International Journal of Computer Science in Sport

Volume 23, Issue 2, 2024

Journal homepage: http://iacss.org/index.php?id=30

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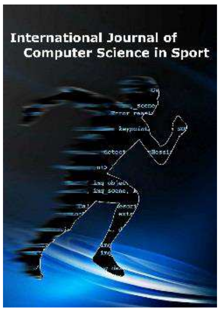
DOI: 10.2478/ijcss-2024-0010



Advancing Artistic Swimming Officiating and Performance Assessment: A Computer Vision Study Using MediaPipe

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ABSTRACT

Artistic Swimming (AS) requires complete execution and synchronization of movements for performance evaluation. The interest in objective and subjective performance analysis worldwide in sports via valid and reliable Artificial Intelligence (AI) tools is spreading depending on the required analysis parameters to design a novel system. This study investigated a novel application of the MediaPipe-based computer vision tool validation by examining biomechanical aspects and the objective performance impact in ballet leg and barracuda AS techniques. Twenty experienced AS athletes participated and executed these techniques under controlled conditions. Thirty-six recorded video trials were captured and analyzed via computer vision using MediaPipe, Kinovea, and AutoCAD (gold standard), with correlations calculated to assess the reliability of measurements and tools. The results indicated a non-significant difference ($p<0.05$) among the software tools, supported by one-way ANOVA and Bland-Altman tests. Notably, in ballet leg technique, maintaining alignment between the upper body trunk and knee in a line had a small correlation with other leg deviations; however, this aspect had a moderate negative correlation in scoring. Overall, this study suggests MediaPipe efficiency in computer vision for AS officiating and performance analysis, offering a reliable, real-time alternative to traditional methods and providing perceptions of AS techniques.

KEYWORDS: ARTIFICIAL INTELLIGENCE, ARTISTIC SWIMMING, MEDIAPIPE COMPUTER VISION, 2D VIDEO ANALYSIS, AUTOCAD.

Introduction

Artistic Swimming (AS) is an Olympic discipline in duet and eight-person team competition, combining swimming, dance, and gymnastics elements to a team-selected musical rhythm to execute the aquatic techniques by optional choices (FINA, 2022; Rincón et al., 2023). In AS, rhythmic abilities with music are key for synchronization to perform precise executions, figures, transitions, and movements in free and technical routines (Ntomali et al., 2021; Bean, 2005). Fundamental skills include body rotation and extensions, mental control, and vertical thrust, where athletes elevate their bodies above the water surface (Kim et al., 2021; Pété et al., 2023). Performance evaluation in AS is based on the difficulty level, execution, and choreography (Ntomali et al., 2021). Three panels of judges determine scoring in AS, the execution panel focusing on technical routines and penalties, the other focusing on difficulty levels, and lastly panel assessing artistic impression. All the referees sit on one side of the pool; thus, it requires the players to control their performance expectations based on the judges' vision. However, limitations exist in human-based judges' ratings, such as the effect of AS players' physical appearance on scoring scales (Dabo et al., 2021; Gambarelli, 2008).

In the AS performance studies, researchers have primarily studied swimmers' feedback through physiological tests, video recording, or scaling AS swimmers' performances based on judges' scores (Bentley et al., 2022; Radaš et al., 2021; Viana et al., 2019, 2020). Some studies measured anthropometric and physical characteristics differences between AS and other aquatic sports athletes (Laski et al., 2024; Vathagavorakul et al., 2020, 2021). For example, in (Laski et al., 2024; Vathagavorakul et al., 2020, 2021) investigations, the difference in lower and upper limbs' strength and coordination among AS players compared with water polo players and freestyle swimmers in breaststroke and eggbeater kicks were measured. The required parameters to measure vertical trust, kicking motions, hand grip strength, and body boost talent in these studies were measured via a motion capture system, force plate, and hand dynamometer. The lower limb strength and breath-controlling skills and development were compared in AS and artistic gymnastics as two aesthetic sports by evaluating physical experiments such as the Sargent test (Markov & Dzimbova, 2023). Despite advancements in Artificial Intelligence (AI) and sports analysis, there is a lack of studies on AI applied to specific AS routines (Martinez et al., 2022).

This study aims to introduce the MediaPipe (developed by Google as an open-source framework) abilities through a new computer vision system as a marker-less Python-based method for body element recognition to introduce a rapid officiating and performance analysis procedure through AS deviation feedback. MediaPipe is a Deep Learning (DL) tool that represents landmarks on a human body in images or videos (Chidambaram et al., 2023). To validate this new MediaPipe-based computer vision tool, a One-way ANOVA and Bland-Altman analysis were meticulously conducted between MediaPipe data compared with Kinovea 0.9.4 video analysis following Yue et al. protocols (Yue et al., 2023) to measure deviations and body poses, alongside the established gold standard, AutoCAD 2024 (Autodesk, Inc.) (Puig-Diví et al., 2019). AutoCAD is useful for studying images to measure required parameters such as angular measurements, and Kinovea is beneficial in offline video analysis (Puig-Diví et al., 2019; Yue et al., 2023). However, this MediaPipe-based computer vision is advantageous for both real-time and offline video analysis for judge panels during the tournaments and for coaches in training sessions. This comprehensive approach aims to comprehensively understand the validity of this computer vision through ballet leg and barracuda techniques.

Subsequently, building upon this groundwork, the study aimed to analyze athleticism and movement freedom through this DL tool in a ballet leg 2D video analysis. While dynamic factors such as the ability to hold these configurations over time are important in some contexts, our analysis is designed to assess the precision of execution at these critical moments. This static approach is suited to the specific scoring criteria used in this discipline. Plus, this study focused on the relation between the shoulder and the stable knee positioning and balance level with scoring and deviation.

Method

Participants and Protocols

Twenty AS athletes (aged 15±2) with over 3 years of experience participated in multiple trials to execute ballet leg and barracuda techniques during training sessions after a 10-minute warm-up with resistance and plyometric exercises. This study used two GoPro cameras (HERO9 Black) as this brand was consumed in other AS studies (Radaš et al., 2021). The cameras were attached precisely vertically to the trolly's pole and placed at the pool edge at a 2-meter distance from the swimmers. One camera was placed 30 cm under and the other 25 cm above the water surface, capturing the swimmers' performance laterally, recording at 120 Hz. The cameras were set only on the jury's side to capture the judges' perspective, which is the main side that swimmers must perform to achieve the optimal score. Figure 1 shows the two cameras' attachment to the pole (panels a and b) and the diagram of the cameras' holding (panel c). In these distances, capturing whole movements with a close gap to the swimmers was possible. The swimmers in the order performed a ballet leg maneuver followed by a barracuda in the controlled environment. For each trial, the total score was calculated based on the score scale outlined in the position's height chart, containing penalties' deductions (FINA, 2022). In total, 36 registered trials were analyzed using ballet leg and barracuda techniques in officiation and performance analysis. The collected data is controlled by statistical calculation methods using MedCalc Statistical Software (MedCalc Software Ltd, Ostend, Belgium, version 22.020). Informed consent was obtained from all participants, and the Internal Research Board of the Rome Tor Vergata University approved the research, and all procedures were carried out following the Helsinki Declaration.

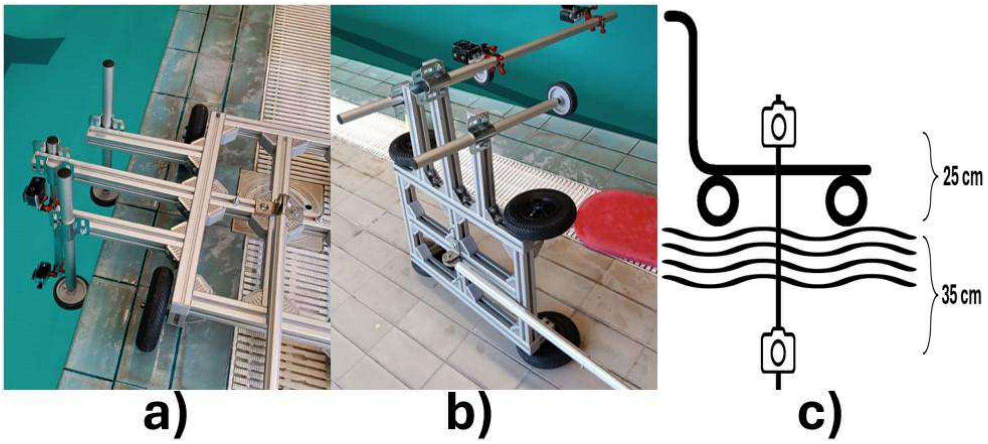

Figure 1. Panels a) and b) show how the system vertically holds the two GoPro cameras on the trolly's pole. The trolly's diagram is shown on panel c).

Procedure

This study analyzes two popular AS techniques, ballet leg, and barracuda since it is possible to assess 2D video analysis as not existing rotational maneuvers during these techniques. Although there is a high similarity among leg execution processes in these two techniques, a difference is that one leg is performing in ballet leg execution while both legs are paired and exhibiting in the barracuda technique (Laski et al., 2019; Ponciano et al., 2023).

Ballet Leg

Swimmers initiate the technique from a back layout position with one leg extended perpendicular to the surface in the ballet leg technique. Then, while one leg is kept straight the whole time, the opposite leg's knee bends and straightens vertically to the water's surface. Following a short pause in this exhibition, the player reverses the actions to return to the back layout position (Zinzen et al., 2013). The exhibition phase is a crucial moment in getting the scores. Score points are awarded based on keeping more leg parts over the water surface, while penalties are incurred for leg deviation. Figure 2 illustrates the deduction scores regarding the deviations where up to 15 degrees result in a deduction of 0.2 scores, between 15 to 30 degrees reduce 0.5 scores, and deviations over 30 degrees deduct 1 score (FINA, 2022).

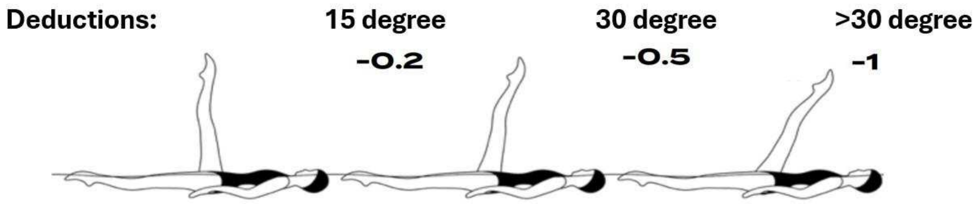

Figure 2. Deviation and deduction limits in ballet leg technique.

Barracuda

In barracuda, the scoring is contingent on an upside-down vertical dynamic height that the body exists above the water surface after a back layout position. The underwater pre-exhibition phases are principal in body positioning preparation to perform a successful show-up. In the preparation time, the legs are raised vertically as the body submerges into a back pike position with toes just under the surface to mark the initiation of thrust and unroll (Peric et al., 2012). In the end, the swimmer reaches the peak height during the execution stage and reaches the points regarding the part of the legs that are pushed up out of the water and the penalty regarding the legs' deviation (Training, 2020). In execution, both legs have to be paired and the penalty scale for the legs' deviation is like a ballet leg, with deductions for deviations up to 15 degrees, between 15 to 30 degrees, and over 30 degrees (FINA, 2022) (Figure 3).

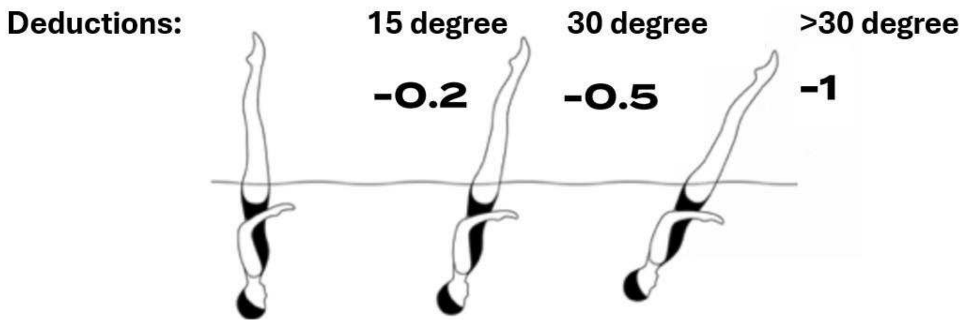

Figure 3. Deviation and deduction limits in the barracuda technique

Coding Procedure

Python coding (verion3.8) within the PyCharm environment incorporated the OpenCV library (cv2) to systematically process the specified video frames along the defined path (Mahulkar et al., 2023). To speed up the analysis process, start and stop variables are added to trim the specific temporal ranges (the execution phases). Furthermore, Holistic pose estimation was conducted using two models from the MediaPipe library concentrated on body landmarks covering facial, hand, and body features (Kim et al., 2023). These models are trained on extensive datasets using deep neural networks, allowing them to learn complex patterns and relationships within the images of each frame. MediaPipe DL tool enables the recognition of 33 key points in the human body for pose estimation in dynamic scenarios (Buttar et al., 2023).

The focused landmarks in this study are right/left hip and right/left ankle (depending on the cameras' side) that were extracted from the pose landmarks detected by the Holistic model to quantify the leg deviations in the ballet leg and barracuda techniques.

An additional function was introduced to calculate the angle between the line formed by the hip and ankle. This angle, expressed in degrees, was computed utilizing trigonometric functions based on the coordinates of the two specified points. Dashed vertical and horizontal lines were covered on the hip, with a solid line connecting the hip and ankle. The created cross line is based on the video frame, proving the necessity of placing the camera vertically in the camera setup. The resulting angle was displayed on each frame near the hip, visually representing pose dynamics. The angles for each frame were systematically gathered and stored in a list for subsequent analysis. This angular measurement DL method was prepared for validity control.

This angular measurement process can be applied in AS performance analysis. Thus, a similar procedure was pursued to calculate the angle between an imaginary horizontal line on the shoulder and the shoulder-to-knee connection line (presenting the Shoulder-Knee angle). Finally, the processed frames, including the visualized lines and calculated angles, were saved in a preferable video format.

Variables

The deviation angle was measured at the performance execution peak in both techniques. the deviation is defined as a leg angle that is either more or less than 90°, indicating whether the leg is oriented vertically relative to the horizontal plane. The deviation calculation processed by the MediaPipe-based DL tool, a horizontal and vertical line covering the right hip's key point in each video frame, and a connection line from the right hip to the tight ankle facilitated the measurement of the deviation angle. Figures 4 and 5 illustrate that the measured angle through the three software is visible at the execution peaks in the ballet leg and barracuda.

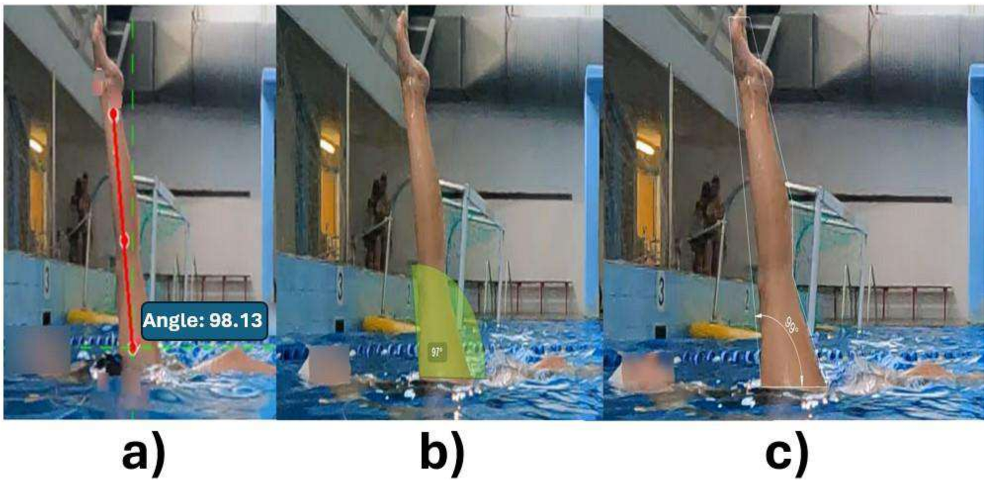

Figure 4. In the ballet leg technique, panel a) shows the deviation angle via MediaPipe-based computer vision (=8.13°), panel b) shows the measured deviation angle via Kinovea (=7°), and the measured angle via gold standard AutoCAD (=9°) is shown in panel c).

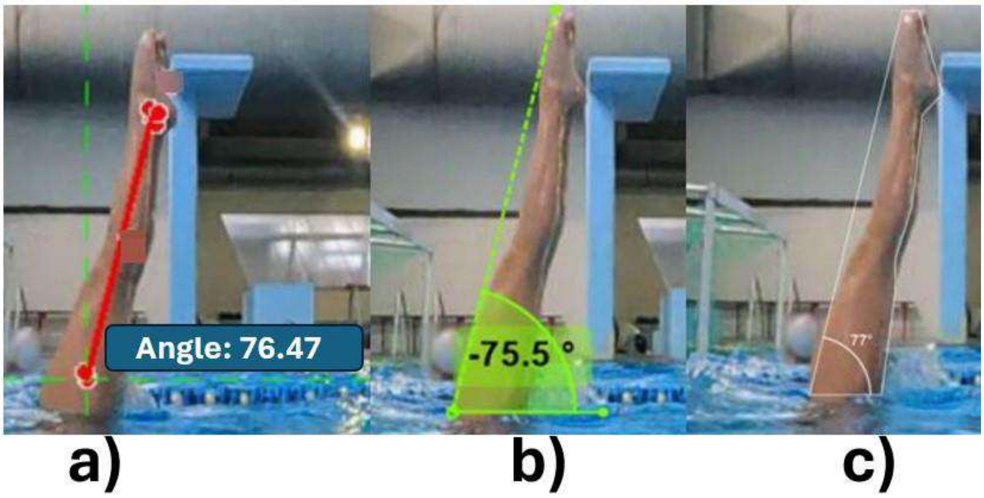

Figure 5. In the barracuda technique, MediaPipe-based computer vision deviation measurement was shown on panel a) (=13.53°), panel b) measured deviation angle via Kinovea (=14.5°), and the measured angle via gold standard AutoCAD (=13°) was located on panel c).

Additionally, in the performance analysis of the ballet leg, the impact of maintaining alignment between the strengthened leg and upper body on the overall score was measured. In this case, a horizontal line was constantly attached to the left shoulder's key point in each frame under the water during the selected time (execution period). Subsequently, a connection line was drawn to the knee of the strengthened leg. The resulting Shoulder-Knee angle was measured and then compared with the total score, where 180° indicates the leg and upper body are kept in a straight line, and any deviation from this angle represents a diagonal alignment of the trunk and leg (Figure 6).

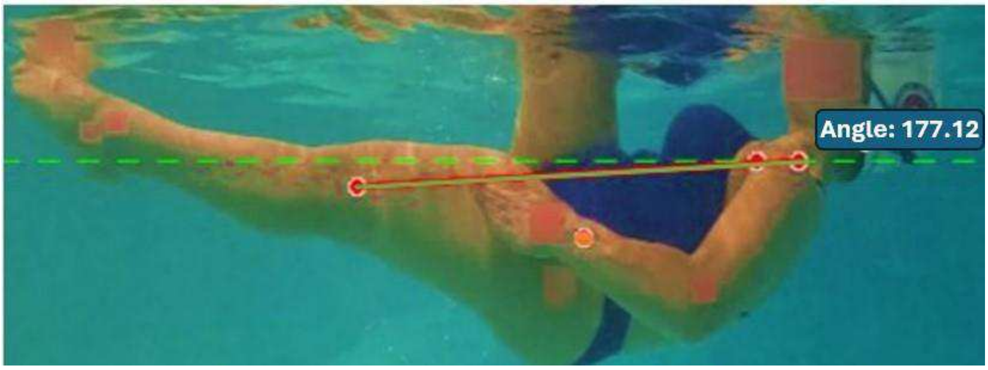

Figure 6. Shoulder-Knee angle was measured (=2.88°) to analyze the effect of keeping the shoulder aligned with the knee at the ballet leg execution stage.

Reliability and Validity

The data validity and reliability processes were followed by the suggested statistical tests and calculations, including one-way ANOVA, Bland-Altman, Standard deviation (SD), Effect Size (ES), correlation coefficients (r), p-value, Intraclass Correlation Coefficient (ICC), 95% Confidence interval (CI), coefficient of variation from duplicate measurement (CV%) (Annino et al., 2021; Romagnoli et al., 2022).

A Pearson correlation analysis within a one-way ANOVA examined the distinctions among the three software tools. The resulting r were classified as trivial ($r < 0.1$), small ($r = 0.1–0.3$), moderate ($r = 0.3–0.5$), large ($r = 0.5–0.7$), very large ($r = 0.7–0.9$), and almost perfect ($r > 0.9$). Lastly, a significance level of $p < 0.05$ was adopted, and the calculated p-value indicates a meaningful difference among parameters in different periods when the value is equal to or less than 0.05. On the other hand, measuring an ICC value by ANOVA test is possible. The ICC usage is to quantify the reliability or agreement between the measurements obtained from the two signals. The values range from 0 to 1, and the ICC score indicates strong agreement (ICC over 0.9), good (ICC = 0.75-0.9), moderate ICC = 0.5-0.75, or poor (ICC < 0.5) reliability between the two signals.

Since no significant deviations from normality were detected, the CV%, ICC, and 95% CI were calculated to determine the software's reliability and validity (J. Bland, 2006; Hyslop & White, 2009). ES was calculated between each pair of software, a value to measure the strength of the relationship between two variables, where the small effect was 0.1, a moderate 0.3, and the large was 0.5 (Cooper & Hedges, 1994).

Subsequently, a Bland-Altman analysis was employed to evaluate the agreement between measurements obtained from MediaPipe and Kinovea, comparing the gold standard AutoCAD. The Bland-Altman plot as an assessment was also used to control the agreement between two measurement methods, particularly when compared against a gold standard (Giavarina, 2015). The validity would occur by assessing consistent agreement, absence of systematic biases, and narrow 95% CI in the plot chart comparing measurements with a gold standard (J. M. Bland & Altman, 1996).

Results

The deviations were measured using DL using MediaPipe, Kinovea, and 2D AutoCAD in the ballet leg and barracuda techniques. Table 1 presents the one-way ANOVA results comparing the measured deviation angles across the three software tools. Table 2 illustrates the correlations and agreement between the software tools, including DL using MediaPipe and Kinovea, as compared with the gold standard 2D AutoCAD, using various statistical metrics.

Table 1. One-way ANOVA to compare the measured deviation angles of the swimmers with three different software. The mean of measured deviation angles ± Standard Deviation (SD) and p-value are measured. The "nr" in "Different (P < 0.05) from factor nr" refers to that number.

	Mean (SD)	Different (p<0.05) form factor nr
AutoCAD	7.83 (5.8)	n. s
MediaPipe	7.80 (5.6)	n. s
Kinovea	7.17 (5)	n. s

Table 2. Presents the three software paired comparisons by measuring statistical values in the 36-ballet leg and barracuda trials' deviation in AS, including "r" Pearson correlation coefficient; Coefficient of Variation (CV), Interclass Correlation Coefficient (ICC), 95% Confidence Interval (CI), and Effect Size (ES).

	r	ICC	95% CI (ICC)	ES	95% CI (ES)	CV%
AutoCAD-MediaPipe	0.93	0.92	0.85 to 0.95	0.005	-0.138 to 0.132	1.55
AutoCAD-Kinovea	0.98	0.98	0.92 to 0.99	0.116	0.052 to 0.183	0.83
MediaPipe-Kinovea	0.91	0.90	0.83 to 0.95	0.119	-0.024 to 0.284	1.66

Figure 7 demonstrates the Bland-Altman test to compare collected data from Kinovea and MediaPipe-based computer vision with AutoCAD. In the plot, the y-axis represents the difference between the measurements obtained from MediaPipe or Kinovea and those obtained from AutoCAD. In contrast, the x-axis represents the average of the two measurements. Each data point on the plot compares a measurement obtained from either MediaPipe or Kinovea and the corresponding measurement obtained from AutoCAD.

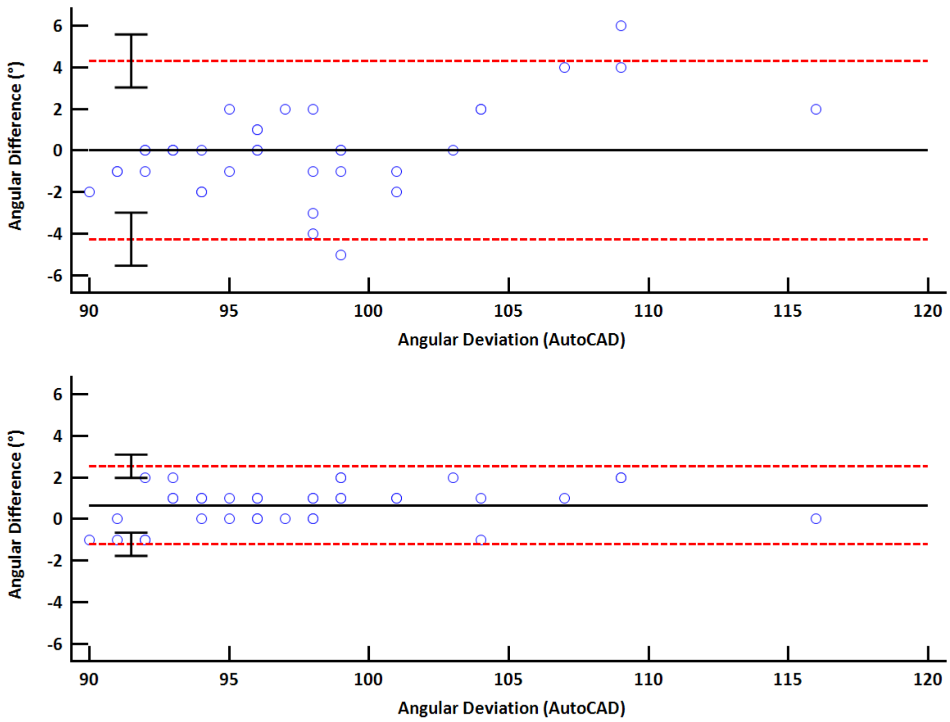

Figure 7. Bland-Altman plot comparing AutoCAD, the gold standard, with deviation angles measured by MediaPipe-based computer vision (a plot) and Kinovea (b plot). The graph features dashed lines indicating the 95% CIs.

In ballet leg evaluation, the Pearson correlations between total scores and angular deviation compared with the Shoulder-Knee angle during the execution phase were analyzed through computer vision via MediaPipe in underwater conditions. The results showed a small negative correlation between shoulder-knee angle and deviation creation ($r=-0.124$), and a moderate negative correlation between shoulder-knee angle and score ($r=-0.444$).

The application of MediaPipe allowed for accurate body element detection and provided immediate feedback on deviations from the desired movements. The statistical analysis showed a significant improvement in the consistency of evaluations compared to traditional methods.

Discussion

This study had two parts: two synchronized cameras were placed vertically under and out of the water within the same 2-meter distance of the AS athletes to observe the swimmers' whole body in the pre-preparation phase to assess overall scores and deviation deduction points. First, a validation of the AI procedure in this study, which merges video processing and MediaPipe utilized in Python and presents its efficacy like a reliable 2D video analysis same as Kinovea and Dartfish (Pueo et al., 2020; Puig-Diví et al., 2019) for performance analysis and officiating in AS in specific angular measurements. Second, the validated computer vision analyzed body recognition and positioning relations in AS performance.

Validation of AI-Based Sports Analysis Tools

AI is expanding its role in sports analysis to access accurate, complex data quickly (Annino et al., 2023). Another advantage of the selected tools in this study is their free access, making them an attractive option for coaches and analysts. Kinovea is a popular method of human motion analysis (Fernández-González et al., 2020). However, the coaches can take advantage of the new alternative method, which can be set as an online and valid method to speed up measuring similar variables.

In the AS performance data comparison, a One-way analysis showed no significant differences among the software measuring swimmers' deviations, indicating high similarity (Table 1). In the three tools examination (Table 2), with AutoCAD and DL through MediaPipe at the forefront, a comprehensive evaluation was conducted to scrutinize their validity and practical implications. AutoCAD paired with DL through MediaPipe showcased a robust level of agreement (r = 0.93) and a high intraclass ICC = 0.92, indicating strong measurement consistency. The 95% CI for ICC (0.85 to 0.95) further substantiates this, illustrating a narrow range of variability and bolstering confidence in the reliability of the measurements obtained through this combination. However, it's pivotal to note that despite the statistical significance, the ES was minimal (0.005), with a CI (-0.138 to 0.132) encompassing zero, suggesting limited practical significance in real-world applications. On the other hand, the integration of AutoCAD with Kinovea demonstrated even higher levels of agreement (r = 0.98) and ICC (0.98), indicating an exceptional degree of consistency in measurements. The narrower 95% CI (0.92 to 0.99) further solidifies the reliability of this pairing, emphasizing its suitability for precise measurements. The effect size (ES = 0.116) was more substantial than AutoCAD-MediaPipe, with a CI (0.052 to 0.183) excluding zero, suggesting a tangible practical impact in applied settings. Considering these findings, while all three tool combinations exhibit strong agreement, the notable differences in ESs and CIs underscore the importance of selecting the most appropriate tool for specific research or practical applications depending on the studies' aims. Moreover, this computer vision validation within this context is particularly significant, as it underscores its reliability and efficacy as a tool for precise measurements.

Additionally, the demonstration availability of the majority of data points fell within the limits of agreement and showed minimal systematic bias (Barr et al., 2024); the Bland-Altman plot (Figure 7) underscored the notable resemblance between the coding procedure using MediaPipe and Kinovea measurements and the gold standard. This underscores DL tools using MediaPipe's potential as a practical and efficient alternative for AS biomechanical analysis, which is advantageous to the quick trim process of large videos without resolution loss or rapid performance analysis processes.

AS Performance Analysis

This-study explained a small correlation in biomechanical factors that make deviation penalties in ballet leg techniques and a moderate correlation in scoring performance. The importance of holding the upper body and stable leg in the ballet leg to gain scores was controlled by measuring the Shoulder-Knee angle by the implemented computer vision via MediaPipe usage. The analysis demonstrated that maintaining upper body stability and body positioning parallel to the water surface in the ballet leg technique was important, with a moderately significant negative correlation (r=-0.444), maintaining alignment between the upper body trunk and the knee with performance outcomes. However, body positioning does not influence deviation creation where a small correlation exists between the deviation and Shoulder-Knee angles (r=-0.124).

Overall, MediaPipe has the potential to revolutionize computer vision systems, especially in AS performance analysis and officiating, primarily due to its quick processing and ability to show biomechanical gestures in air or underwater conditions (He & Luo, 2021). This capability is critical in a sport where timing, precision, and consistent feedback are crucial for success. By rapidly processing large volumes of video data, this coding procedure allows coaches and referees to assess performances in real time, providing immediate insights into technique execution and deviation degrees and identifying the errors. Besides, the detailed biomechanical analysis offered by MediaPipe aids in understanding the nuances of each technique, leading to improved alignment and form, ultimately contributing to better athletic performance. As discovered in this study, the MediaPipe function avoided confusion where just one leg or both legs were executed, and a person's body parts would not create noises in body estimation processes.

Limitation

While our findings highlight the potential of MediaPipe in enhancing performance evaluation, certain limitations were noted. For instance, variations in lighting and background can affect the accuracy of the system. Plus, MediaPipe cannot recognize multiple participants. Future research should focus on addressing these limitations exploring the application of this technology in other aspects of AS training, and comparing the variables with reliable wearable devices such as Xsens IMUs (Chieffo & Motta, 2021; Edriss et al., 2024).

Conclusion

This study contributes valid insights into the biomechanical analysis of AS techniques focusing on the ballet leg and barracuda maneuvers. And demonstrates that MediaPipe can serve as an effective tool to improve the objectivity and efficiency of performance evaluations in AS. The findings emphasized the MediaPipe as a reliable tool used in computer vision coding procedures in objective performance analysis and officiating in AS, demonstrating its high similarity with the gold standard, AutoCAD, by measuring deviation or body joints' angles. This DL tool offers distinct advantages, including rapid processing and permission to select specific video durations for detailed analysis. It is a practical and efficient option for AS biomechanical assessment. Thus, by providing rapid and accurate feedback, it has the potential to significantly enhance the training and officiating processes. Moreover, our study highlights key biomechanical factors that influence AS performance. Specifically, maintaining alignment between the upper body trunk and knee emerges as a critical determinant of performance outcomes in ballet leg maneuvers. The DL tool can be practical in the officiating and analysis process of AS athletes at different levels. While this study primarily focuses on the validation of MediaPipe-based computer vision to analyze static positions at the peak execution phase in AS techniques, we acknowledge that athlete performance is not entirely static. The ability of athletes to maintain these configurations over time is critical, especially during longer routines where fatigue or slight deviations may impact performance. Further research in this area will enhance our understanding of AS biomechanics and contribute to developing effective kinematic and dynamic training methodologies and performance-enhancement strategies in other AS techniques, aquatic, and aesthetic sports.

Acknowledgment

In memory of Francesca Erisi, the Centro Sportivo Le Colline AS team owner, her AS team had an appropriate collaboration with us throughout this study.

Author contributions statement

Conceptualization and methodology, S.E., L.C., and G.A; writing—original draft preparation, S.E., C.R., G.A., and V.M.; writing—review and editing, V.B, E.P, V.M, G.A., and F.C.; visualization and supervision, G.A., V.M., C.R., and S.E. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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