of the representative cycle for each kinematic variable was performed using two bespoke MATLAB scripts. In the first step, all consecutive cycles identified for each side (right and left) were aggregated, their structural homogeneity was verified, and the point-by-point mean across the entire normalised cycle (0-100%) was computed for each variable. The resulting mean (meanCycles) represents the intra-athlete reference mean profile for each variable (spatial or angular). Because FA, LA, PA and PS represent different spatial or angular features of the paddle trajectory and may therefore show different cycle-to-cycle variability, catch values (0% of the cycle) could derive from different cycles. This variable-specific selection was intended to maximise the representativeness of each metric, since the cycle that was most representative for one variable was not necessarily the most representative for the others. In the second step, each individual cycle was compared with the corresponding mean profile. For each variable, the root mean square error (RMSE) between the single-cycle temporal profile and the mean curve was calculated, thereby quantifying the deviation of the cycle pattern from the athlete's typical behaviour. The representative cycle for each variable was then identified as the one with the minimum RMSE, i.e. the profile most similar to the corresponding intra-athlete mean cycle. From the representative cycle, the point value corresponding to 0% of the cycle (FirstValue), i.e. the moment of paddle entry into the water (catch), was extracted. For angular variables, the value was subsequently mapped to the conventional interval [-180°, 180°] to avoid numerical discontinuities due to the cyclic nature of angular measurement.

# Comparison with the Olympic-derived OSP reference

Finally, the script calculated, for each side-specific variable, the z-score $(x - \mu)/\sigma$ with respect to the mean values and standard deviations of the Optimal Stroke Profile (OSP) (Table 2) proposed by López López and Ribas Serna (2011), where x is the point value (FirstValue) extracted from the representative cycle, μ is the mean and σ is the standard deviation of the corresponding values in the Olympic model. The OSP reference values used for the present comparison were taken directly from the summary values reported by López López and Ribas Serna (2011) and were not re-estimated from the graphical time-history plots. The calculation was performed separately for the four kinematic variables (PA, PS, FA, LA) and for each side, because a non-side-specific analysis could attenuate or mask deviations predominantly present in one of the two hemicycles; therefore, each side was compared with the OSP reference mean values (mean ± SD) reported in the literature, in order to quantify the magnitude and direction of deviations relative to the Olympic-derived reference model (Ae, 2008).

Table 2
Mean ± SD and units of the Olympic Optimal Stroke Profile (OSP) reference variables reported by López López and Ribas Serna (2011).

| Variable | Mean ± SD | Unit |
|---|---|---|
| Frontal water-paddle angle (FA) | 36.4 ± 1.8 | ° |
| Lateral water-paddle angle (LA) | 43.3 ± 1.6 | ° |
| Paddle advance (PA) | 1.009 ± 0.052 | m |
| Paddle separation (PS) | 0.330 ± 0.040 | m |

A z-score value of 0 indicates that the athlete's data coincide with the mean of the reference model (OSP). Positive values indicate that the variable assumes a higher value than the Olympic mean, whereas negative values indicate a reduction relative to it. The magnitude of the deviation was interpreted according to the following thresholds: $|z| < 1$ indicates a negligible deviation (within the expected variability); $1 \leq |z| < 2$ indicates a moderate deviation; $|z| \geq 2$ indicates a large deviation relative to the variability reported in the published OSP reference sample and may warrant cautious interpretation as a possible individual or functional adaptation. This classification allows an objective quantification of the technical distance between the para-athletes' movement pattern and the reference optimal profile, distinguishing both the direction (sign of the z-score) and the magnitude of the deviation for each kinematic variable analysed.

# Statistical Analysis

Given the small size of the OSP reference sample (n = 6), inferential analysis was performed using the modified single-case t-test proposed by Crawford and Howell (1998) and subsequently validated by Crawford and Garthwaite (2012). This approach, widely used in single-case studies with small control groups (Danckert et al., 2009; Cremoux et al., 2013; Cuadra et al., 2019), allows a reliable comparison of a single participant's value with a limited reference sample by adjusting the variance estimate to avoid excessive inflation of Type I error. The test was also designed to maintain good robustness with small control samples, moderate departures from normality and asymmetry in the data distribution, conditions frequently present in experimental designs similar to ours (Crawford et al., 2006; Crawford & Garthwaite, 2012). The test was applied separately for each side (right and left) to the four reference kinematic variables (Frontal Angle-FA, Lateral Angle-LA, Paddle Advance-PA, Paddle Separation-PS), using the mean values and standard deviations of the OSP model (FA = 36.4 ± 1.8°, LA = 43.3 ± 1.6°, PA = 1.009 ± 0.052 m, PS = 0.330 ± 0.040 m; n = 6). All tests were two-tailed with a significance level of $\alpha = 0.05$. For each comparison, the difference between the observed value and the OSP model mean, the standard error, the t value, degrees of freedom (df = 5), the theoretical p-value, the 95% confidence interval and effect size measures expressed in standard deviation units (d) and as Hedges' g, corrected for the small sample size, were calculated. Hedges' g values were interpreted according to the conventional thresholds proposed by Cohen (1988): 0.2 = small, 0.5 = medium, 0.8 = large, with values greater than 1 indicating very large effects. To increase statistical robustness with respect to parametric assumptions and the small size of the OSP sample, a parametric Monte Carlo bootstrap was implemented (B = 10,000 replications, fixed seed = 20251027). Comparison between the simulated distribution and the observed value allowed estimation of a two-tailed empirical p-value (pMC), used as the reference for significance assessment and for multiple-comparison correction. Correction for multiple comparisons was performed using the Holm-Bonferroni method, applied separately for each side of each athlete to control the family-wise Type I error rate (FWER = 0.05) across the four tests (FA, LA, PA and PS) (Vickerstaff et al., 2019). The corrected p-value (pHolm) was computed from the pMC values generated by the bootstrap. A result was considered statistically significant when $pHolm < 0.05$. Approximate normality of values in the OSP group was assumed; no formal normality tests were performed given the small sample (n = 6). All analyses were conducted in MATLAB (Version 25.1, MathWorks Inc., Natick, MA, USA).

# Results

Results are presented separately for each athlete. Details regarding the selection of the representative cycle are provided in the Supplementary Material (Supplementary Table S1). Supplementary Table S1, different cycle numbers may appear for different variables because the RMSE-based selection was performed independently for each side-specific kinematic variable. This procedure was used to identify, for each metric, the stroke cycle whose temporal profile was closest to the corresponding intra-athlete mean profile. For each participant, we report: (i) the recorded values for each of the four reference kinematic variables (Frontal Angle-FA, Lateral Angle-LA, Paddle Advance-PA, Paddle Separation-PS) relative to the reference Optimal Stroke Profile (OSP) model, together with the z-scores calculated with respect to the mean and standard deviation of the OSP sample; (ii) the results of the inferential analysis based on the modified single-case t-test (Crawford & Howell, 1998; Crawford & Garthwaite, 2012) and the parametric Monte Carlo bootstrap, with multiple-comparison correction according to the Holm-Bonferroni method. The absolute catch values of the four OSP-related variables are reported for each athlete and side in Table 3.

Table 3
Absolute catch values of the four OSP-related variables for each athlete and side.

| Athlete | Class | Side | FA (°) | LA (°) | PA (m) | PS (m) |
|---|---|---|---|---|---|---|
| Athlete 1 | KL1 | Right | 44.8 | 30.5 | 1.38 | 0.25 |
| Athlete 1 | KL1 | Left | 57.9 | 44.8 | 1.34 | 0.32 |
| Athlete 2 | KL1 | Right | 51.6 | 50.2 | 1.20 | 0.25 |
| Athlete 2 | KL1 | Left | 50.1 | 46.6 | 1.20 | 0.21 |
| Athlete 3 | KL3 | Right | 45.0 | 52.3 | 1.03 | 0.34 |
| Athlete 3 | KL3 | Left | 51.6 | 59.2 | 0.94 | 0.35 |
| Athlete 4 | KL3 | Right | 38.5 | 25.4 | 1.44 | 0.21 |
| Athlete 4 | KL3 | Left | 48.3 | 48.8 | 1.28 | 0.28 |

Table 3. FA = Frontal Angle; LA = Lateral Angle; PA = Paddle Advance; PS = Paddle Separation; OSP = Optimal Stroke Profile. Values are reported at catch from the representative cycle selected for each side-specific variable.

Descriptive z-scores and modified single-case test results are summarised in Table 4.

Table 4
Descriptive and inferential comparison between each athlete and the Olympic OSP reference.

| Athlete | Variable | Right side | | | | Left side | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | z-score | Δ [95% CI] | pHolm | Hedges' g | z-score | Δ [95% CI] | pHolm | Hedges' g |
| Athlete 1 (KL1) | FA (°) | + 4.64 | + 8.4 [3.4; 13.4] | 0.015* | 3.91 | + 11.93 | + 21.5 [16.5; 26.5] | $1.2\times10^{-6}$* | 10.05 |
| | LA (°) | −8.02 | −12.8 [− 17.3; −8.4] | 0.002* | −6.75 | + 0.91 | + 1.5 [− 3.0; 5.9] | 0.889 | 0.76 |
| | PA (m) | + 7.17 | + 0.37 [0.23; 0.52] | 0.002* | 6.04 | + 6.35 | + 0.33 [0.19; 0.47] | 0.006* | 5.34 |
| | PS (m) | −2.13 | −0.09 [− 0.20; 0.03] | 0.108 | −1.79 | −0.30 | −0.01 [− 0.12; 0.10] | 0.889 | −0.25 |
| Athlete 2 (KL1) | FA (°) | + 8.46 | + 15.2 [10.2; 20.2] | 0.0008* | 7.12 | + 7.59 | + 13.7 [8.7; 18.7] | 0.0024* | 6.39 |
| | LA (°) | + 4.33 | + 6.9 [2.5; 11.4] | 0.0312* | 3.64 | + 2.09 | + 3.3 [− 1.1; 7.8] | 0.1069 | 1.76 |
| | PA (m) | + 3.62 | + 0.19 [0.04; 0.33] | 0.0422* | 3.04 | + 3.65 | + 0.19 [0.05; 0.33] | 0.0594 | 3.08 |
| | PS (m) | −1.93 | −0.08 [− 0.19; 0.03] | 0.1341 | −1.62 | −3.08 | −0.12 [− 0.23; −0.01] | 0.0718 | −2.59 |
| Athlete 3 (KL3) | FA (°) | + 4.76 | + 8.6 [3.6; 13.6] | 0.0195* | 4.01 | + 8.43 | + 15.2 [10.2; 20.2] | 0.0018* | 7.10 |
| | LA (°) | + 5.61 | + 9.0 [4.5; 13.4] | 0.0164* | 4.72 | + 9.97 | + 15.9 [11.5; 20.4] | 0.0008* | 8.39 |
| | PA (m) | + 0.38 | + 0.02 [− 0.12; 0.16] | 1.000 | 0.32 | −1.33 | −0.07 [− 0.21; 0.08] | 0.546 | −1.12 |

| Athlete | Variable | Right side | | | | Left side | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | z-score | Δ [95% CI] | pHolm | Hedges' g | z-score | Δ [95% CI] | pHolm | Hedges' g |
| | PS (m) | + 0.28 | + 0.01 [− 0.10; 0.12] | 1.000 | 0.23 | + 0.55 | + 0.02 [− 0.09; 0.13] | 0.632 | 0.46 |
| Athlete 4 (KL3) | FA (°) | + 1.17 | + 2.1 [− 2.9; 7.1] | 0.333 | 0.98 | + 6.62 | + 11.9 [6.9; 16.9] | 0.0052* | 5.57 |
| | LA (°) | −11.17 | −17.9 [− 22.3; −13.4] | 0.0008* | −9.40 | + 3.46 | + 5.5 [1.1; 10.0] | 0.041* | 2.92 |
| | PA (m) | + 8.35 | + 0.43 [0.29; 0.58] | 0.0009* | 7.03 | + 5.15 | + 0.27 [0.12; 0.41] | 0.0153* | 4.34 |
| | PS (m) | −2.98 | −0.12 [− 0.23; −0.01] | 0.0798 | −2.51 | −1.38 | −0.06 [− 0.17; 0.06] | 0.262 | −1.16 |

Table 4. FA = Frontal Angle; LA = Lateral Angle; PA = Paddle Advance; PS = Paddle Separation; OSP = Optimal Stroke Profile. z-scores are descriptive and indicate the standardised deviation from the OSP mean. Δ = athlete value - OSP mean. pHolm is the Holm-corrected p-value derived from the modified single-case test and Monte Carlo bootstrap. Hedges' g is the small-sample-corrected standardised effect size. *pHolm < 0.05.

The following subsections describe the main athlete-specific and side-specific patterns observed across the four variables.

# Case 1 - Athlete KL1

For Athlete 1, the absolute catch values are reported in Table 3 and the case-OSP comparisons are reported in Table 4. The z-score analysis showed positive deviations for FA and PA on both sides. LA showed a side-specific pattern, with a negative deviation on the right side and a value close to the OSP reference mean on the left side. For PS, the right side showed a negative deviation, whereas the left side remained close to the reference value. The Holm-corrected single-case comparisons showed significant positive case-OSP differences for FA on both sides. LA showed a significant negative case-OSP difference on the right side, while the left-side comparison was not significant. PA showed significant positive case-OSP differences on both sides. PS showed no significant case–OSP difference on either side after Holm correction.

# Case 2 - Athlete KL1

For Athlete 2, Table 3 reports the absolute catch values and Table 4 reports the descriptive z-scores and corrected case–OSP comparisons. The z-score analysis showed that FA was above the OSP reference on both sides. LA was also above the reference bilaterally, with a larger deviation on the right side. PA was above the OSP reference on both sides, whereas PS was below the reference bilaterally, with the larger negative deviation on the left side. The Holm-corrected single-case comparisons showed significant positive case-OSP differences for FA on both sides. On the right side, LA and PA also showed significant positive case-OSP differences, whereas PS was not significant. On the left side, LA and PA showed positive case-OSP differences that did not remain significant after Holm correction. PS showed a negative case-OSP difference on the left side, but this comparison was also not significant after correction.

# Case 3- Athlete KL3

For Athlete 3, the absolute catch values are reported in Table 3, and the descriptive z-scores and corrected single-case comparison results are reported in Table 4. The z-score analysis showed that the main deviations concerned the angular variables. FA and LA were above the OSP reference on both sides. In contrast, the spatial variables showed smaller deviations. PA was close to the reference on the right side and below the reference on the left side, while PS was slightly above the reference bilaterally. The corrected single-case comparisons confirmed significant positive case-OSP differences for FA and LA on both sides. No significant case-OSP differences were observed for PA or PS on either side after Holm correction.

# Case 4 - Athlete KL3

For Athlete 4, the absolute catch values are reported in Table 3, and the descriptive z-scores and corrected single-case comparison results are reported in Table 4. The z-score analysis showed a side-specific angular pattern. On the right side, LA was markedly below the OSP reference, whereas FA was close to the reference. On the left side, both FA and LA were above the reference. For the spatial variables, PA was above the OSP reference on both sides, whereas PS was below the reference bilaterally. The corrected single-case comparisons showed a significant negative case-OSP difference for right-side LA, whereas right-side FA was not significant. On the left side, FA and LA both showed significant positive case-OSP differences. PA showed significant positive case-OSP differences on both sides. PS showed negative case-OSP differences, but neither side remained significant after Holm correction.

## Discussion and implications

The aim of this study was to compare the individual kinematic profiles of four paracanoeists (KL1 and KL3) with the Optimal Stroke Profile (OSP) derived from Olympic kayakers, analysing for each athlete the four key catch variables (FA, LA, PA, PS) and quantifying the distance from the reference through z-scores and single-case tests. The paddle trajectory is a technical determinant closely related to stroke efficiency and, therefore, to kayak speed; small variations in paddle orientation may influence propulsive effectiveness (Löppönen et al., 2022). The high resistance of water necessitates continuous refinement of technique to optimise the trajectory and preserve propulsive effectiveness, making the study of movement kinematics a crucial step for performance improvement (Limonta et al., 2010). Within this framework, the four catch variables provide a focused description of paddle configuration at a biomechanically relevant event of the stroke, rather than an exhaustive representation of overall paddling technique. The catch represents the first defining event of the

water phase and precedes the pull phase, during which paddle orientation and position influence the subsequent direction and development of propulsive force (McDonnell et al., 2012; Gomes et al., 2015). Paddle orientation at the moment of water entry represents one of the main determinants of stroke propulsive effectiveness. From a biomechanical perspective, an effective stroke maximises the force component aligned with the direction of travel and reduces lateral components and roll.

Fluid-dynamic studies conducted by Sumner et al. (2003) showed that the drag force generated by the blade, the component useful for propulsion, depends sensitively on its orientation relative to the water flow. A blade held closer to the vertical allows a greater propulsive force to be generated and more effectively oriented in the direction of travel. Moreover, the same study showed that differences in blade shape or curvature have a smaller impact on efficiency than angle of attack, indicating that orientation at the catch constitutes an important determinant of blade hydrodynamic behaviour during the entry and early pull phase.

From a biomechanical standpoint, the findings of Michael, Rooney and Smith (2012) confirm that elite kayakers tend to keep the paddle as vertical as possible during the catch and the first half of the pull phase, a condition that promotes a more direct transfer of the applied force and is associated with greater propulsive efficiency. These findings support the relevance of analysing paddle configuration at the catch, while also indicating that this event should be interpreted within the broader sequence of the pull phase.

PA was included because it describes the forward position of the paddle at the catch along the kayak axis. In kayaking, a more forward entry may anticipate the start of the underwater propulsive phase, increase the effective stroke length and prolong the duration of force application. Since mean speed depends on the product of displacement per stroke and stroke rate, increasing the useful pull distance without compromising cadence represents a key technical objective. In the literature, a more advanced catch (forward reach) distinguishes higher-level paddlers: it increases with intensity, lengthens the immersed portion of the blade and increases the work per stroke; when combined with a high stroke rate, it is associated with higher power output and speed (Brown et al., 2011; Bjerkefors et al., 2018). However, PA is an absolute spatial variable and may be influenced by anthropometry, seating position and the athlete–ergometer configuration. For this reason, PA was interpreted in the present study as a descriptive indicator of catch position relative to the published OSP values, rather than as a standalone indicator of technical quality or propulsive effectiveness.

Analysis of the kinematic profiles relative to the OSP model made it possible to identify, for each athlete, specific catch-phase paddle configurations that may be compatible with their functional and postural characteristics. In our sample, Paddle Separation (PS) did not show statistically significant differences relative to the mean values of the Optimal Stroke Profile (OSP) for any of the four athletes (after Holm correction). This suggests that the lateral position of the paddle at entry was relatively close to the published reference values in the present sample, although this finding should be interpreted cautiously because PS, like PA, is an absolute spatial variable. Among KL1 athletes, significant differences mainly concerned the angles and the advance along the kayak axis. Both showed higher FA than the OSP; Athlete 2 presented greater PA on the right side (with higher right-side LA), whereas Athlete 1 showed greater PA on both sides but a significant reduction in right-side LA.

KL1 athletes generally maintain a more upright or slightly extended posture, with limited trunk flexion compared with KL2-KL3 and athletes without disabilities. This configuration arises from impairment of the trunk and hip flexors and extensors, which reduces the ability to lean forwards and necessitates the use of backrests or straps to stabilise the trunk and prevent anterior collapse, further limiting the ability to flex and rotate (Bjerkefors et al., 2019; Rosén et al., 2021).

From a performance perspective, the combined rotation of trunk and pelvis represents a determinant factor for force and power production: unlike “trunk rotation” alone (rotation of the trunk relative to the pelvis), the trunk-and-pelvis rotation angle, which includes the contribution of the pelvis, is closely correlated with performance levels and clearly distinguishes functional groups (Bjerkefors et al., 2018; Limonta et al., 2010; Begon et al., 2010). Non-impaired athletes show the highest values, followed by KL3 and finally KL1, supporting the relevance of pelvic mobility in kayak paddling. Athletes who are able to maintain a more forward-flexed position and combine this posture with large trunk and pelvis rotation can achieve greater forward reach during paddle entry, extending the useful pull distance (Brown, Lauder & Dyson, 2011).

In light of these constraints (limited trunk flexion and reduced pelvic rotation), the emergence in KL1 athletes of higher paddle angles at the catch (higher FA and, in some cases, higher LA) and a more forward entry point (higher PA) may be interpreted as a possible catch-phase configuration compatible with greater involvement of the shoulder girdle (Rosén et al., 2021). This interpretation is consistent with previous kinematic evidence in para-kayakers, although the present data cannot directly confirm the underlying joint or muscle mechanisms. It is plausible that, in the absence of the propulsive contribution of the pelvis and lower limbs, athletes may compensate through greater shoulder excursion, increasing forward reach and orienting the paddle closer to the vertical to align the applied force with the direction of travel and prolong the effective pull phase. This hypothesis is consistent with kinematic evidence describing, in more severely impaired para-kayakers, upper-limb compensatory patterns characterised by large shoulder flexion-extension and a greater contribution of the scapular girdle, alongside reduced trunk-pelvis rotation, which remains the parameter most closely associated with higher levels of force and power in less impaired groups and contributes to greater efficiency (Rosén et al., 2021). This possible compensation, which may involve the scapular girdle in place of the pelvis-trunk contribution, could reflect the principle of degeneracy within the ecological-dynamics approach, understood as “the capacity of structurally different elements to perform the same function or produce the same outcome” (Edelman & Gally, 2001). The reduction in right-side LA observed in Athlete 1 may be interpreted as a possible side-specific limitation in paddle orientation at catch, consistent with his functional profile characterised by reduced upper-limb strength, particularly of the biceps bilaterally and the right triceps. This finding was considered alongside the athlete’s broader functional profile and highlights the value of side-specific monitoring when interpreting individual paddling strategies.

In KL3 athletes, the picture is more heterogeneous, plausibly due to the differing nature of impairment within the same class. Athlete 3 (who presented a unilateral lower-limb impairment) showed positive differences limited to the angular variables (FA and LA on both sides), while maintaining PA and PS aligned with the OSP; conversely, Athlete 4 (who presented a neurological lower-limb impairment) presented higher FA-L and LA-L and greater PA on both sides, but significantly lower LA-R. In both cases, it is plausible to hypothesise involvement of the scapular girdle in supporting blade verticality and/or forward entry, similar to that described in KL1 athletes but less pronounced, as KL3 athletes have full trunk function (with impairment

predominantly affecting the lower limbs). The asymmetry in LA-R in Athlete 4 may reflect side-dependent specificities (e.g. differences in scapulothoracic control or postural compensations related to the athlete's impairment profile), with a reduced ability to elevate/rotate the blade on the right at the catch.

The differences observed in FA/LA and PA describe possible adaptive technical configurations at the catch phase within individual functional constraints, but they cannot, on their own, be considered exhaustive indicators of overall performance. High or low values in these variables may reflect individual technical choices, functional constraints or measurement-related factors, and their functional meaning requires support from kinetic, neuromuscular and performance-related data. Kayaking performance, and even more so paracanoe performance, should be interpreted within a systemic and multifactorial perspective that includes the interaction between stroke rate, displacement per stroke, force and power capacity, technical efficiency and intersegmental coordination, boat stability and management of hydrodynamic resistance (Michael et al., 2009; Limonta et al., 2010; Redwood-Brown et al., 2021). In paracanoeists, stroke rate represents the strongest predictor of speed, whereas displacement per stroke and catch kinematic variables carry different weight depending on class and sex, reflecting force availability, trunk-pelvis rotation capacity and postural stability (Redwood-Brown et al., 2021; Rosén et al., 2021). Comparative analyses show that mean completion times for KL1 and KL3 remain higher than those of Olympic able-bodied athletes (Ribeiro Neto et al., 2024). This suggests that performance in paracanoe requires a global perspective capable of integrating multiple biomechanical and physiological determinants, and of directing training towards individualised technical goals consistent with each athlete's functional profile.

Although based on a small sample, the results of this study provide initial indications that may be useful for technical assessment and monitoring in paracanoeists. The four variables analysed (FA, LA, PA, PS) could be useful in quantitatively describing paddle configuration at the catch, offering parameters that can support analysis and interpretation of technical execution. In the analysed sample, PS did not show significant differences after correction and was generally close to the OSP reference values, suggesting that lateral paddle position at entry was relatively close to the reference model. Moreover, the observation of side-specific asymmetries suggests that analysing variables separately for each side may be useful for identifying differences in movement symmetry, an aspect that the literature recognises as potentially relevant to propulsive efficiency and boat stability. Studies on elite kayakers have shown that even minimal asymmetries in technique or in the distribution of force between sides can alter stroke alignment, leading to micro-variations in trajectory and energy dissipation due to postural or directional corrections (Kertészné Német et al., 2019; McDonnell et al., 2012). Periodic monitoring of these side-specific variables could provide coaches with a complementary tool for technical analysis, capable of supporting traditional qualitative assessments and guiding observation and reflection on individual execution strategies, particularly in understanding and managing asymmetries and the functional constraints specific to each athlete.

# Limitations and future perspectives

This study has several limitations that should be considered when interpreting the results. First, the small number of paracanoe athletes and the limited size of the OSP reference sample restrict the generalisability of the findings. However, this limitation should be interpreted in light of the elite paracanoe context, where the

pool of Paralympic-level athletes is intrinsically small and heterogeneous, particularly when stratified by KL class and impairment profile. The use of single-case statistics with parametric bootstrap partially addressed this issue, but future studies should verify these preliminary observations in larger class-specific samples, ideally through multicentre or international collaborations. Second, the OSP was used as a published Olympic-derived kinematic reference model, not as a universally validated gold standard of kayak technique. In particular, PA and PS were retained in the absolute units reported in the original OSP study to preserve comparability; however, these spatial variables may be influenced by anthropometry, seating position, and athlete-ergometer configuration. Spatial deviations should therefore be interpreted cautiously. Finally, the ergometer-based setting ensured consistency with the original OSP study and provided a controlled environment for three-dimensional kinematic analysis, but it does not fully reproduce on-water paddling, particularly with respect to boat instability, blade–water interaction, and environmental constraints. Future studies should integrate on-water measurements of boat velocity, stability, direction, paddle force, and blade trajectory, together with complementary kinematic and neuromuscular measures, to better understand the relationship between individual technical adaptations and performance in paracanoe.

## Conclusions

This study represents an initial exploratory attempt to describe paracanoe paddling technique quantitatively and systematically in relation to the Olympic Optimal Stroke Profile (OSP), used here as an external comparative reference. Although derived from a limited sample, the results highlight the potential of catch kinematic variables as objective analytical tools, capable of providing indications of individual style and of the adaptive strategies adopted by athletes in accordance with their functional constraints. Rather than proposing a universal technical model, the work encourages an interpretation of differences as expressions of adaptation, offering a methodological approach that can be extended and refined in subsequent studies. Expanding sample sizes, integrating biomechanical and performance measures, and applying on-water analysis systems may allow these preliminary findings to be verified and enriched, helping to define class-specific technical profiles and to improve understanding of the relationships between technique and performance. In a research field that remains underdeveloped, this study therefore provides a preliminary foundation from which future investigations can develop, supporting the growth of paracanoe both scientifically and in applied practice.

## Declarations

# Conflicts of Interest

No potential conflict of interest was reported by the author(s).

**Ethical approval**

The study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Ethics Committee of the Department of Human, Philosophical and Education Sciences of the University of Salerno (Protocol Number: 0125702).

**Consent to participate**

Informed consent was obtained from all individual participants included in the study.

**Informed consent**

The authors affirm that the participants provided consent for the publication of data.

# Funding

No funding was received.

# Author Contribution

M.T.B. contributed to all stages of the work, including study conception, methodology, data interpretation, manuscript writing, and final revision. D.A., F.C., and E.S. contributed to data processing and methodology. E.C. contributed to manuscript writing. C.C. prepared the figures and tables. S.C. contributed to manuscript revision and writing refinement. R.V. contributed to the overall project design, methodology, supervision, and manuscript revision. All authors reviewed and approved the final manuscript.

# Acknowledgement

The authors gratefully thank the athletes for donating their time to participate in this study and the Italian Canoe Kayak Federation for its support.

# Data Availability

The data are available at the following DOI: 10.6084/m9.figshare.31071868

## References

1. Ae, M. (2008). A biomechanical method for the evaluation of sports techniques by standard motion, motion variability and motion deviation. ISBS-Conference Proceedings Archive.
2. Baker, J. (2012). Biomechanics of paddling. ISBS-Conference Proceedings Archive.
3. Begon, M., Colloud, F., & Sardain, P. (2010). Lower limb contribution in kayak performance: modelling, simulation and analysis. *Multibody System Dynamics*, *23*(4), 387-400. https://doi.org/10.1007/s11044-010-9189-8
4. Bjerkefors, A., Rosén, J. S., Tarassova, O., & Arndt, A. (2019). Three-dimensional kinematics and power output in elite para-kayakers and elite able-bodied flat-water kayakers. *Journal of Applied Biomechanics, 35*(2), 93-100. https://doi.org/10.1123/jab.2017-0102

5. Bjerkefors, A., Tarassova, O., Rosén, J. S., Zakaria, P., & Arndt, A. (2018). Three-dimensional kinematic analysis and power output of elite flat-water kayakers. *Sports Biomechanics, 17*(3), 414-427. https://doi.org/10.1080/14763141.2017.1359330
6. Brown, M. B., Lauder, M. A., & Dyson, R. (2011). Notational analysis of sprint kayaking: Differentiating between ability levels. *International Journal of Performance Analysis in Sport, 11*(1), 171-183. https://doi.org/10.1080/24748668.2011.11868538
7. Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawrence Erlbaum Associates. https://doi.org/10.4324/9780203771587
8. Crawford, J. R., & Howell, D. C. (1998). Comparing an individual's test score against norms derived from small samples. *The clinical neuropsychologist*, *12*(4), 482-486. https://doi.org/10.1076/clin.12.4.482.7241
9. Crawford, J. R., & Garthwaite, P. H. (2012). Single-case research in neuropsychology: a comparison of five forms of t-test for comparing a case to controls. *Cortex, 48*(8), 1009-1016. https://doi.org/10.1016/j.cortex.2011.06.021
10. Crawford, J. R., Garthwaite, P. H., Azzalini, A., Howell, D. C., & Laws, K. R. (2006). Testing for a deficit in single-case studies: effects of departures from normality. *Neuropsychologia, 44*(4), 666-677. https://doi.org/10.1016/j.neuropsychologia.2005.06.001
11. Cremoux, S., Tallet, J., Berton, E., Dal Maso, F., & Amarantini, D. (2013). Does the force level modulate the cortical activity during isometric contractions after a cervical spinal cord injury? *Clinical Neurophysiology, 124*(5), 1005-1012. https://doi.org/10.1016/j.clinph.2012.11.007
12. Cuadra, C., Falaki, A., Sainburg, R., Sarlegna, F. R., & Latash, M. L. (2019). Case studies in neuroscience: the central and somatosensory contributions to finger interdependence and coordination: lessons from a study of a “deafferented person”. *Journal of Neurophysiology, 121*(6), 2083-2087. https://doi.org/10.1152/jn.00153.2019
13. Danckert, J., Goldberg, L., & Broderick, C. (2009). Damage to superior parietal cortex impairs pointing in the sagittal plane. *Experimental Brain Research, 195*, 183-191. https://doi.org/10.1007/s00221-009-1766-9
14. Dansprint. (n.d.). *Dansprint kayak ergometers*. https://www.dansprint.com (accessed 13 October 2025)
15. Edelman, G. M., & Gally, J. A. (2001). Degeneracy and complexity in biological systems. *Proceedings of the National Academy of Sciences, 98*(24), 13763-13768. https://doi.org/10.1073/pnas.231499798
16. Garnier, Y. M., Hilt, P. M., Sirandre, C., Ballay, Y., Lepers, R., & Paizis, C. (2023). Quantifying paddling kinematics through muscle activation and whole body coordination during maximal sprints of different durations on a kayak ergometer: A pilot study. *International Journal of Environmental Research and Public Health*, *20*(3), 2430. https://doi.org/10.3390/ijerph20032430
17. Goreham, J. A., Landry, S. C., Kozey, J. W., Smith, B., & Ladouceur, M. (2018). Functional data analysis: a new method to investigate pacing strategies in elite canoe kayak sprint. *ISBS Proceedings Archive, 36*(1), 426.
18. International Canoe Federation. (2021). Paracanoe. Accessed 14 December 2025, from https://www.canoeicf.com/disciplines/paracanoe

19. Gomes, B. B., Ramos, N. V., Conceição, F. A., Sanders, R. H., Vaz, M. A., & Vilas-Boas, J. P. (2015). Paddling force profiles at different stroke rates in elite sprint kayaking. *Journal of Applied Biomechanics*, *31*(4), 258-263. https://doi.org/10.1123/jab.2014-0114
20. International Canoe Federation. (2023). *International canoe federation - paracanoe*. Accessed 14 December 2025, from https://www.canoeicf.com/disciplines/paracanoe
21. Kertészné Német, B., Terebessy, T., & Bejek, Z. (2019). Ép és mozgásukban korlátozott kajakos sportolók biomechanikai mozgáselemzése és összehasonlító vizsgálata. *Orvosi Hetilap*, *160*(52), 2061-2066. https://doi.org/10.1556/650.2019.31444
22. Limonta, E., Squadrone, R., Rodano, R., Marzegan, A., Veicsteinas, A., Merati, G., & Sacchi, M. (2010). Tridimensional kinematic analysis on a kayaking simulator: key factors to successful performance. *Sport Sciences for Health*, *6*(1), 27-34. https://doi.org/10.1007/s11332-010-0093-7
23. López, C. L., & Serna, J. R. (2011). Quantitative analysis of kayak paddling technique: definition of an optimal stroke profile. *Revista Andaluza de Medicina del Deporte*, *4*(3), 91-95. ISSN: 1888-7546
24. Löppönen, A., Vänttinen, T., Haverinen, M., & Linnamo, V. (2022). The effect of paddle stroke variables measured by Trainesense SmartPaddle® on the velocity of the kayak. *Sensors*, *22*(3), 938. https://doi.org/10.3390/s22030938
25. McDonnell, L. K., Hume, P. A., & Nolte, V. (2012). An observational model for biomechanical assessment of sprint kayaking technique. *Sports biomechanics*, *11*(4), 507-523. https://doi.org/10.1080/14763141.2012.724701
26. McDonnell, L. K., Hume, P. A., & Nolte, V. (2013). A deterministic model based on evidence for the associations between kinematic variables and sprint kayak performance. Sports biomechanics, 12(3), 205-220. https://doi.org/10.1080/14763141.2012.760106
27. Michael, J. S., Smith, R., & Rooney, K. B. (2009). Determinants of kayak paddling performance. *Sports biomechanics*, *8*(2), 167-179. https://doi.org/10.1080/14763140902745019
28. Michael, J. S., Rooney, K. B., & Smith, R. M. (2012). The dynamics of elite paddling on a kayak simulator. *Journal of Sports Sciences, 30*(7), 661-668. https://doi.org/10.1080/02640414.2012.655303
29. Rebensburg, A. J., Boettcher, A. E., Perrin, O. D., Rettke, D. J., Hawke, A. L., & Breen, S. (2019). The use of a lower-limb prosthetic device to improve performance factors in elite paracanoe. *ISBS Proceedings Archive*, *37*(1), 169.
30. Redwood-Brown, A. J., Brown, H. L., Oakley, B., & Felton, P. J. (2021). Determinants of boat velocity during a 200 m race in elite Paralympic sprint kayakers. *International Journal of Performance Analysis in Sport*, *21*(6), 1178-1190. https://doi.org/10.1080/24748668.2021.1986351
31. Ribeiro Neto, F., Dos Santos, L. G. T. F., Castelli Correia de Campos, L. F., Winckler, C., & Gomes Costa, R. R. (2024). Paralympic Versus Olympic Canoe Sprint: Comprehension of the Development Trajectory of the Kayak 200 Meters. *Perceptual and Motor Skills*, *131*(4), 1291-1307. https://doi.org/10.1177/00315125241247859
32. Rosén, J. (2015). Biomechanical differences between elite able-bodied kayakers and elite para-kayakers during paddling: The second and third step of creating the new Paralympic classification system. URN: urn:nbn:se:gih:diva-3897

33. Rosén, J. (2021). *Performance determinants and classification in paracanoe*. Swedish School of Sport and Health Sciences (Sweden). URN: urn:nbn:se:gih:diva-6851
34. Sumner, D., Sprigings, E. J., Bugg, J. D., & Heseltine, J. L. (2003). Fluid forces on kayak paddle blades of different design. *Sports Engineering*, *6*(1), 11-19. https://doi.org/10.1007/BF02844156
35. Vickerstaff, V., Omar, R. Z., & Ambler, G. (2019). Methods to adjust for multiple comparisons in the analysis and sample size calculation of randomised controlled trials with multiple primary outcomes. *BMC medical research methodology*, *19*(1), 129. https://doi.org/10.1186/s12874-019-0754-4

## Figures

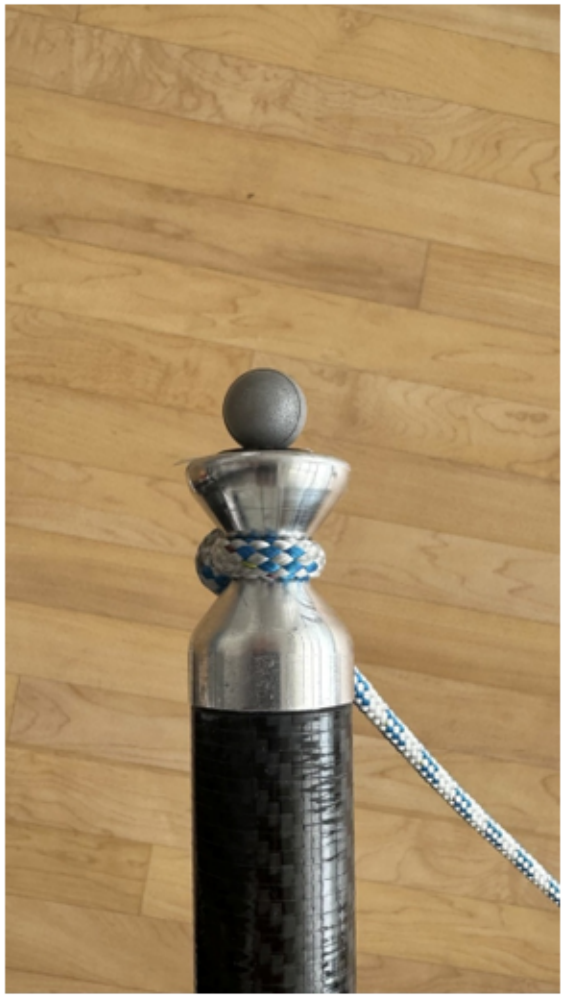

**Figure 1**

Paddle-marker placement used for three-dimensional kinematic reconstruction.

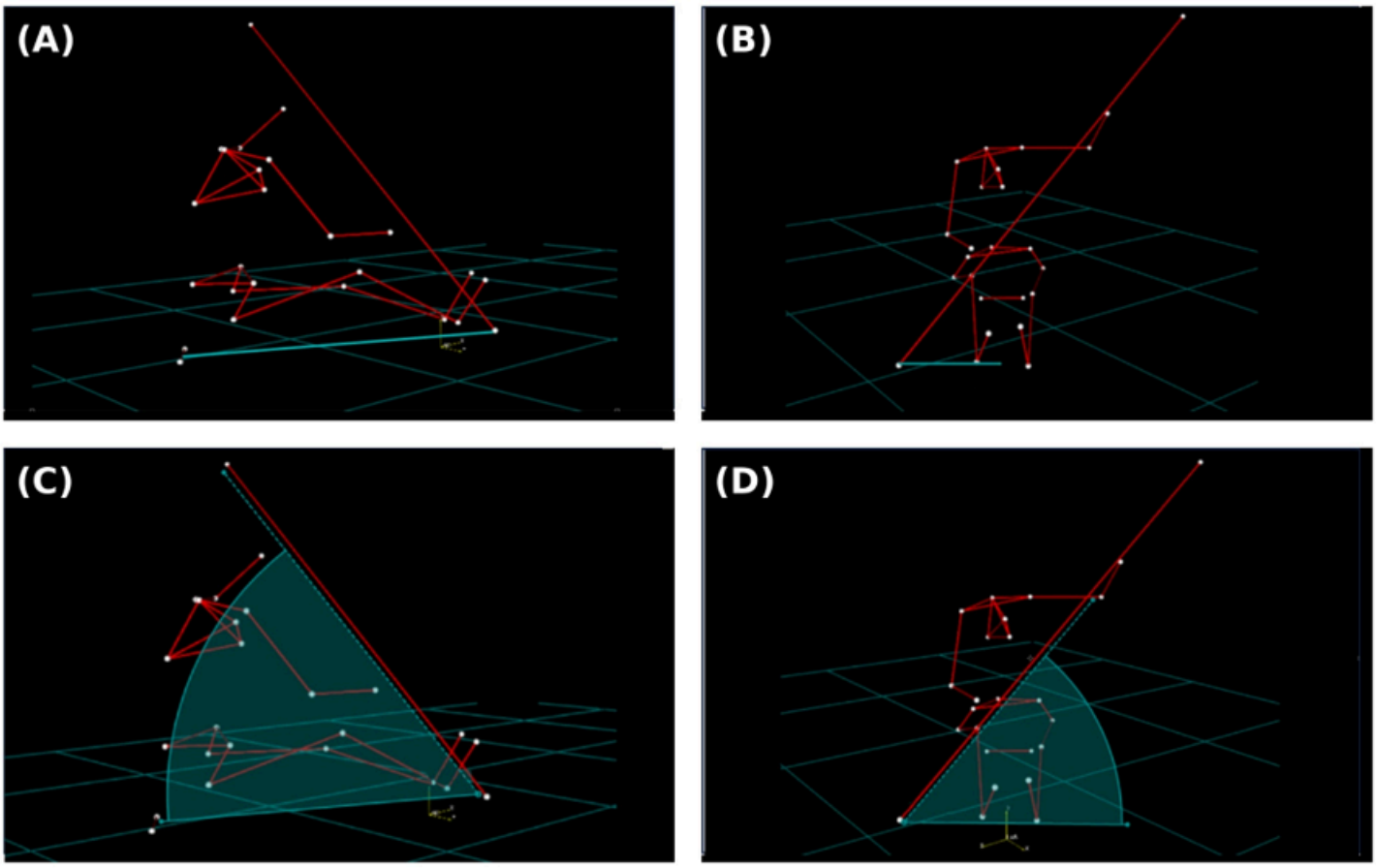


**Figure 2**

**Operational representation of the four kinematic variables used in the Optimal Stroke Profile (OSP) analysis.**

**(A)** Paddle Advance (PA), **(B)**Paddle Separation (PS), **(C)** Lateral Angle (LA), and **(D)** Frontal Angle (FA).

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementary.docx