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Kinematics of the Hiking Position in Optimist-Class Sailors Using a 2D Analysis Method

Kahea Abdillah Zulfikar^{1*}, Mona Fiametta Febrianty², Angga M Syahid³

^{1,2,3}Study Program of Sport Physical Coaching, Faculty of Sport and Health Education, Universitas Pendidikan Indonesia, Bandung, West Java, Indonesia

*Corresponding Author: Mona Fiametta Febrianty, e-mail: monafiametta@upi.edu

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Abstract

Study purpose. This study aimed to analyze 2D kinematic characteristics (joint angles and posture displacement) and evaluate the effects of the maneuver side (port and starboard) and movement phase transitions (before, during, and after) during hiking maneuvers in elite Optimist class sailing.

Materials and methods. A quantitative approach with a Within-Subjects Design (Repeated Measures) was employed, involving two National Champion Optimist athletes from the West Java Regional Training Center. Each participant performed 25 repetitions per maneuver side, yielding a total of 50 analyzed trials ($N = 50$). Data were collected using a controlled land-based actual boat simulation recorded from frontal and sagittal planes. Data were extracted via Kinovea software and analyzed using Two-Way Repeated Measures ANOVA with Greenhouse-Geisser correction ($\alpha = 0.05$).

Results. The findings indicated no statistically significant difference in kinematic profiles between Port and Starboard maneuvers, $F(1,49) = 0.257$, $Sig. = 0.614$, and no interaction effect between side and phase factors, $Sig. = 0.561$. However, a highly significant difference in postural adaptation was found across movement phases, $F(1.04, 51.16) = 2082.239$, $Sig. < 0.001$. The effect size was extremely strong ($\eta_p^2 = 0.977$), signifying that postural changes were dominated by the mechanical transition of wind-holding phases (replicated by a knee lock of $\sim 80^\circ$, sagittal trunk extension of $\sim 26^\circ$, and frontal trunk tilt of $\sim 66^\circ$).

Conclusions. These findings offer empirical evidence that elite-level athletes possess a mature level of movement automation without bilateral functional asymmetry. The numerical formulation of joint angles in this study can be implicated as a kinematic blueprint for coaching programs to optimize performance and prevent asymmetrical injuries (low back pain) in junior sailors.

Keywords: Optimist, Kinematics, Hiking, Sailing, Kinovea

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Introduction

Achieving peak performance in modern sports requires a comprehensive understanding of human movement. Biomechanical analysis enables athletes to refine technique, develop effective rehabilitation strategies, and reduce injury risk (Penichet-Tomas, 2024; Wallace et al., 2022). Furthermore, recent advancements in sports science demonstrate that video-based motion analysis serves as an effective, practical method for evaluating complex joint kinematics and movement efficiency in field settings (Hermawan et al., 2026). As the body functions as a kinetic chain, the stability and alignment of one segment influence the overall balance. Consequently, kinematic analysis is essential for coaches seeking to optimize movement patterns (Bandeiras, 2019; Cruz et al., 2024; Tai et al., 2023). In disciplines such as sailing, athletes depend on precise posture and a detailed relationship between the body, equipment, and environmental factors (Brandt et al., 2016; Rothera, 2019).

The Optimist single-handed class acts as a foundational platform for the development of young sailors globally (Palomino-Martín et al., 2017). Within the sports categorization framework, sailing is classified as a measurable sport, where competitive success is determined by the athlete's ability to reach the finish line efficiently and without technical errors (Febrianty et al., 2024). Given its foundation on time efficiency, a thorough understanding of the biomechanical factors that optimize boat speed within foundational classes such as the Optimist is necessary for formulating sustainable athlete development programs (Caraballo et al., 2024; Pezelj et al., 2025). Among technical maneuvers, the hiking technique plays a particularly important role in determining the Velocity Made Good (VMG) of a dinghy sailboat. This technique requires the athlete to extend the upper body outward beyond the hull to counteract the heeling moment produced by hydrodynamic and aerodynamic forces (Buchardt et al., 2017; Cella et al., 2021). From a biomechanical standpoint, hiking is a highly dynamic “quasi-isometric” activity that requires continuous adjustment of joint angles (Bourgois et al., 2017).

The isometric biomechanical demands of hiking techniques place significant maintenance loads on the spine (Pan et al., 2024; Pan & Sun, 2022). Kinematic posture errors, such as asymmetric trunk extension angles, disrupt the distribution of supporting forces. Empirical evidence indicates that 43% of Optimist class sailors experience chronic low back pain during the competition season, a condition strongly associated with functional asymmetry and disproportionate pitching under load (Kostański et al., 2019). Furthermore, inadequate maintenance of articulation locking posture can displace the center of gravity from its optimal position, resulting in reduced heave rate (Friesenbichler et al., 2018).

Despite widespread recognition of the mechanical significance of hiking, a notable research gap persists. Most comprehensive kinematic studies focus on adult athletes in large-boat classes, whereas investigations involving the Optimist class are typically restricted to general performance metrics or anthropometric data (Caraballo et al., 2024; Pan et al., 2022). Literature specifically addressing the symmetry of kinematic adaptations on both the port and starboard sides is scarce. This paucity of data is largely attributable to the reluctance to employ laboratory-based 3D sensors, which are costly, highly complex, and susceptible to damage in field or open-water environments. Consequently, employing 2D kinematic tracking via accessible open-source tools like Kinovea presents a significant methodological advantage. It provides researchers and coaches with a cost-effective, portable, and highly reliable alternative for conducting precise postural evaluations in practical dry-land or field settings, completely bypassing the logistical barriers of traditional 3D motion capture systems.

In response to this research gap, the present experimental study researches 2D kinematic characteristics, including sagittal joint angle, frontal tilt, and pelvic shift, and evaluates the effects of boat side (port versus starboard) and maneuver phase transitions (before, during, and after hiking) on postural changes in elite Optimist athletes. The study delivers a methodological innovation by integrating Kinovea software, which has demonstrated reliability in clinical

spatial analyses (Leporace et al., 2023; Puig-Diví et al., 2019), with simulations of actual boat conditions in a controlled land-based environment. The findings are anticipated to establish quantitative angle benchmarks for early technical training that is symmetrical, efficient, and minimizes the risk of musculoskeletal disorders. Therefore, this study primarily hypothesizes that there will be no statistically significant kinematic differences between port and starboard maneuvers, reflecting a high degree of bilateral movement automation in elite sailors. A secondary hypothesis posits that significant and systematic postural adaptations will occur across the movement phase transitions to accommodate shifting isometric demands.

Materials and methods

Study participants

The target population comprised Optimist-class sailors enrolled in the West Java Regional Training Center (Pelatda). Purposive sampling was employed. The sample included two male athletes who met the following inclusion criteria: active participation in the Optimist class (maximum age of 15 years) and a record of achievement as National Champions. The anthropometric characteristics of the sample indicated an average height of 169.5 ± 0.7 cm and an average weight of 51.5 ± 4.9 kg. Selecting this specific sample is methodologically justified in advanced sports biomechanics research, as it enables the observation of elite, automated motor skills, making their kinematic profiles appropriate as standard benchmarks. All data collection procedures received approval from central management and the relevant coaches.

Study organization

A descriptive quantitative approach was implemented using a within-subjects (repeated measures) design. In contrast to cross-sectional studies, this methodology evaluates the same participants repeatedly under varying conditions or treatments (Field, 2018). Kinematic performance was assessed across two ship-side conditions (Port and Starboard) and three movement phase transitions (Before, During, and After hiking). Due to the limited availability of elite athletes meeting the stringent inclusion criteria, this study is methodologically positioned as a single case-series benchmark. Consequently, the primary unit of analysis was the execution of movement repetitions (trials) rather than the number of individuals ($N = 50$ repetitions per side). While treating trials as independent samples in ANOVA introduces pseudo-replication regarding population generalizability, this approach was deliberately chosen to evaluate the intra-individual mechanical consistency and trial-to-trial variance of highly automated motor skills.

Research instrument

The principal instrument utilized in this study was the most recent version of Kinovea analysis software. This open-source software is internationally recognized for its validity and reliability in measuring angles using the Angle Tool and two-dimensional distances in centimeters for both static and dynamic movements (Puig-Diví et al., 2019; Roggio et al., 2021). Additionally, the recording camera is equipped with an APS-C sensor to minimize lens distortion, specifically barrel distortion.

Procedure

Data collection was performed using a land-based simulation of the actual boat. This approach enhances ecological validity by maintaining authentic deck dimensions, hiking strap placement, and gunwale configuration, while eliminating confounding variables such as wave distortion (Fontana & Naddeo, 2025). The procedure commenced with the placement of high-contrast anatomical markers at the lower cervical region/T1, greater trochanter (hip), lateral epicondyle of the femur (knee), and sacral/lumbar region. Recordings were obtained from two

statically mounted cameras (2K 1440p resolution, 60 fps, 27mm prime lens) positioned 2.3 meters from the athlete's stance at a lens height of 1 meter. The first camera was positioned alongside the hull to capture the frontal plane (trunk tilt and sitting shift), while the second camera was placed at the stern facing the bow to capture the sagittal plane (back, hip, and knee flexion).

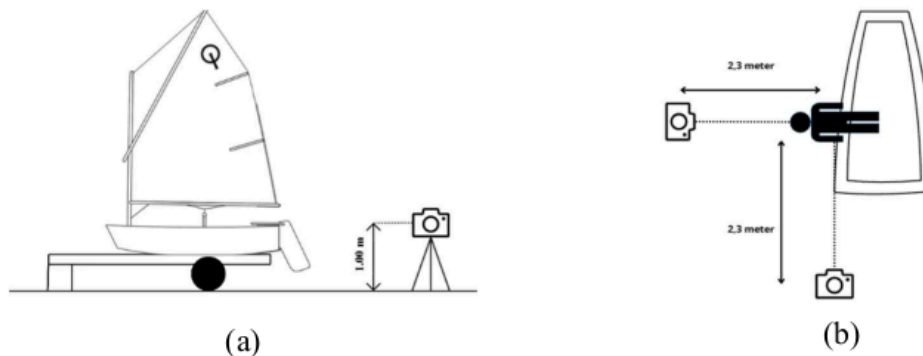


Figure 1. Schematic representation of the camera recording setup in the land boat simulation: (a) Side view illustrating the camera lens positioned 1 meter above the athlete's footrest; (b) Top view depicting the camera located 2.3 meters from the object. Adapted from (Fontana & Naddeo, 2025)

Athletes performed hiking simulations at maximum isometric intensity to replicate on-water conditions. To generate authentic aerodynamic resistance and heeling moment on land, the simulator was fully rigged with an actual sail. The boat was specifically oriented to simulate an upwind trajectory against real environmental wind conditions, with recorded wind speeds ranging from 10 to 13 knots during data collection. This setup ensured that the athletes experienced genuine aerodynamic loads, thereby validating the maximum isometric intensity of their hiking postures in the absence of hydrodynamic variables. Each athlete completed 25 repetitions on the port side and 25 on the starboard side, resulting in a total of 50 analyzed repetitions. Movements were extracted from video recordings based on three operational key frames: Pre-Phase (relaxed on the deck), During-Phase (peak wind resistance), and Post-Phase (return to the starting position). Spatial data were digitized using the Angle Tool in Kinovea.

Statistical analysis

Data Quantitative data obtained from Kinovea digitization were analyzed using IBM SPSS Statistics software. Descriptive statistics were used to report the mean and standard deviation for each phase and side of the maneuver. Due to differing units of measurement (degrees and centimeters), data were transformed into composite T-scores for parametric analysis. The assumption of normality was assessed using the Shapiro-Wilk test, and equality of variances across conditions was evaluated with Mauchly's Test of Sphericity. The primary inferential analysis employed a two-way repeated measures ANOVA with a significance level of $\alpha = 0.05$ to assess the main effects of side and phase, as well as their interaction. If the sphericity assumption was violated, the Greenhouse-Geisser correction was applied. Effect size, expressed as Partial Eta Squared (η_p^2), was also reported to quantify the proportion of performance variance explained by the treatment.

Results

Figures 2 and 3 present visual profiles of athletes' body mechanics, which were continuously recorded during the extraction process using Kinovea software..

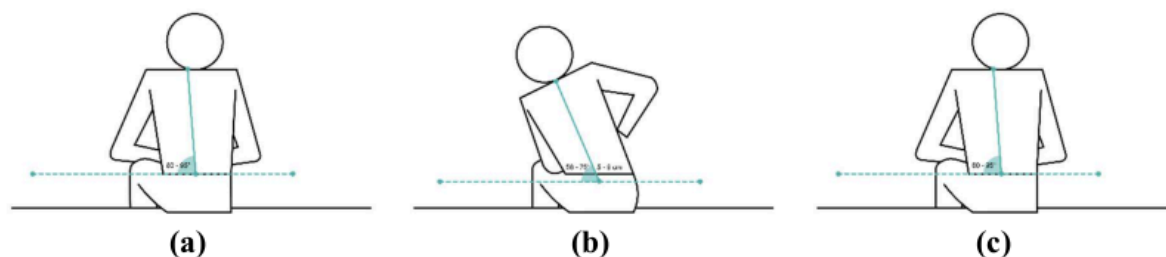


Figure 2. Illustrative schematic based on Kinovea data extraction, showing an athlete's two-dimensional kinematic movement in the frontal plane (the left side of the image indicates the stern of the boat): (a) pre-phase in a relaxed position; (b) peak phase while maintaining position against wind resistance (hiking); and (c) post-phase upon returning to the initial position.

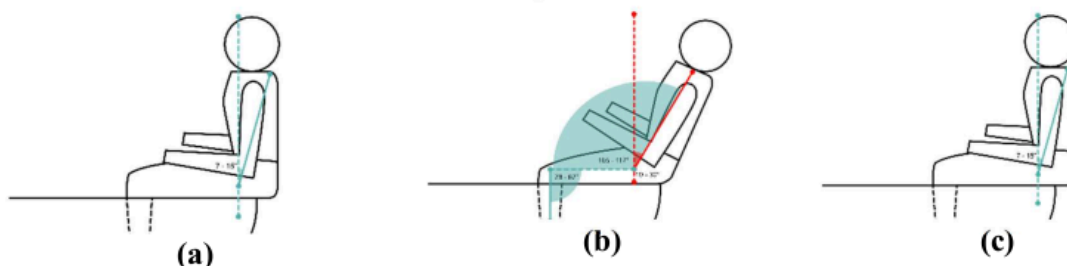


Figure 3. Illustrative schematic based on Kinovea data extraction, showing an athlete's two-dimensional kinematic movement in the sagittal plane (captured from the stern facing the bow): (a) pre-phase in a relaxed position; (b) peak phase during wind holding (hiking); and (c) post-phase upon return to the starting position.

Descriptive statistical analysis [Table 1](#) reveals significant and systematic postural changes as athletes transition between phases. In the frontal plane (body tilt toward the front or rear of the boat), initial angles were nearly perpendicular to the vertical axis (88.19° on Port and 87.04° on Starboard). During the peak hiking phase, athletes leaned backward to 66.95° and 66.01° , respectively. This adjustment was accompanied by a forward displacement of the pelvis by 6.76 cm (Port) and 6.49 cm (Starboard). In the sagittal plane, trunk flexion angle shifted from a relaxed posture of approximately $\sim 8^\circ$ to isometric extension away from the hull by 26.77° (Port) and 25.54° (Starboard). Lower extremity balance was maintained, as indicated by stable hip (approximately $\sim 110^\circ$) and knee (approximately $\sim 80^\circ$) joint angles.

Table 1. Descriptive Statistics of Hiking Position Kinematics

Kinematic Variable	Side	Phase	N	Min	Max	Mean	Std. Deviation
Frontal Trunk Tilt ($^\circ$)	Port	Before	50	80.80	94.90	88.19	2.63
		During	50	58.20	75.40	66.96	4.93
		After	50	79.20	94.60	87.08	3.46
	Starboard	Before	50	79.70	92.40	87.04	2.93
		During	50	58.60	75.10	66.02	4.63
		After	50	79.20	90.40	86.53	3.22

Frontal Pelvic Displacement (cm)	Port	During	50	4.95	8.6	6.76	1.08
	Starboard	During	50	4.85	8.2	6.49	0.96
Sagittal Trunk Extension (°)		Before	50	7.20	11.10	8.98	1.00
		During	50	21.40	32.20	26.77	2.97
	Port	After	50	9.20	14.60	11.87	1.48
		Before	50	5.80	11.40	8.72	1.44
	Starboard	During	50	19.40	30.20	25.55	3.07
		After	50	10.80	15.50	12.75	1.17
Sagittal Hip Flexion (°)	Port	During	50	104.60	115.40	109.90	2.88
	Starboard	During	50	105.40	117.20	111.93	3.11
Sagittal Knee Flexion (°)	Port	During	50	75.30	86.50	80.67	2.88
	Starboard	During	50	78.10	87.30	82.97	2.56

Prior to inferential analysis, prerequisite assumptions were systematically verified Table 2. The Shapiro-Wilk test results confirmed normal distribution for all kinematic parameters ($Sig. > 0.05$).

Table 2. Tests of Normality

Kinematic Variable	Side	Phase	Shapiro-Wilk		
			Statistic	df	Sig.
Frontal Trunk Tilt (°)	Port	Before	.985	50	.785
		During	.956	50	.062
		After	.973	50	.305
	Starboard	Before	.969	50	.212
		During	.958	50	.077
		After	.968	50	.188
Frontal Pelvic Displacement (cm)	Port	During	.960	50	.085
	Starboard	During	.970	50	.229
		Before	.969	50	.204
Sagittal Trunk Extension (°)	Port	During	.966	50	.162
		After	.964	50	.135
		Before	.977	50	.449
	Starboard	During	.955	50	.054
		After	.980	50	.570
		Before	.972	50	.281
Sagittal Hip	Port	During	.972	50	.281

Flexion (°)	Starboard	During	.962	50	.108
Sagittal Knee	Port	During	.974	50	.339
Flexion (°)	Starboard	During	.964	50	.127

Assessment of variance equality using Mauchly's Test of Sphericity Table 3 revealed a violation of the sphericity assumption (Mauchly's $W = 0.085$, $\chi^2 = 118.526$, $Sig. < 0.001$) for the main variables. To address this, the ANOVA results were interpreted using the Greenhouse-Geisser correction (Epsilon = 0.522), thereby maintaining the robustness of the findings and minimizing the risk of Type I errors.

Table 3. Mauchly's Test of Sphericity

Within-Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig. (p)	Epsilon (G-Geisser)
Phase	0.085	118.526	2	<0.001	0.522
Side × Phase	0.012	213.167	2	<0.001	0.503

Table 4. Two-Way Repeated Measures ANOVA

Source	Assumption Type	df	MS	F	p	η_p^2
Side	Sphericity Assumed	1	551.109	0.257	0.614	0.005
Phase	Greenhouse-Geisser	1.044	3030115.334	2082.239	<0.001	0.977
Side × Phase	Greenhouse-Geisser	1.006	1499.942	0.345	0.561	0.007

According to Table 4, the ANOVA test of the general linear model yielded substantial results. The maneuver side factor did not produce statistically significant differences in kinematic performance, $F(1,49) = 0.257$, $Sig. = 0.614$. In contrast, the movement phase factor had a highly significant effect on changes in athletes' body posture, $F(1.04, 51.16) = 2082.239$, $Sig. < 0.001$. The effect size for this phase transition was classified as very strong ($\eta_p^2 = 0.977$), indicating that 97.7% of the variance in the kinematic angle profile is attributable to mechanical adaptation between movement phases. Additionally, the model detected no interaction effect between the maneuver side and the movement phase, $F(1.00, 49.29) = 0.345$, $Sig. = 0.561$, indicating that the angular strain response from the relaxation phase to the peak is executed with a stable and parallel spatial rhythm regardless of the tacking side.

Discussion

This experimental study investigated the geometric parameter profiles of hiking posture in elite-level Optimist-class sailors. Descriptive analysis and ANOVA results indicated that athletes demonstrated significant yet controlled postural adaptations during transitions between movement phases ($Sig. < 0.001$, $\eta_p^2 = 0.977$). During the peak upwind phase, biomechanical modifications occurred concurrently in both the sagittal and frontal planes. In the sagittal plane, a trunk extension of approximately $\sim 26^\circ$ combined with a knee lock at approximately $\sim 80^\circ$ constitutes an effective strategy to maximize the moment arm relative to the boat's centerline. This quasi-isometric approach is consistent with the theory that achieving maximum righting moment (torque) is necessary for maintaining a flat hull during upwind sailing (Bourgois et al., 2017). Simultaneously, in the frontal plane, athletes stabilized the hull's heel angle by leaning backward to approximately $\sim 66^\circ$ and counter-balancing with a pelvic displacement of ~ 6.5 cm toward the bow. This cross-compensation mechanism minimizes

stern submergence and optimizes the hydrodynamic performance of the dinghy (Cella et al., 2021).

Regarding the influence of the maneuver side, statistical evidence indicated no significant difference in kinematic profiles between port and starboard maneuvers ($Sig. = 0.614$), demonstrating a high degree of functional symmetry within the elite sample. In Optimist racing, frequent tacking is required due to constant disruptions in boat speed caused by wind direction dynamics. The observed bilateral symmetry in isometric force distribution suggests advanced movement automation, where elite sailing performance is characterized by minimal asymmetry between the two sides of the body (Caraballo et al., 2021). However, it is important to acknowledge from a biomechanical perspective that absolute mathematical symmetry is rarely achievable in human movement. Slight functional asymmetries often exist naturally due to inherent lateral dominance, such as handedness or footedness. In the context of this study, the lack of statistical significance implies that any existing natural asymmetry in these elite athletes is extremely minimal and actively compensated for by highly automated motor control, preventing it from disrupting the overall hiking geometry. Furthermore, the analysis revealed no interaction effect between the maneuver side and the movement phase ($Sig. = 0.561$). Mathematically, the trajectories of angular adaptation across movement phases on both sides of the torso remain parallel. This finding confirms that athletes' spatial body positions are not compromised by trunk misalignment regardless of the tacking side, verifying that dryland core endurance training programs effectively promote bilateral development and may reduce the prevalence of low back pain associated with asymmetrical hiking (Kostański et al., 2019; Öztürk et al., 2024).

While these empirical findings deliver valuable quantitative insights, several methodological limitations constrain their generalizability. First, the biomechanical evaluation employed 2D video analysis software (Kinovea), which accurately documents sagittal and frontal planes of motion but does not comprehensively accommodate the analysis of transverse rotational vectors, such as spinal segment rotation. Because sailing maneuvers frequently require athletes to perform subtle shoulder rotations or look backward while trimming the mainsheet, axial trunk rotation is a constant biomechanical factor. The inherent inability of a 2D planar system to capture these out-of-plane rotational shifts may obscure underlying torsional loads on the spine, highlighting a critical area that future 3D motion capture studies must address. Second, the use of a land-based boat simulation effectively eliminates camera distortion and validates the pure hiking geometry; however, this approach diminishes the influence of hydrodynamic disturbance variables, such as wave effects, inherent in open-water conditions. Third, although analyzing movement repetitions ($N=50$) is appropriate for assessing intra-individual mechanical consistency, the small sample size of only two athletes limits the applicability of these outcomes to populations such as beginner athletes who have not yet achieved movement automation. Future research with larger sample sizes is necessary to validate this kinematic blueprint across more extensive populations.

Conclusions

The kinematic performance characteristics of advanced-level Optimist-class sailors exhibit a structured, stable, and consistent pattern of postural geometry adaptation. Inferential analysis verifies the absence of functional asymmetry, with no significant differences between port- and starboard-side maneuvers, and verifies that postural mechanics are not disrupted by imbalance regardless of maneuver side (no interaction effect). Spatial postural adaptation is governed by transition mechanisms throughout movement phases. During the wind-resisting phase, the peak locked posture is characterized by a knee flexion angle of approximately $\sim 80^\circ$, sagittal trunk extension of approximately $\sim 26^\circ$, frontal tilt of approximately $\sim 66^\circ$, and a hydrodynamic stabilization strategy involving a pelvic shift of approximately ~ 6.5 cm. To

translate these empirical findings into actionable coaching strategies, training staff are highly recommended to physically configure dry-land hiking benches to strictly replicate these exact geometric parameters. By explicitly targeting the $\sim 80^\circ$ knee flexion lock and $\sim 26^\circ$ sagittal trunk extension during core endurance modules, coaches can ensure junior sailors develop symmetrical and highly efficient isometric load distribution, serving as a concrete preventative measure against chronic lower back strain.

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Conflict of interest

The authors declare no conflict of interest.

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Information about the authors:

Kahea Abdillah Zulfikar: kaheazulfikar@upi.edu, <https://orcid.org/0009-0008-2607-1575>; Study Program of Sport Physical Coaching, Faculty of Sport and Health Education, Universitas Pendidikan Indonesia, Bandung, West Java, Indonesia

Dr. Mona Fiametta Febrianty, M.Pd: monafiametta@upi.edu, <https://orcid.org/0000-0002-3411-9646>; Study Program of Sport Physical Coaching, Faculty of Sport and Health Education, Universitas Pendidikan Indonesia, Bandung, West Java, Indonesia

Angga M Syahid, S.Si., M.Pd: angga_syahid@upi.edu, <https://orcid.org/0000-0001-9152-8000>; Study Program of Sport Physical Coaching, Faculty of Sport and Health Education, Universitas Pendidikan Indonesia, Bandung, West Java, Indonesia

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