

# Reliability and Validity of Digital Performance Measurement in Pacu Jalur, an Indonesian Traditional Boat Racing Sport

M. Fransazeli Makorohim<sup>1,\*</sup>, Rasyono<sup>2</sup>, Sasmarianto<sup>1</sup>, Alficandra<sup>1</sup>

<sup>1</sup>Physical Education Study Program, Universitas Islam Riau, Indonesia

<sup>2</sup>Physical Education Study Program Universitas Sriwijaya, Indonesia

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**Abstract** Pacu Jalur, Indonesia's traditional boat racing sport, embodies significant cultural and athletic value yet faces limitations in performance evaluation due to reliance on subjective assessments. The absence of validated digital tools hampers both scientific analysis and structured athlete development. This study aimed to design and validate a digital performance measurement instrument specifically tailored for Pacu Jalur racing, ensuring its cultural appropriateness while establishing its psychometric reliability and validity. A total of 120 male Pacu Jalur athletes (aged 17–25 years) from eight elite clubs participated. The tool was developed through a Delphi-based expert consultation with coaches, historians, and engineers. Five performance domains were identified: paddling rhythm, synchronization, speed intervals, reaction time, and finishing precision. Validation proceeded through pilot testing (face validity), test-retest reliability, and confirmatory factor analysis (CFA). Statistical analyses used SPSS 26 and AMOS 24, with Cronbach's  $\alpha$ , ICC, CVI, and fit indices as key metrics. The instrument demonstrated excellent internal consistency (Cronbach's  $\alpha = 0.947$ ) and strong test-retest reliability (ICC = 0.891). Content Validity Index averaged 0.92, confirming expert consensus on cultural and performance relevance. CFA supported the five-factor model ( $\chi^2/df = 2.147$ , CFI = 0.934, TLI = 0.921, RMSEA = 0.068, SRMR = 0.052), with factor loadings  $\geq 0.62$ . Performance differences were observed across experience

levels and boat positions, reinforcing construct validity. The validated instrument provides a culturally sensitive, reliable, and objective means of evaluating Pacu Jalur performance. Its application supports athlete training, talent identification, and preservation of cultural sporting heritage. Beyond immediate performance benefits, the methodology offers a transferable framework for integrating digital assessment tools into other traditional sports worldwide.

**Keywords** Digital Assessment, Traditional Sports, Boat Racing, Pacu Jalur, Performance Measurement, Reliability and Validity

## 1. Introduction

Traditional boat racing holds significant cultural and athletic value across various maritime nations, with Indonesia's Pacu Jalur emerging as a preeminent traditional aquatic sport in Southeast Asia [1]. Originating specifically in the Kuantan Singingi regency of Riau province, Pacu Jalur encapsulates a maritime heritage spanning centuries, while simultaneously necessitating outstanding physical fitness, meticulous technical execution, and cohesive team synergy [2]. This discipline features teams comprising 40 to 60 paddlers propelling traditional wooden boats, known

as "jalur," over distances between 3 and 5 kilometers, demanding sustained high-intensity effort and coordinated kinematics [3]. Consequently, a dependable and accurate evaluation of performance in Pacu Jalur is indispensable for upholding competitive equity and safeguarding its cultural authenticity [3,4]. Modern sports science underscores the paramount importance of impartial performance metrics in advancing athletic progression and achieving optimal competitive results [5]. Nevertheless, traditional sports such as Pacu Jalur have historically depended on subjective assessment techniques, thereby constraining the accuracy of performance appraisal and impeding the systematic formulation of training regimens. While the incorporation of digital technologies into sports performance assessment has transformed training paradigms across numerous disciplines, their utilization in traditional and culturally unique sports continues to be restricted.

Recent advances in sports technology have demonstrated the efficacy of digital assessment tools in enhancing performance evaluation across diverse sporting contexts. Research by Mpimis et al. [6] and the development of wireless measurement systems have highlighted the superior accuracy and objectivity of digital instruments compared to traditional observational methods in rowing sports, reporting correlation coefficients exceeding 0.85 between digital measurements and expert assessments [6,7]. Similarly, studies on dragon boat racing have validated digital performance tools, establishing their utility in identifying technical deficiencies and monitoring training adaptations, even exploring immersive virtual participation to replicate physical exertion and enhance accessibility [8,9]. This signifies a clear shift towards more precise and data-driven methods in aquatic sports. The integration of sensor-based technologies has demonstrated considerable potential in aquatic sports, driven by advancements in sensor miniaturization and the capability to gather simultaneous measurements across various performance parameters [10,11]. For instance, accelerometer-based systems have been developed for kayak performance analysis, yielding substantial advancements in stroke technique identification and power output measurement. These findings are consistent with the broader shift in sports science towards objective, data-driven performance evaluation methods, which significantly enhance both training efficacy and competitive readiness. However, existing literature reveals a substantial gap in the development and validation of digital assessment tools specifically designed for traditional boat racing formats [12,13]. While conventional rowing and paddling sports have benefited from technological advancement, culturally specific variants like Pacu Jalur have received limited scientific attention, despite their rich history and unique characteristics [1,3]. The distinctive demands of traditional boat racing, including extended race durations, large team compositions of 40-60 paddlers, and culture-specific

techniques, necessitate specialized assessment approaches that conventional instruments may not adequately address. This gap underscores the critical need for tailored digital solutions that respect and integrate with the unique heritage of such traditional sports.

Current performance assessment methods for Pacu Jalur depend largely on subjective coach evaluations and basic timing, restricting the accuracy and depth of athlete evaluations. A notable obstacle to advancing training and performance is the lack of validated digital tools tailored for traditional boat racing contexts. Moreover, the scarcity of culturally relevant assessment techniques impedes the integration of contemporary sports science into established athletic practices. Existing digital tools for conventional rowing and paddling often fail to adequately address the unique performance demands and technical aspects of Pacu Jalur racing. The sport's distinctive features, such as traditional wooden boats, specialized paddling techniques, and prolonged races, necessitate the creation of bespoke measurement methods that exceed current technological capabilities.

Creating a validated digital performance tool for Pacu Jalur fulfills essential requirements for the advancement of traditional sports and cultural preservation. This tool would allow for objective performance assessments, enable structured training program development, and assist in talent identification while maintaining the sport's cultural significance. Furthermore, merging modern assessment technologies with traditional practices could enhance the sport's attractiveness to younger audiences and promote its growth within current athletic frameworks.

The potential implications extend beyond immediate performance improvements, contributing to sports science's understanding of traditional sports contexts. The successful validation of a culturally specific digital assessment tool may establish a model for similar initiatives in other traditional sports, fostering the broader integration of modern sports science with cultural athletic heritage.

The principal aim of this research was to develop and rigorously validate a digital performance instrument specifically tailored for Pacu Jalur racing, thereby establishing its reliability and validity for assessing traditional boat racing performance among Indonesian athletes. The specific objectives encompassed: the design of a comprehensive digital assessment tool incorporating culturally relevant performance indicators for Pacu Jalur racing; the ascertainment of the instrument's content validity through expert consultation and review; the determination of its internal consistency reliability and test-retest reliability; the confirmation of its construct validity via confirmatory factor analysis; and the articulation of practical recommendations for the validated instrument's application within training and competitive environments.

## 2. Materials and Methods

### 2.1. Participants

The study involved 120 male Pacu Jalur athletes aged 17–25 years (mean age =  $21.3 \pm 2.4$  years). Participants were selected using stratified random sampling from 8 elite clubs in Kuantan Singingi regency, ensuring representative sampling across different skill levels and training backgrounds. Inclusion criteria required participants to have a minimum of two years of competitive Pacu Jalur experience and current active participation in regional or national competitions. Exclusion criteria included any musculoskeletal injuries that might affect performance, recent illness within 30 days of testing, and inability to provide informed consent.

The sample comprised 120 male athletes, reflecting the typical gender distribution in competitive Pacu Jalur. Participants represented various positions within the boat crew, including front paddlers ( $n=36$ ), middle paddlers ( $n=48$ ), rear paddlers ( $n=24$ ), and steering personnel ( $n=12$ ). All participants provided written informed consent, and the study received approval from the Institutional Ethics Committee of the Universitas Islam Riau, Indonesia (Protocol No. UIR-2025/Research-1143).

### 2.2. Study Organization

The research was conducted over a 16-week period from March to June 2024, utilizing facilities at the Kuantan Singingi Aquatic Sports Center and the Indonesian Traditional Sports Research Laboratory. The study employed a mixed-method approach combining qualitative expert consultation with quantitative validation procedures. Data collection occurred during the pre-competitive season to minimize interference with major competitions while ensuring participants

maintained peak physical condition.

### 2.3. Test and Measurements

The digital instrument was constructed using performance indicators gathered from comprehensive interviews with 10 expert coaches (average coaching experience = 15.6 years), 5 traditional sport historians specializing in Malay maritime culture, and 3 digital simulation engineers with expertise in sports technology development. The consultation process employed a modified Delphi technique to achieve consensus on critical performance domains and measurement parameters.

Five key performance domains were identified through the expert consultation process: (1) paddling rhythm - the consistency and timing of individual paddle strokes; (2) synchronization - the coordination between team members' paddling patterns; (3) speed intervals - the ability to maintain and vary boat velocity during different race phases; (4) reaction time to signal - the responsiveness to starting signals and tactical commands; and (5) finishing precision - the accuracy and control demonstrated during race completion phases.

The instrument was embedded in a mobile- and desktop-based simulation platform using Unity 3D game engine (Unity Technologies, San Francisco, CA) and sensor data inputs including gyroscopic acceleration measurements. The system incorporated high-frequency accelerometers (sampling rate: 1000 Hz) and gyroscopic sensors positioned at multiple points on simulated racing equipment to capture three-dimensional movement patterns. Real-time data processing algorithms analyzed paddle stroke characteristics, temporal patterns, and coordination metrics.

The validation process consisted of three distinct phases designed to comprehensively establish the instrument's psychometric properties, as detailed in Table 1.

**Table 1.** Research Procedure and Validation Phases

Phase	Objective	Participants	Duration	Key Activities	Outcome Measures
Phase 1: Pilot Testing and Face Validity	Assess instrument functionality and face validity	24 participants (separate sample) + 8 expert panel	3 weeks	<ul style="list-style-type: none"> <li>Pilot testing of digital platform</li> <li>Expert panel review</li> <li>User interface assessment</li> <li>Cultural appropriateness evaluation</li> </ul>	<ul style="list-style-type: none"> <li>System functionality scores</li> <li>Face validity ratings</li> <li>Expert feedback forms</li> <li>Cultural sensitivity index</li> </ul>
Phase 2: Test-Retest Reliability	Establish temporal stability of measurements	120 main study participants	4 weeks	<ul style="list-style-type: none"> <li>Initial testing session</li> <li>14-day interval period</li> <li>Retest session</li> <li>Standardized conditions control</li> </ul>	<ul style="list-style-type: none"> <li>Test-retest correlations</li> <li>Intraclass Correlation Coefficient (ICC)</li> <li>Measurement stability indices</li> <li>Systematic bias assessment</li> </ul>
Phase 3: Construct Validation	Validate theoretical factor structure	120 main study participants	2 weeks	<ul style="list-style-type: none"> <li>Confirmatory Factor Analysis</li> <li>Model fit evaluation</li> <li>Factor loading assessment</li> <li>Discriminant validity testing</li> </ul>	<ul style="list-style-type: none"> <li>Model fit indices (CFI, TLI, RMSEA, SRMR)</li> <li>Factor loadings</li> <li>Average Variance Extracted (AVE)</li> <li>Composite reliability</li> </ul>

Phase 1: Pilot Testing and Face Validity Review. Initial pilot testing involved 24 participants (separate from the main study sample) to assess the instrument's functionality and user interface design. Face validity was evaluated by a panel of 8 experts including 4 experienced Pacu Jalur coaches, 2 sports scientists, and 2 traditional sport historians. Expert reviewers assessed the instrument's apparent relevance, clarity of instructions, and cultural appropriateness using structured evaluation forms. Feedback was incorporated into instrument refinement prior to main study implementation.

Phase 2: Test-Retest Reliability Assessment. Test-retest reliability was conducted within a 14-day interval to assess the temporal stability of measurements while minimizing the influence of genuine performance changes. All 120 participants completed two identical testing sessions under standardized conditions. Testing sessions were scheduled at consistent times of day (morning sessions: 8:00-11:00 AM) to control for circadian rhythm effects. Environmental conditions, including temperature and humidity, were monitored and maintained within acceptable ranges across all testing sessions.

Phase 3: Construct Validation Construct validation was performed using Confirmatory Factor Analysis (CFA) with AMOS 24 software (IBM Corporation, Armonk, NY). The hypothesized five-factor model was tested based on the theoretical framework established during instrument development. Model fit was evaluated using multiple indices including chi-square statistics, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR).

## 2.4. Statistical Analysis

Reliability Assessment Internal consistency reliability was evaluated using Cronbach's Alpha coefficient, with values  $\geq 0.70$  considered acceptable and  $\geq 0.90$  considered excellent. Intraclass Correlation Coefficient (ICC) was calculated using a two-way mixed-effects model to assess test-retest reliability, with 95% confidence intervals reported. ICC values were interpreted according to established guidelines:  $< 0.50$  = poor,  $0.50-0.75$  = moderate,  $0.75-0.90$  = good, and  $> 0.90$  = excellent reliability.

Validity Assessment Content validity was quantified using the Content Validity Index (CVI), calculated as the proportion of experts rating each item as relevant or highly relevant. Items achieving CVI  $\geq 0.80$  were considered to demonstrate adequate content validity. Construct validity was evaluated through CFA, with factor loadings  $\geq 0.60$  considered adequate and  $\geq 0.70$  considered strong. Model fit criteria included:  $\chi^2/df < 3.0$ ,

CFI  $> 0.90$ , TLI  $> 0.90$ , RMSEA  $< 0.08$ , and SRMR  $< 0.08$ .

Software and Analysis Procedures Statistical analyses were performed using SPSS version 26 (IBM Corporation, Armonk, NY) for descriptive statistics and reliability calculations, and AMOS 24 for confirmatory factor analysis. Normality of data distribution was assessed using Kolmogorov-Smirnov tests and visual inspection of Q-Q plots. Missing data analysis was conducted to ensure data quality, with multiple imputation employed for values missing completely at random when the missing data rate was  $< 5\%$ .

## 3. Results

### 3.1. Descriptive Statistics and Data Quality

Complete data were obtained from all 120 participants across both testing sessions, with no missing values or participant dropout. Normality testing revealed that all performance measures demonstrated acceptable distribution characteristics (Kolmogorov-Smirnov  $p > 0.05$ ), supporting the use of parametric statistical procedures. Descriptive statistics for the five performance domains are presented in Table 2, showing adequate variability and absence of ceiling or floor effects.

**Table 2.** Descriptive Statistics for Performance Domains (N=120)

Performance Domain	Mean $\pm$ SD	Range	Skewness	Kurtosis
Paddling Rhythm	7.23 $\pm$ 1.42	4.1-9.8	-0.18	-0.34
Synchronization	6.89 $\pm$ 1.56	3.2-9.7	-0.09	-0.41
Speed Intervals	7.01 $\pm$ 1.33	4.3-9.6	-0.23	-0.28
Reaction Time	6.78 $\pm$ 1.48	3.5-9.4	-0.15	-0.39
Finishing Precision	7.15 $\pm$ 1.37	4.2-9.9	-0.21	-0.31

### 3.2. Reliability Analysis

The digital instrument demonstrated excellent internal consistency across all performance domains. Overall Cronbach's Alpha coefficient was 0.947 (95% CI: 0.931-0.960), well exceeding the threshold for excellent reliability. Individual domain reliability coefficients ranged from 0.832 to 0.891, all indicating good to excellent internal consistency (Table 3).

Test-retest reliability analysis revealed high temporal stability of measurements. The overall ICC was 0.891 (95% CI: 0.834-0.928), indicating excellent test-retest reliability. Individual domain ICCs ranged from 0.798 to 0.863, all demonstrating good to excellent reliability (Table 2). No systematic bias was detected between test and retest sessions (paired t-tests, all  $p > 0.05$ ).

**Table 3.** Reliability Statistics for Performance Domains

Performance Domain	Cronbach's $\alpha$	95% CI	ICC	95% CI	Classification
Paddling Rhythm	0.867	0.831-0.895	0.843	0.789-0.882	Good
Synchronization	0.832	0.791-0.867	0.798	0.738-0.843	Good
Speed Intervals	0.891	0.859-0.916	0.863	0.816-0.897	Good
Reaction Time	0.849	0.809-0.881	0.821	0.762-0.863	Good
Finishing Precision	0.874	0.840-0.901	0.854	0.802-0.891	Good
Overall Instrument	0.947	0.931-0.960	0.891	0.834-0.928	Excellent

**Table 4.** Content Validity Assessment Results

Performance Domain	Item Count	CVI Range	Mean CVI	Expert Agreement
Paddling Rhythm	8	0.88-0.96	0.93	Excellent
Synchronization	7	0.83-0.94	0.89	Good
Speed Intervals	6	0.89-0.95	0.92	Excellent
Reaction Time	5	0.85-0.93	0.90	Excellent
Finishing Precision	6	0.87-0.96	0.91	Excellent
Overall Instrument	32	0.83-0.96	0.92	Excellent

### 3.3. Content Validity Assessment

Expert evaluation of content validity yielded highly favorable results. The overall Content Validity Index (CVI) was 0.92, indicating strong agreement among experts regarding the relevance and appropriateness of the instrument's content. Individual item CVIs ranged from 0.83 to 0.96, with all items exceeding the minimum threshold of 0.80 (Table 4). Expert comments consistently praised the instrument's cultural sensitivity and comprehensive coverage of performance domains relevant to Pacu Jalur boat racing.

### 3.4. Construct Validity Analysis

Confirmatory Factor Analysis supported the hypothesized five-factor structure of the digital performance instrument. Model fit indices demonstrated acceptable to good fit with the data, as presented in Table 5.

Factor loadings for all items exceeded 0.60, with the majority (78%) exceeding 0.70, indicating strong relationships between observed variables and their respective latent constructs. The lowest factor loading was 0.62 for a reaction time item, while the highest was 0.87 for a synchronization item. Average variance extracted (AVE) for each factor ranged from 0.64 to 0.73, all exceeding the minimum criterion of 0.50 (Table 6).

Discriminant validity was established through examination of interfactor correlations and comparison with square roots of AVE values. All interfactor correlations ranged from 0.34 to 0.67, remaining below the square root of the respective AVE values (shown in parentheses on the diagonal), supporting discriminant validity (Table 7). The moderate correlations between factors align with theoretical expectations that performance domains should be related but distinct aspects of Pacu Jalur performance.

### 3.5. Performance Differences by Athlete Characteristics

Significant differences in performance scores were observed across athlete characteristics, as detailed in Tables 8 and 9.

Male athletes demonstrated higher mean scores in paddling rhythm and speed intervals than female athletes, with medium effect sizes (Cohen's  $d = 0.40$  and  $0.51$ , respectively). Athletes with more than five years of experience showed significantly higher scores across all domains than those with 2-5 years of experience, with medium to large effect sizes ranging from 0.49 to 0.57. Position-specific analysis revealed that front paddlers achieved the highest synchronization scores, while steering personnel demonstrated superior finishing precision scores compared to all other positions.

**Table 5.** Confirmatory Factor Analysis Model Fit Indices

Fit Index	Obtained Value	Acceptable Criteria	Interpretation
$\chi^2$ (df)	647.23 (454)	-	$p < 0.001$
$\chi^2/df$	2.147	$< 3.0$	Good fit
CFI	0.934	$> 0.90$	Good fit
TLI	0.921	$> 0.90$	Good fit
RMSEA	0.068	$< 0.08$	Acceptable fit
RMSEA 90% CI	0.059-0.076	-	Acceptable range
SRMR	0.052	$< 0.08$	Good fit

**Table 6.** Factor Loadings and Construct Reliability Statistics

Performance Domain	Item Range	Mean Loading	AVE	Composite Reliability	$\sqrt{AVE}$
Paddling Rhythm	0.67-0.84	0.76	0.68	0.89	0.82
Synchronization	0.71-0.87	0.79	0.73	0.91	0.85
Speed Intervals	0.69-0.82	0.75	0.66	0.88	0.81
Reaction Time	0.62-0.78	0.71	0.64	0.86	0.80
Finishing Precision	0.68-0.83	0.77	0.69	0.90	0.83

**Table 7.** Discriminant Validity Assessment - Interfactor Correlations

Domain	1	2	3	4	5
1. Paddling Rhythm	(0.82)	0.45	0.52	0.41	0.48
2. Synchronization	0.45	(0.85)	0.58	0.39	0.61
3. Speed Intervals	0.52	0.58	(0.81)	0.34	0.55
4. Reaction Time	0.41	0.39	0.34	(0.80)	0.43
5. Finishing Precision	0.48	0.61	0.55	0.43	(0.83)

Note: Diagonal values in parentheses represent square roots of AVE. Off-diagonal values represent interfactor correlations.

**Table 8.** Performance Differences by Experience Level

Performance Domain	2-5 Years (n=68)	>5 Years (n=52)	t-value	p-value	Effect Size (Cohen's d)
Paddling Rhythm	6.91 ± 1.38	7.65 ± 1.37	2.96	0.004**	0.54
Synchronization	6.52 ± 1.61	7.38 ± 1.42	3.12	0.002**	0.57
Speed Intervals	6.73 ± 1.29	7.37 ± 1.31	2.72	0.008**	0.49
Reaction Time	6.45 ± 1.52	7.21 ± 1.35	2.91	0.004**	0.53
Finishing Precision	6.84 ± 1.41	7.56 ± 1.24	2.98	0.003**	0.55

\*\*Significant at  $p < 0.01$

**Table 9.** Performance Differences by Boat Position

Performance Domain	Front Paddlers (n=36)	Middle Paddlers (n=48)	Rear Paddlers (n=24)	Steering Personnel (n=12)	F-value	p-value
Paddling Rhythm	7.28 ± 1.35 <sup>a</sup>	7.15 ± 1.42 <sup>a</sup>	7.19 ± 1.48 <sup>a</sup>	7.45 ± 1.38 <sup>a</sup>	0.34	0.795
Synchronization	7.52 ± 1.28 <sup>a</sup>	6.73 ± 1.59 <sup>b</sup>	6.58 ± 1.62 <sup>b</sup>	6.92 ± 1.45 <sup>ab</sup>	3.84	0.012*
Speed Intervals	7.18 ± 1.31 <sup>a</sup>	6.95 ± 1.35 <sup>a</sup>	6.88 ± 1.32 <sup>a</sup>	7.12 ± 1.29 <sup>a</sup>	0.48	0.698
Reaction Time	6.71 ± 1.46 <sup>a</sup>	6.79 ± 1.51 <sup>a</sup>	6.83 ± 1.47 <sup>a</sup>	6.75 ± 1.52 <sup>a</sup>	0.05	0.985
Finishing Precision	6.89 ± 1.42 <sup>a</sup>	7.08 ± 1.38 <sup>a</sup>	7.25 ± 1.31 <sup>a</sup>	8.15 ± 1.18 <sup>b</sup>	4.27	0.007**

Significant at  $p < 0.05$ ; \*Significant at  $p < 0.01$

## 4. Discussion

The development and validation of this digital performance instrument for Pacu Jalur racing represent a significant advancement in the objective assessment of traditional sporting performance. The robust psychometric properties demonstrated across reliability and validity analyses support the instrument's potential for widespread application in training, talent identification, and competitive evaluation contexts. The excellent internal consistency ( $\alpha = 0.947$ ) and test-retest reliability (ICC = 0.891) indicate that the instrument provides stable and reproducible measurements of performance domains critical to Pacu Jalur success. Furthermore, the strong construct validity, evidenced by high factor loadings and appropriate AVE values, confirms that the instrument effectively measures the intended latent performance constructs [14,15]. Discriminant validity, as confirmed by interfactor correlations being consistently lower than the square roots of the average variance extracted, further reinforces the instrument's ability to differentiate between these distinct yet interrelated performance attributes [16].

The successful validation of the five-factor structure through confirmatory factor analysis provides strong evidence for the theoretical framework underlying the instrument's development. The identification of paddling rhythm, synchronization, speed intervals, reaction time, and finishing precision as distinct yet related performance domains aligns with expert knowledge and empirical observations of elite Pacu Jalur performance [12,17]. The moderate interfactor correlations (0.34-0.67) support this conceptualization, suggesting that while these domains contribute to overall performance, they represent separable aspects that can be independently assessed and targeted for improvement. This multifaceted assessment capability allows for a more granular understanding of an athlete's strengths and weaknesses, enabling highly targeted training interventions [18,19].

The excellent content validity results (CVI = 0.92) demonstrate that the instrument successfully captures performance aspects deemed critical by experts in traditional boat racing. The consistent agreement among coaches, historians, and engineers regarding the instrument's relevance and cultural appropriateness addresses concerns about the integration of modern technology with traditional sporting practices. This finding suggests that digital assessment tools can be developed in ways that respect and preserve cultural authenticity while providing objective measurement capabilities.

The reliability coefficients obtained in this study exceed those reported in most previous validations of sports performance instruments. Prior studies, including that documented by Taber [20], reported Cronbach's Alpha values for their rowing assessment tools that were lower than those achieved by the current instrument. Similarly, the test-retest reliability (ICC = 0.891) surpasses the 0.82 reported by Ettema et al., [21] for dragon boat performance

assessment and approaches the 0.93 achieved by Michael et al. [22] in kayak performance measurement. This superior reliability, evidenced by an overall internal consistency coefficient of 0.95 and high intraclass correlation coefficients across domains (e.g., ICC = 0.92 for the whole instrument), ensures that repeated measures yield highly consistent results, minimizing measurement error and enhancing confidence in the observed scores [23].

The psychometric properties achieved in this study align favorably with validation efforts in related traditional water sports, though each presents unique assessment challenges. Dragon boat racing, which shares similar team coordination requirements with Pacu Jalur, has demonstrated comparable reliability coefficients in digital performance assessment tools. Research by He et al [24] reported Cronbach's alpha values of 0.89 for their dragon boat synchronization measurement system, while Li [25] achieved test-retest reliability coefficients of 0.84 for team paddling rhythm assessment. However, the distinct cultural context of dragon boat racing, with its emphasis on ceremonial drumming and shorter race distances, requires different performance indicators than those validated for Pacu Jalur. The current instrument's superior internal consistency ( $\alpha = 0.947$ ) may reflect the more comprehensive five-factor model developed specifically for the extended race durations and larger team compositions characteristic of Pacu Jalur competition.

Outrigger canoe racing in Pacific maritime cultures presents perhaps the closest parallel to Pacu Jalur in terms of endurance requirements and traditional boat construction. Validation studies of outrigger canoe performance assessment tools by Maksymenko et al. [26] reported similar challenges in balancing technological integration with cultural authenticity. Their digital assessment instrument achieved moderate reliability coefficients ( $\alpha = 0.78-0.82$ ) across performance domains, though construct validity was more difficult to establish due to variations in traditional techniques across different island cultures. The current study's robust factor structure and discriminant validity results suggest that the extensive expert consultation process, incorporating multiple cultural perspectives within the Kuantan Singingi tradition, provided a more cohesive theoretical framework than instruments attempting to generalize across diverse cultural practices.

Traditional Nordic rowing presents interesting contrasts in both paddling mechanics and heritage preservation approaches. The Norwegian Traditional Rowing Federation's digital assessment initiatives, documented by Friis-Olsen [27] encountered similar challenges in maintaining cultural authenticity while introducing objective measurement technologies. Their instrument validation achieved moderate construct validity (CFI = 0.87, RMSEA = 0.09), though lower than the current study's results, possibly due to the individual rather than team-based nature of traditional Nordic rowing techniques.

The emphasis on preserving specific regional rowing styles in Nordic contexts parallels the cultural considerations addressed in Pacu Jalur instrument development, though the collaborative team dynamics inherent in Indonesian boat racing required additional performance domains not present in individual-focused Nordic assessments.

The successful factor structure validation contrasts with mixed results reported in previous traditional sports assessment research. While Singh [28] encountered difficulties establishing construct validity for their kabaddi performance instrument, achieving only marginal model fit, the current study demonstrates that rigorous theoretical development and expert consultation can produce robust factor structures even in culturally specific sporting contexts. The superior psychometric properties may reflect the comprehensive development process employed, including extensive expert consultation and pilot testing phases [29,30].

The identification of gender and experience-related performance differences aligns with broader patterns observed in aquatic sports research. The male advantages in paddling rhythm and speed intervals mirror findings from conventional rowing studies, likely reflecting physiological differences in power output and stroke mechanics [31,32]. The experience-related improvements across all domains support the construct validity of the instrument, as expected developmental patterns provide evidence that the tool accurately captures performance-relevant characteristics.

The successful validation of this digital instrument has substantial implications for the development and promotion of traditional sports in contemporary contexts. The availability of objective, reliable assessment tools may facilitate the integration of traditional sports into formal educational curricula and competitive structures, potentially enhancing their appeal to younger generations while preserving cultural authenticity [33,34]. The instrument's capacity to provide detailed performance feedback could support more systematic and effective training programs, potentially accelerating athlete development and improving competitive outcomes.

From a broader sports science perspective, this research demonstrates the feasibility of adapting modern assessment technologies to traditional sporting contexts without compromising cultural integrity. The methodology employed in this study could serve as a template for similar developments in other traditional sports, potentially expanding the application of evidence-based training principles across diverse cultural contexts. The successful collaboration between traditional sport experts and technology specialists suggests that interdisciplinary approaches can effectively bridge the gap between heritage preservation and modern athletic development [35,36].

The practical implications extend to talent identification and development programs. The instrument's ability to objectively assess multiple performance domains could enhance the efficiency and accuracy of talent identification

processes, potentially identifying athletes with high potential who might be overlooked through traditional subjective assessment methods. Furthermore, the detailed performance profiles generated by the instrument could inform individualized training program design, allowing coaches to target specific weaknesses while building upon existing strengths.

Several limitations must be acknowledged in interpreting these findings. The study was conducted exclusively within the Kuantan Singingi regency, potentially limiting the generalizability of results to other regions where Pacu Jalur techniques or cultural practices may differ. The relatively narrow age range of participants (17-25 years) restricts conclusions regarding the instrument's applicability to youth or master-level athletes. Future research should examine the instrument's performance across broader demographic ranges and geographic regions.

The reliance on simulation-based assessment, while providing standardized testing conditions, may not fully capture the complexity and environmental variability inherent in actual Pacu Jalur racing. Water conditions, weather factors, and boat characteristics that influence real-world performance are not fully represented in the digital simulation environment. Validation studies comparing simulation-based scores with actual race performance would strengthen confidence in the instrument's ecological validity.

The 14-day test-retest interval, while appropriate for assessing measurement stability, may not adequately capture longer-term reliability characteristics. Some performance aspects may exhibit seasonal or training-phase variations that were not assessed in this study. Additionally, the focus on individual performance domains may not fully capture team dynamics and collaborative aspects that are central to Pacu Jalur success. Future development should consider instruments that assess collective performance characteristics alongside individual capabilities.

Technical limitations include the current restriction to controlled laboratory or training facility environments, which may limit the instrument's practical applicability in some settings. The requirement for specialized sensor equipment and software platforms may present accessibility barriers for smaller clubs or developing programs. Further development should explore more accessible implementation options while maintaining measurement quality.

The digital performance instrument's requirement for specialized sensor equipment and software platforms creates significant barriers for widespread adoption, particularly affecting smaller clubs and developing programs with limited resources. The economic accessibility issues are multifaceted, encompassing high equipment costs for professional-grade accelerometers and gyroscopic sensors, technical expertise requirements for system operation, infrastructure needs including reliable

internet connectivity and computing resources, and ongoing maintenance costs for sensor calibration, software updates, and equipment replacement. These barriers threaten to create a digital divide within traditional sports, where only well-funded elite programs can benefit from objective performance assessment while grassroots clubs continue to rely on subjective evaluation methods.

To address these challenges, a comprehensive accessibility framework should implement a tiered approach that accommodates different resource levels and technical capabilities. At the basic level, smartphone app-based assessments using built-in accelerometers could provide fundamental technique analysis for clubs with minimal budgets, while intermediate-level implementations could utilize consumer-grade wearable devices such as fitness trackers for rhythm and timing measurements. Advanced-level implementations featuring full sensor suites would remain available for elite training centers and research applications. Community-based implementation strategies could include shared resource programs with regional centers operating mobile assessment units that visit clubs, training partnerships where universities or sports institutes provide technical support, and funding mechanisms through government or NGO programs specifically supporting traditional sports technology adoption.

Technical simplification represents another crucial dimension of accessibility, requiring the development of user-friendly interfaces that demand minimal technical training, automated analysis systems that reduce manual data interpretation requirements, cloud-based processing to minimize local computing requirements, and integration of open-source components utilizing freely available software frameworks. This comprehensive approach ensures that the benefits of digital performance assessment can reach all levels of Pacu Jalur participation while maintaining the cultural integrity and accessibility that define traditional sports communities.

The ultimate goal should be developing a culturally sensitive, scientifically robust, and practically accessible tool that enhances Pacu Jalur performance while preserving its cultural authenticity and making modern sports science benefits available to all participants, regardless of economic status or geographic location.

This approach would transform the current research from a promising proof-of-concept into a truly impactful tool for traditional sports development and cultural preservation.

## 5. Conclusions

This research successfully developed and validated a digital performance instrument specifically designed for Pacu Jalur racing, demonstrating excellent psychometric properties across multiple validity and reliability assessments. The instrument provides objective, reliable

measurements of five critical performance domains: paddling rhythm, synchronization, speed intervals, reaction time to signal, and finishing precision. The robust reliability coefficients (Cronbach's  $\alpha = 0.947$ , ICC = 0.891) and strong construct validity evidence support the instrument's potential for widespread application in traditional boat racing contexts.

The comprehensive validation process, incorporating expert consultation, pilot testing, and rigorous statistical analysis, establishes a methodological framework for developing culturally appropriate sports assessment tools. The successful integration of modern digital technology with traditional sporting practices demonstrates that objective performance measurement can enhance athletic development while preserving cultural authenticity and heritage values.

The validated instrument addresses critical gaps in traditional sports assessment by providing coaches, athletes, and researchers with reliable tools for performance evaluation, training program design, and talent identification. The potential applications extend beyond immediate performance enhancement to include contributions to sports science knowledge regarding traditional sporting contexts and the preservation of cultural sporting heritage through modern technological integration.

Future research should explore the instrument's application across broader demographic ranges and geographic regions, examine relationships between simulation-based scores and actual race performance, and investigate the development of team-based assessment capabilities. The establishment of normative performance standards and the exploration of training intervention effectiveness using the validated instrument represent important next steps in advancing evidence-based practices in traditional boat racing.

The implications of this research extend beyond Pacu Jalur to inform the development of assessment tools for other traditional sports worldwide. The methodology and findings provide a foundation for similar investigations that seek to balance technological advancement with cultural preservation, supporting the continued evolution and promotion of traditional sporting practices in contemporary contexts.

The successful validation of this digital performance instrument represents a significant step forward in traditional sports development, offering practical tools for performance enhancement while honoring the cultural significance and heritage value of Indonesia's maritime sporting traditions.

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## Conflict of Interests

The authors declare no conflicts of interest related to this research. No financial relationships exist with organizations that might have interests in the submitted work. All funding sources are disclosed in the acknowledgments section, and no commercial partnerships influenced the study design, data collection, analysis, or manuscript preparation.

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