

Training the brain to play the game: a single-case study of personalized action observation training in an elite basketball player

P. Presti · A. Ciraolo · S. Bizzozzi · A. Marallo · P. Avanzini · Fabbri-Destro Maddalena 

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Abstract

Optimizing motor learning in sports ideally requires procedures influencing both the physical and cognitive dimensions of performance. The Action Observation Training (AOT) operationalizes this principle by combining action observation, motor imagery, and physical practice and has shown promise in facilitating skill acquisition. However, evidence for its ecological applicability remains scarce. Here, we developed an on-court AOT protocol for basketball shooting, administered it to a single player and examined whether it was associated with biomechanical and behavioral changes over time. A single basketball player completed a self-modelled AOT program targeting three shooting gestures. Outcomes were examined both behaviorally, by collecting the training session scores and match performances, and biomechanically, by tracking his movement kinematics before and after training. Behaviorally, the player performed the trained movements more frequently during official matches after the training, a finding compatible with a potential transfer of benefits to competition and increased confidence in recalling the trained skills. Biomechanically, upper-limb movement kinematics appeared more compact and efficient than baseline, a pattern apparently preserved at a six-month follow-up (conducted only for one of the three gestures). Overall, this proof-of-concept indicates that AOT can be transferred to ecological sport settings, tailored on individual performance, and complemented with behavioral and biomechanical measures. These considerations support the feasibility of the proposed approach and, along with the single-case report, encourage the AOT use as a brain-informed complement to traditional training methods. Controlled studies with larger samples are still needed to provide proof of evidence of the ecological-AOT efficacy in basketball, and sports in general.

Keywords Self-modelling · Motor learning · Biomechanics changes · Action observation

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Introduction

The continuous evolution of sport training methodologies necessitates the integration of innovative and scientifically validated approaches to optimize athletic performance. Effective training strategies are designed not only to enhance skill acquisition, decision-making, and motor execution but also to account for the complex interplay between cognitive and physiological demands that the athletes face during both training and competition¹.

Traditionally, sports training has strongly emphasized physical repetition and deliberate practice as fundamental pillars of skill refinement². However, contemporary research increasingly highlights the crucial role of cognitive processes in motor learning, emphasizing how mental engagement and neural adaptation contribute to performance enhancement³. Among the emerging approaches that leverage the cognitive dimension, Action Observation Training (AOT) has gained significant attention for its potential to facilitate motor learning and refine movement patterns by engaging the brain's action-related networks⁴.

AOT is rooted in the discovery of mirror neurons, a neural mechanism transforming different types of sensory information into a motor representation⁵. By combining action observation, motor imagery and physical execution in a structured sequence, AOT aims to maximize the reciprocal benefits of each phase. Indeed, the observation of a given action activates the fronto-parietal network and motor imagery prolongs such activation; the pre-activation of these neural substrates subsequently facilitates the execution of the observed action. Due to its capacity to activate the motor system independently of an individual's current movement capacities, AOT has been effectively employed in both motor recovery^{4,6–8} and motor training context^{9–12}.

Within this theoretical framework, recent evidence suggests that repeated exposure to modeled actions enhances neural plasticity, enabling athletes to refine motor patterns and develop more efficient movement strategies¹³. Drawing inspiration from Vygotsky's concept of the Zone of Proximal Development (ZPD)¹⁴, the effectiveness of AOT may be maximized when the modeled actions are slightly beyond the observer's current skill level but still achievable with support, thereby fostering learning through guided challenge. But can this theoretical principle find a physiological counterpart? Recent evidence from Bazzini et al.⁹, suggests that repeated exposure to a more skilled model can act as an “attractor” for the neuromuscular system, gradually guiding the learner's motor output toward the observed pattern.

This theoretical and physiological convergence is particularly relevant in sport, where the calibration of training stimuli just beyond the athlete's current ability can facilitate skill acquisition and technical refinement. In elite sports, this translates into using an athlete's best performances as an optimal reference model for learning, as self-modeling enhances motor representation and facilitates skill retention^{15,16}. This approach ensures that training remains optimally challenging yet achievable, fostering a continuous progression toward higher performance levels. Athletes can enhance their technical and strategic proficiency by integrating observational learning with physical practice while reducing the risk of overtraining and injury¹⁷.

Several studies have already demonstrated the efficacy of AOT in promoting motor learning in sport contexts (Al-Abood, Davids, & Bennett^{18,19–22};;). However, despite these encouraging results, current AOT interventions often lack ecological validity and long-lasting impact. Specifically, few protocols offer clearly defined procedures that can be implemented in practical training environments, such as gyms or directly on the field. This limits the applicability and scalability of AOT interventions for coaches and athletes seeking structured, evidence-based training tools²³.

Building on existing AOT frameworks, the present study evaluates a personalized AOT protocol that combines immersive VR with self-modeling in an ecologically valid sport setting. The protocol employs 360° video recording of the athlete's own best performances, viewed through a head-mounted display. This setup provides a highly engaging and realistic experience, hypothesized to amplify motor resonance^{24,25} and attentional engagement²⁶. The primary objective of our study was to evaluate the feasibility of the protocol and to characterize the biomechanical and behavioral changes temporally associated with the intervention. To this end, a professional basketball player was followed across two consecutive seasons. Changes were evaluated by analyzing the biomechanics

of specific basketball gestures and tracking their frequency and accuracy during official matches. Additionally, a six month follow-up evaluation, only for one gesture, was conducted to explore the persistence long term retention of the observed AOT-related motor changes.

Materials and methods

Participant

This study involved a 20-year-old male professional athlete during the 2023/2024 and 2024/2025 seasons. The athlete was right-handed and presented limited proficiency with his non-dominant left hand at baseline. At the time of the intervention, he primarily played as a small forward/power forward (3/4), although the coaching staff aimed to progressively develop a more perimeter-oriented profile (2/3) to increase his offensive versatility and ball-handling skills. The athlete had extensive competitive experience at both youth and senior levels. During the 2023/2024 season, he participated in two championships, namely the senior league (the fourth-highest division of the Italian basketball league) and the Under-19 youth league, accumulating a total of 67 appearances in official matches between October 2023 and June 2024. In the 2024/2025 season, he competed in the third-highest division of the Italian basketball league, making 19 appearances between September 2024 and January 2025. Despite this change in competitive level, the athlete maintained a comparable playing role and average playing time across the two seasons (32.9 ± 6.0 min per game during the first season vs. 32.7 ± 5.0 min during the second season). Importantly, throughout the study period, the athlete maintained his regular training and competition schedule. The AOT intervention was integrated into his standard basketball activities and did not replace any component of his usual training program. All procedures have been approved by the CNR research ethics and integrity committee (project QUASAR, dated 22 September 2022) and informed consent was obtained from the athlete.

Experimental procedure

The experimental procedure consisted of three consecutive phases. In the first phase, i.e., pre-training, two experienced coaches identified three basketball-specific gestures (jump shot, hesitation jump shot, and spin move) as targets for training. Recordings were obtained with two 360° cameras (Ricoh Theta SC2 and Humaneyes Vuze 3D) positioned on the court, while an Xsens Awinda motion capture system (17 IMUs, 60 Hz) captured full-body kinematics. Each movement was executed multiple times, and the best performance was selected to generate training stimuli.

The second phase, namely AOT, lasted 10 weeks and included 13 sessions sequentially structured as follows: action observation, motor imagery, and physical execution of the observed movements. AOT was delivered through a customized Unity-based application installed on a Meta Quest 2 headset, allowing immersive visualization of self-modeled best performance on the court.

In the third phase, at the end of the training, the athlete's movements were re-recorded as in the pre-training phase, allowing direct comparison of kinematic data before and after the training. Finally, a six-month follow-up test was conducted for one of the trained movements to assess the persistence of training-induced biomechanical adaptations over time. The overall workflow of the study is illustrated in Fig. 1.

Pre-training: movement selection and recording

At the time of the intervention, the athlete's developmental needs included expanding his offensive repertoire beyond catch-and-shoot situations, increasing involvement in one-on-one play, promoting a more balanced use of both sides of the body, and enhancing his ability to create scoring opportunities independently. Consequently, the selected gestures were chosen because they directly addressed these technical and tactical objectives while also

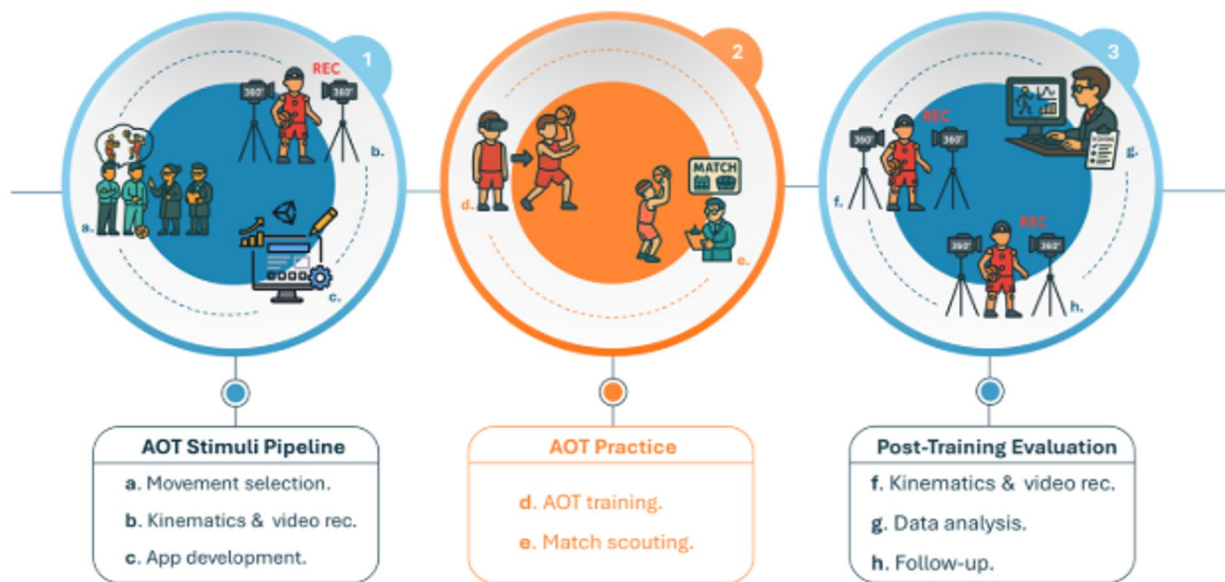


Fig. 1 Study workflow. Schematic representation of the personalized Action Observation Training (AOT) protocol in a basketball player. The three circles represent the main phases: 1) AOT stimuli Pipeline (blue circle on the left) includes: (a) identification of target movements ($n=3$) by coaches, (b) movement recording using synchronized 360° video and motion tracking, and (c) generation of individualized immersive stimuli for the training and storage of baseline kinematic data; 2) AOT Practice (orange circle) includes (d) a 10-week intervention and (e) systematic performance logging during practice and official matches; 3) Post-training evaluation (blue circle on the right) includes (f) the re-recording of kinematic data at the end of the training and (h) after 6 months (follow-up assessment) whose data were analyzed and integrated with scouting outcomes (g).

targeting coordinative and biomechanical aspects considered relevant for performance development. Accordingly, the chosen movements were:

- Jump Shot (JS): a two-point jump shot executed after dribbling with the non-dominant (left) hand while moving leftward.
- Hesitation Jump Shot (HJS): a variation of the JS that includes a hesitation move to deceive the defender before executing the leftward two-point jump shot.
- Spin Move (SM): is a layup sequence initiated with a left-handed dribble, followed by a 180° spin on the right foot before a layup shot.

During the initial session, the athlete repeated each movement until the coaches identified the execution that best represented his maximal performance capability. The best trial was selected after 15 repetitions for JS, 13 for HJS, and 8 for SM. Each repetition was simultaneously recorded using two 360° cameras positioned to provide complementary viewpoints of the movement. Beyond videorecording the exercised movements, we tracked the relative kinematics using a motion capture system based on wearable inertial measurement units (IMUs, Xsens MVN Link, with software MVN Analyze, version 2021.0.0). A total of 17 IMUs sensors were placed on the athlete's body to track the movement of 23 body segments (sampling frequency 60 Hz), and calibration was performed in a typical N-pose see^{27,28}.

Action observation training (AOT)

The 360° videos relative to the best performance for each movement were adopted as stimuli for the Action Observation Training (AOT). A customized application was developed using the Unity Engine software (version 2021.3.16f1) and then installed on a wireless all-in-one Oculus Meta Quest 2 headset (<https://www.meta.com/it/q>

[uest/products/quest-2/](#)), thus allowing the athlete to perform the training directly on the court. The VR application opened with a menu from which the athlete could select the movement to observe. For each movement, videos were presented from two viewpoints in a fixed order across sessions. Each viewpoint was shown three times. Video durations were 5 s for JS (30 s total), 6 s for SM (36 s total), and 10 s for HJS (60 s total). Following the observation phase, the participant received a standardized prerecorded instruction prompting him to mentally rehearse the observed movement. Motor imagery was performed during a 12-s black-screen interval. No formal assessment of motor imagery adherence or quality was performed during the study. Following the imagery phase, the athlete was instructed to remove the headset and physically execute 20 repetitions of the same movement. This observation-imagery-execution sequence was repeated for all three trained movements during each training session.

The athlete completed 13 AOT sessions over a 10-week period, starting on March 19 and ending on May 27 (4 sessions in March, 6 in April, and 3 in May). Throughout the intervention, he maintained his regular team training and competition schedule, which included daily strength training, technical skill practice, and team-based tactical sessions. No additional technical training specifically targeting the three trained movements was performed outside the AOT protocol. The intervention was therefore integrated into the athlete's standard training routine without substantially modifying the overall training load.

Post-training performance and follow-up

Post-training kinematic data were collected at the end of the AOT, using the same procedure as in the pre-training phase. A total of 20 repetitions per trained movement were recorded to evaluate the kinematics changes induced by the training. Finally, we had the chance to assess whether such changes persisted even after the training because the kinematics of the JS movement were re-recorded 6 months later as part of a new experimental procedure unrelated to the present study.

Data analysis

The effects of AOT on the trained movements were assessed at three complementary levels: (1) scoring performance during the training sessions, (2) scoring performance during official matches, and (3) biomechanical changes in movement kinematics. This multi-level approach provided a comprehensive evaluation of the AOT impact, capturing changes in both controlled and ecological-competitive context.

Given the single-case design of the present study, inferential statistics were used to evaluate whether post-intervention changes exceeded the natural intra-individual variability of the athlete's performance across repeated executions. Consistent with recommendations for single-case research in elite sport settings, statistical outcomes were interpreted as indicators of the consistency and magnitude of change within the participant rather than as evidence supporting population-level generalizations²⁹.

Training scoring

For each AOT session, the percentage of made shots (*Training Shooting Percentage, TSP*) was computed. A linear regression model was then applied to highlight whether shooting performances showed a systematic improvement across sessions. The significance of the slope coefficient b_1 was assessed to determine whether training led to systematic improvements, relative to the following equation:

$$y = b_1x + b_2$$

where x indicates the session number and b_1 the slope coefficient.

Match scouting

To evaluate whether the AOT effects transferred to real-game scenarios (official matches), an independent coach, blind to the training procedure, evaluated videotaped recordings of the athlete's official matches. The coach reviewed 55 matches played from October 2023 to June 2024 and 19 matches played from September 2024 to January 2025. For each match, the coach tracked the number of times the athlete tried the trained movements (*Number of Shots, NoS*) along with the shooting percentage (*Match Shooting Percentage, MSP*).

NoS and MSP were first averaged on a monthly basis and qualitatively compared before and after the intervention. To statistically evaluate changes over time, the 12-match duration of the AOT intervention was used as the reference window to generate overlapping blocks of 12 consecutive matches across the entire observation period. The analysis window advanced by one match at a time (i.e., matches 1–12, 2–13, 3–14, etc.), and pairwise comparisons were performed between all blocks using two-tailed two-sample t-tests. To account for multiple comparisons, statistical significance was assessed using a permutation-based Monte Carlo cluster correction (5000 permutations). Clusters were defined as groups of adjacent significant comparisons ($\alpha=0.05$) using 8-neighbour connectivity in the pairwise comparison matrix. Thus, two cells were considered adjacent when they represented comparisons between 12-match blocks differing by a one-match shift in either or both comparison dimensions. Cluster significance was set at $\alpha=0.05$.

Finally, considering that observation collected during consecutive official matches might not be fully independent due to contextual factors inherent to match dynamics, Tau-U was also computed as a nonparametric effect-size measure specifically developed for single-case experimental designs. Baseline trend correction was applied to account for potential pre-existing performance changes over time³⁰. Furthermore, the autocorrelation function (ACF) of the match scouting variables was examined separately for the pre- and post-AOT phases to assess the degree of serial dependence between consecutive observations within each phase.

Kinematics evaluation

A kinematic comparison between pre- and post-AOT movement execution was performed considering three-dimensional information on segment position, velocity, acceleration, joint angles, and the body center of mass (CoM) position. Kinematic data were exported directly from the Xsens MVN software in MVNX format after HD reprocessing. No additional custom filtering was applied, as HD reprocessing performs offline optimization of the complete recording to reduce noise and kinematic inconsistencies while improving movement reconstruction (xsens.com). Based on kinematic cues, we first identified temporal landmarks within each repetition. Specifically, Jump Shot and Hesitation Jump Shot movements were segmented from the point of minimal right knee flexion preceding the last dribble before shooting to the maximal CoM elevation, typically associated with the optimal timing for ball release in a shot³¹. Furthermore, by referring to the elevation of the center of mass (zCoM), we identified three distinct phases: the dribbling phase (from the starting point to the first local maximum of the zCoM), the loading phase (from the first local maximum to the absolute minimum of the zCoM), and the pushing phase (from the absolute minimum of the zCoM to the end point).

Spin Move segmentation began with minimal left knee flexion before initiating rotation over the right foot, culminating in maximal CoM elevation. Also in this case, the elevation of zCoM was used as a reference to divide the movement into two phases. Specifically, the absolute minimum of the zCoM defined the end of the rotation and the beginning of the pushing phase. Temporal normalization was performed to allow comparison across repetitions with different durations. Specifically, each trial was resampled using linear interpolation onto a normalized 0–100 time scale, where 0% corresponds to movement onset and 100% corresponds to movement completion. The 100% point was mapped to the median trial duration, so that the normalized trajectories could be displayed on a common temporal axis while preserving the original signal amplitudes.

No statistical outlier-removal procedure was applied. However, trials affected by evident acquisition or tracking errors (e.g., gross segment misalignment or implausible joint trajectories) were excluded before analysis.

To identify key biomechanical changes, a PCA was applied on the pool of time-normalized pre- and post-AOT trials, separately for JS, HJS, and SM. Features for the analysis were restricted to those joint angles that mostly describe a shooting movement (Slawinsky et al., 2018), as well as the x, y, and z coordinates of the CoM. Specifically, we considered 18 joint angle features, i.e. shoulder flexion, elbow flexion, wrist flexion, hip flexion, hip abduction, knee flexion, ankle dorsiflexion, ankle abduction, ankle internal rotation, all considered for both right and left side. Hence, a (Time x Number of Trial) X Joint Angles matrix was organized and provided as input to the *pca.m* Matlab function. PCA was used to identify the components that explain at least 80% of the variance in each trained movement. For each of them, we further extracted the most representative biomechanical degree of freedom, i.e., the feature with the highest weight. On these latter features, a time-wise two-sample t-test was performed to compare pre-AOT vs. post-AOT shots and test for training-induced differences. An alpha value of 0.05 (Bonferroni corrected) was set, and only differences lasting at least 100ms were considered. Furthermore, the time-wise standard error (SE) of all repetitions (computed separately for Pre- and Post-AOT) was used as an indirect measure of movement consistency, with lower SE values interpreted as reflecting greater movement stability across repetition.

A separate PCA was performed for each of the three key features previously identified as the most descriptive of the JS. Each PCA was thus conducted on a matrix of dimensions Number of Trials (Pre and Post AOT Number of Trial) $\times$ Time, thus representing each angular variation during the movement as a point on a plane defined by the first two principal components. K-means clustering analysis was then employed to identify two clusters and evaluate whether pre- and post-training shots segregated onto this plane. To assess long-term retention of biomechanical changes, JS kinematics recorded 6 months after the end of the AOT were projected onto such a plane, and the Euclidean distance from the centroids of the previously identified clusters was computed. This approach assessed whether the angular joint variations induced by AOT were retained over time or were transient.

Results

Training scoring

The linear fitting of time-wise Training Shooting Percentage (TSP) for JS, HJS, and SM movements showed that the first two movements stabilized within the 60–80% range, with a positive trend particularly evident for HJS. In contrast, SM movement reached ceiling scores near 100%, which was expected, given that the main challenge of this movement lies in the efficiency of the spin move rather than the final layup. Consistently, the estimated slope coefficients were not statistically significant for JS and SM movements (JS: $b_1 = -0.69$, $p = 0.49$; SM: $b_1 = -0.30$, $p = 0.23$), whereas a positive trend was observed for HJS ($b_1 = 1.40$, $p = 0.12$).

Match scouting

Across the 74 analyzed matches, a progressive increase was observed in the number of movement-specific attempts (NoS; Fig. 2), suggesting that the athlete was increasingly able to internalize and apply the trained movements in competitive contexts. The same reasoning does not apply to match shooting percentage (MSP), whose scores apparently increased during training (especially for HJS and SM) but then decreased soon after training (see Table 1).

Considering that the AOT started at the end of March (with only one game played in March during the AOT treatment), a noticeable increase in either the frequency of attempts or the shooting success rate was already evident from April across all the trained movements. This was particularly evident for Hesitation Jump Shot (Fig. 2, middle panel), which was never attempted in the 37 games prior to the AOT. From April onward, however, the athlete executed the HSJ approximately once every two games, achieving a 100% success rate. The trend persisted into the following season (September 2024–January 2025), reaching nearly one attempt per game. A

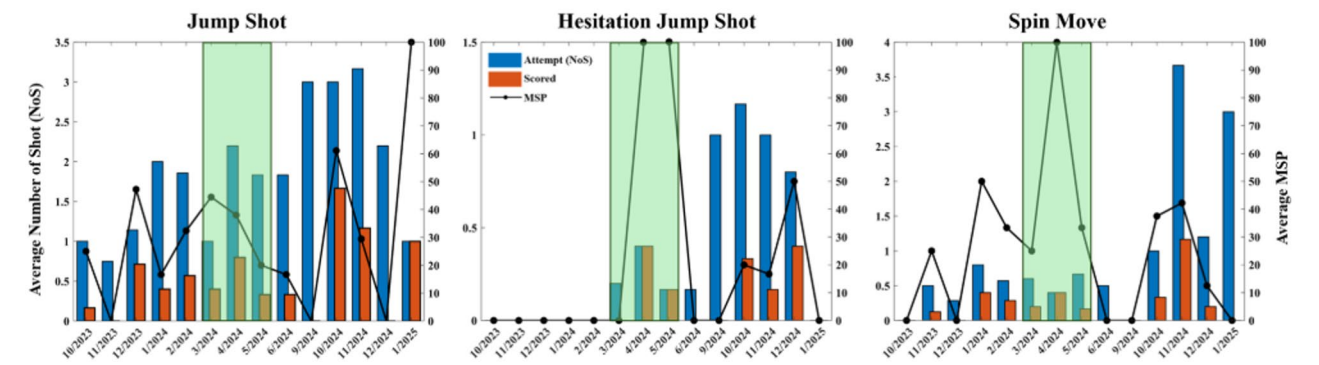


Fig. 2 Monthly progression of NoS and MSP from October 2023 to January 2025. AOT training periods are highlighted in green. Blue bars stand for the average Number of attempted Shots (NoS) and orange ones for the average number of scores. Black dots show the match shooting percentage (MSP).

Table 1 Monthly summary of match scouting variables. NoS indicates the mean number of attempts per match for each movement during the corresponding month, whereas MSP indicates the mean percentage of successful attempts. Months during which the AOT intervention was administered are highlighted in green.

Month	JS		HJS		SM	
	NoS	MSP (%)	NoS	MSP (%)	NoS	MSP (%)
Oct-23	1.00	25.00	0.00	0.00	0.00	0.00
Nov-23	0.75	0.00	0.00	0.00	0.38	25.00
Dec-23	1.14	47.20	0.00	0.00	0.29	0.00
Jan-24	2.00	16.70	0.00	0.00	0.80	50.00
Feb-24	1.86	32.40	0.00	0.00	0.57	33.30
Mar-24	1.00	44.00	0.20	0.00	0.60	25.00
Apr-24	2.20	38.00	0.40	100.00	0.40	100.00
May-24	1.83	20.00	0.17	100.00	0.67	33.30
Jun-24	1.83	16.70	0.17	0.00	0.50	0.00
Sep-24	3.00	0.00	1.00	0.00	0.00	0.00
Oct-24	3.00	61.10	1.17	20.00	1.00	37.50
Nov-24	3.17	29.40	1.00	16.70	3.67	42.20
Dec-24	2.20	0.00	0.80	50.00	1.20	12.20
Jan-25	1.00	100.00	0.00	0.00	3.00	0.00

similar pattern was observed for the Spin Move (Fig. 2, right panel), with a marked increase in the success rate in April, and a consistent rise in attempts during the 2024–2025 season. For instance, in November 2024, the athlete attempted the spin move approximately 3.5 times per game, with a success rate of around 40%. In contrast, the Jump Shot scouting (Fig. 2, left panel) showed subtler variation. Nevertheless, attempts increased, exceeding two per game in April 2024, and continued to follow a positive trend in the subsequent months.

Building on these initial qualitative observations, the quantitative comparisons across game blocks was particularly effective in revealing the AOT related changes in the JS NoS. Indeed, the two-tailed, two-sample *t*-test relative to theNoS revealed a significant increase in JS attempts compared to early-season games only as from the start of the AOT onward ($p < 0.05$). The consolidation of the motor pattern appears to be stronger during the first matches of the 2024/2025 season, during which the JS attempts are significantly higher compared to those of the previous season (see Fig. 3). Results of the comparisons across game blocks for NoS (HJS and SM) and MSP (JS, HJS, and SM) are presented in the Supplementary Material (Figure S1), as the significant effects matched the qualitative trends described above (Fig. 2).

To complement the cluster-based analysis, Tau-U with baseline trend correction was computed as a nonparametric effect-size measure for single-case experimental designs. The analysis confirmed significant increases in the

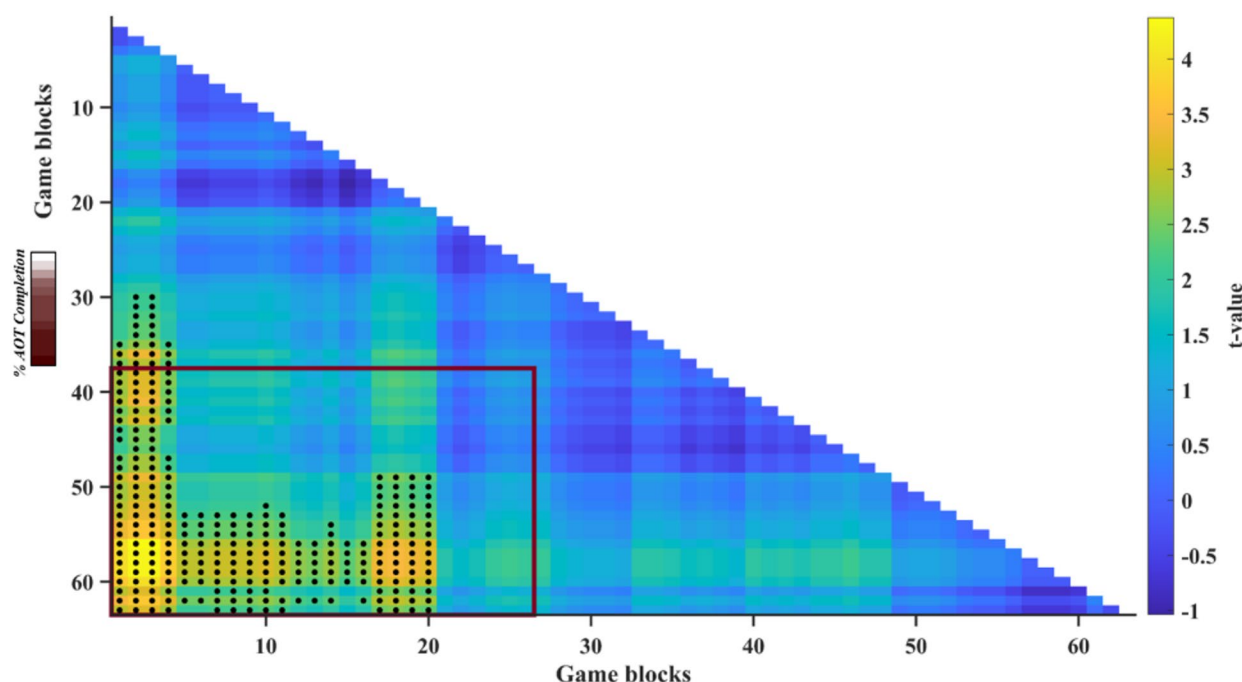


Fig. 3 Comparisons across blocks of 12 games in terms of the number of attempted Jump Shots. The color of each comparison encodes the corresponding t -value. Along the y-axis, a scale from white (0%) to dark brown (100%) indicates the percentage of Action Observation Training completion relative to the played matches. Training starts at the 27th game block and reaches completion at the 38th block. Black dots mark comparisons ($p < 0.05$) belonging to significant clusters. The red rectangle encompasses the comparisons between pre- and post-training blocks.

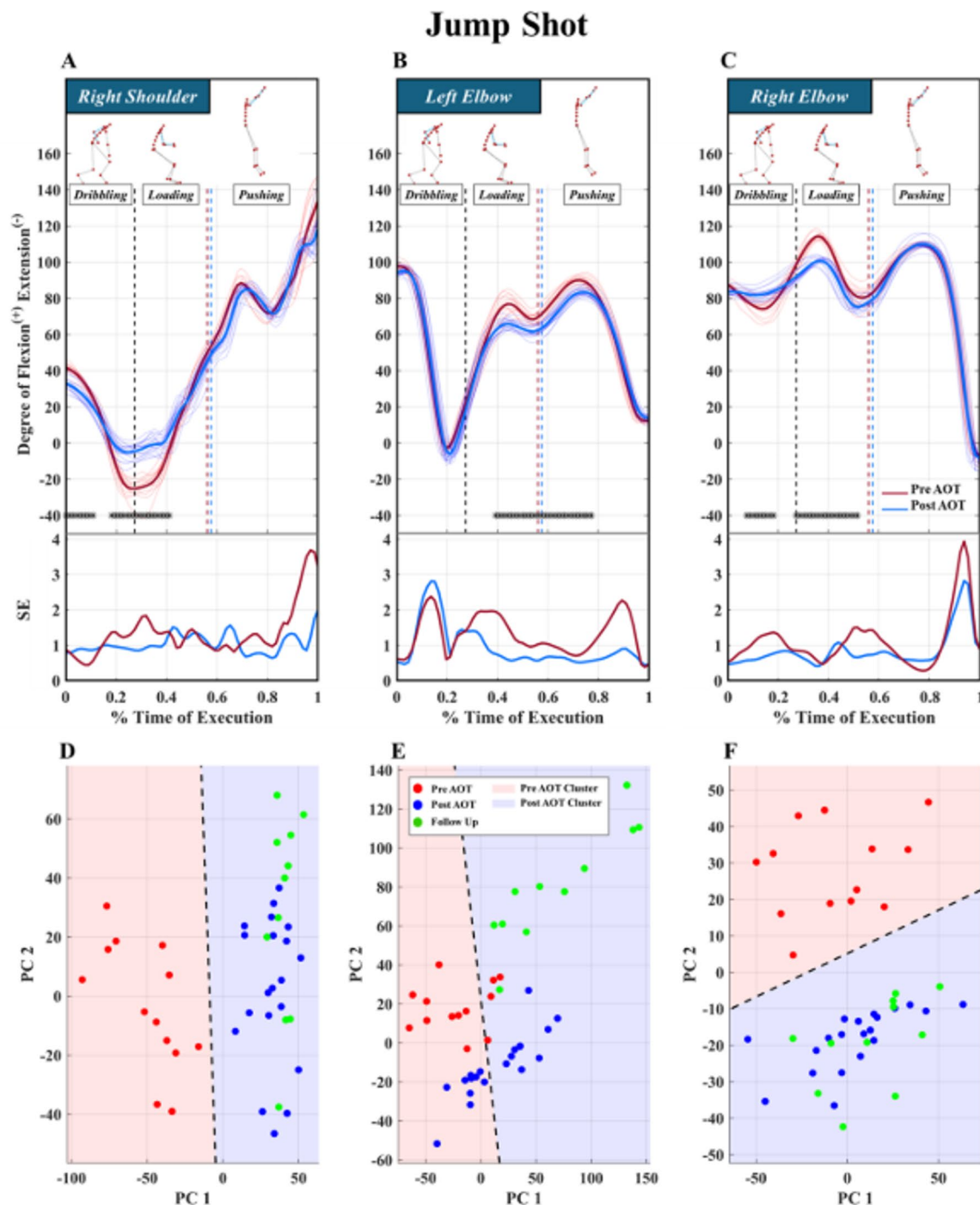
NoS for all three trained movements following the intervention (JS: Tau-U = 0.470, $p = 0.001$; HJS: Tau-U = 0.563, $p = 0.002$; SM: Tau-U = 0.371, $p = 0.026$). In contrast, no significant changes were observed in MSP for any movement (JS: Tau-U = 0.219, $p = 0.206$; HJS: Tau-U = 0.279, $p = 0.230$; SM: Tau-U = 0.270, $p = 0.165$).

Autocorrelation analysis performed separately for the pre- and post-AOT phases revealed no evidence of substantial serial dependence in the match scouting variables (MSP and NoS). With the exception of two isolated significant autocorrelation coefficients observed for SM NoS during the post-AOT phase, all autocorrelation coefficients fell within the 95% confidence limits, suggesting that serial dependence was highly limited.

Kinematic analysis

The PCA conducted on the kinematics of the Jump Shot indicated a first principal component explaining the 40.8% of the total variance, and mostly represented by the flexion-extension of the right shoulder (Fig. 4, panel A). The second and third principal components explained 33.3% and 9.1% of the variance, respectively, with the largest weights corresponding to the left and right elbows flexion-extension (Fig. 4, panel B and C). Compared to pre-AOT shots, post-AOT repetitions exhibit a significantly reduced range of motion in the flexion-extension of the right shoulder in the initial part of movement execution, encompassing the dribbling and loading phase. This reduction extends beyond shoulder movement to the entire upper-limb kinematic chain. In fact, a smaller range of motion is observed in the left-elbow flexion-extension, with significantly reduced flexion between the loading and pushing phases before the shot.

Beyond the sole range of motion, AOT apparently impacted on the movement repeatability as demonstrated by the lower standard error in post-AOT repetitions compared with pre-AOT ones (Fig. 4, lower part of the panels A, B, and C). This effect was evident throughout the entire movement execution and became particularly



pronounced during the final pushing phase, immediately before ball release. Such a pattern indicates increased stability in movement execution achieved after the AOT period.

To further explore the angular variations, PCA was performed on each of these joints, i.e., the right shoulder flexion-extension, left and right elbow flexion-extension. Specifically, for the right shoulder flexion-extension, the first two principal components accounted for 73% of the total variance. The k-means clustering identifies two clusters that perfectly separate pre-AOT from post-AOT shots. Additionally, movements recorded six months after AOT lie entirely in the PCA space devoted to post-AOT movements, indicating retention of the trained pattern (Fig. 4, panel D). A similar result emerged for the right elbow flexion-extension, for which the first two

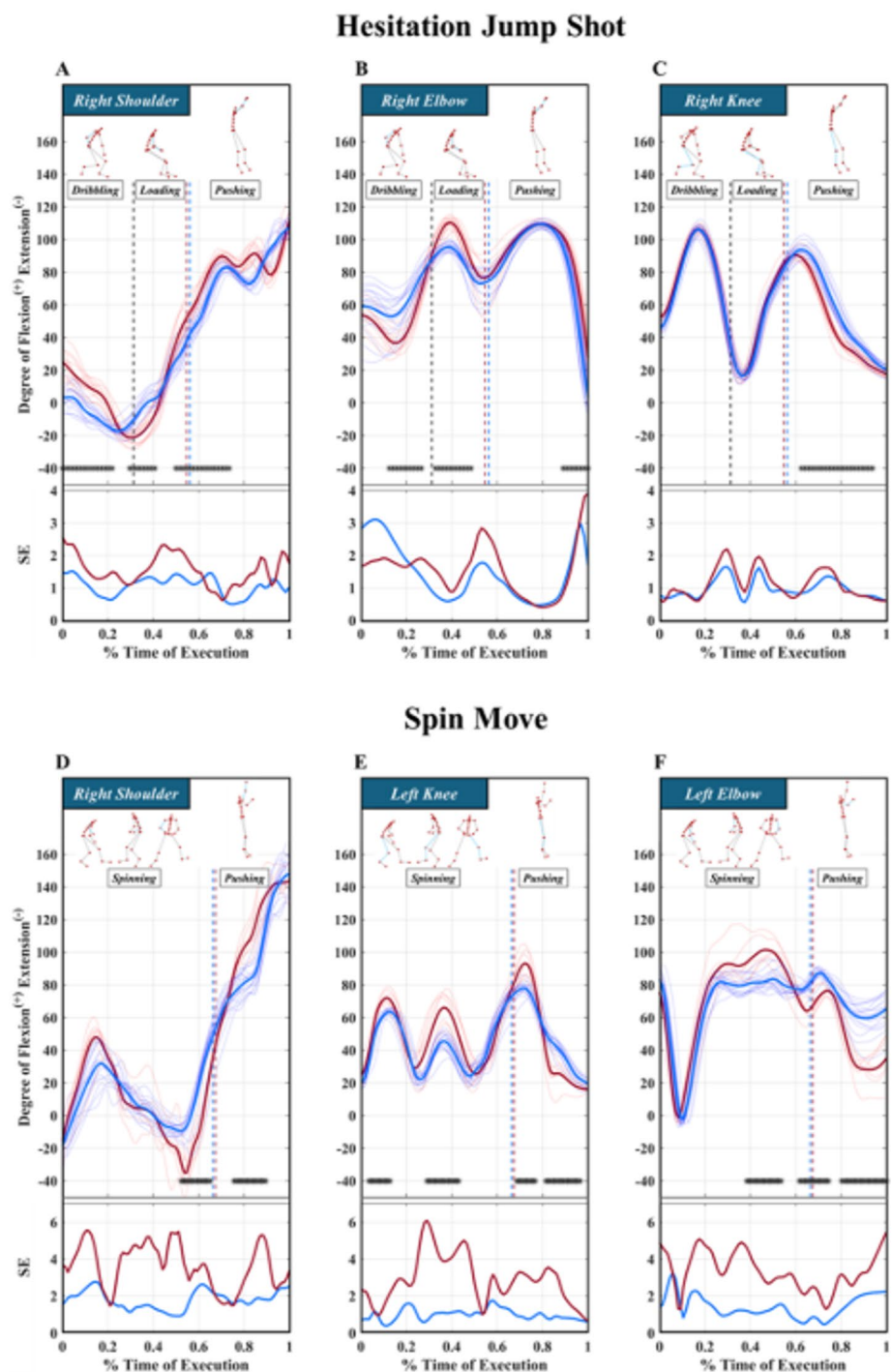
Fig. 4 Biomechanical characterization of the Jump Shot. Panels A–C: Joints’ angular variations explaining most of the variance as emerged from the PCA. Light red and blue curves represent individual pre- and post-AOT repetitions, with bold curves indicating the mean trajectories. Black asterisks mark time points with significant pre- vs. post-AOT differences ($p < 0.05$). Dashed vertical lines separate, from left to right, the dribbling, loading, and pushing phases: they are shown in black when the phase transition occurs at the same instant in both pre- and post-AOT trials, and in red (pre) or blue (post) when the two instants are temporally distinct. Below each set of angular-variation trajectories, and temporally aligned with them, the SE across repetitions is shown for pre-AOT (red line) and post-AOT (blue line) trials over the entire movement execution. Panels D–F: Single-joint cluster analyses: each repetition is projected into the space of the two principal components and represented as a single point. Red, blue, and green dots correspond to pre-AOT, post-AOT, and follow-up repetitions, respectively. K-means clustering based on pre- and post-AOT repetitions partitions the space into two regions (light red = pre-AOT cluster, light blue = post-AOT cluster). In all panels, follow-up repetitions consistently fall within the post-AOT cluster.

principal components accounted for 75.5% of the total variance. K-means clustering again fully distinguished pre- from post-AOT trials, and all six-month follow-up trials fell within the cluster associated with post-AOT shots (Fig. 4, panel F). Finally, for the left elbow flexion-extension, the first two principal components explain 74% of the total variance. However, the two clusters were less distinct (Fig. 4, panel E). The pre-AOT cluster contained 69.9% of the pre-AOT shots, while the post-AOT cluster included 50% of the post-AOT shots. Nonetheless, all follow-up trials were classified within the cluster with a higher prevalence of post-AOT shots, indicating partial but consistent retention of this biomechanical feature.

Considering the Hesitation Jump Shot (HJS), the first three principal components accounted for 50.6%, 15.7%, and 14.7% of the total variance. The biomechanical joints contributing most to each component were the right shoulder, the right elbow, and the right knee. Figure 5 (Panels A, B, and C) illustrates the trajectory of these angles during the movement execution, spanning from the final dribble to the point of maximum CoM elevation. As with the standard Jump Shot, post-AOT trials revealed a reduced range of variation in the upper limb kinematics. Specifically, the right shoulder in post-AOT trials showed less flexion during the initial dribbling phase with the left hand and less extension during the loading phase, effectively resulting in an earlier initiation of the shooting motion compared to pre-AOT repetitions. The onset of right-shoulder flexion occurred, on average, at approximately 0.30% of the movement cycle in the pre-AOT repetitions and at around 0.25% in the post-AOT shots, corresponding to an advance of roughly 50 ms in the initiation of the shooting movement. Also, during the pushing phase, the right shoulder was more flexed in pre-AOT repetitions. Similar differences emerged in the right elbow (Fig. 5, panel B). Post-AOT trials exhibited more flexion during the dribble and reduced flexion during the loading phases. Furthermore, at the point of maximal CoM elevation, i.e., at the end of the trial, the right elbow presented a larger flexion in pre-AOT trials than post-AOT ones, indicating that the ball release occurred closer to the time of maximum elevation after the AOT training. Indeed, peak elbow extension occurred, on average, approximately 61 ms after the moment of maximal CoM elevation in the pre-AOT repetitions, whereas this delay was halved in the post-AOT condition, with a gap of only 30 ms. Finally, during the pushing phase, the right knee was more flexed in the post-AOT repetitions (Fig. 5, panel C). The examination of the SE profiles returned a picture highly similar to the case of JS (Fig. 5, lower part of the panels A, B, and C).

The Spin Move (SM) also exhibited meaningful biomechanical adaptations following AOT. The most representative biomechanical joint within the first principal component (57.6% of the variance) was the flexion-extension of the right shoulder (Fig. 5, panel D). Specifically, post-AOT repetitions exhibited less extension during the final rotation phase preceding the shot as well as reduced flexion during the final shooting phase. The second principal component explained 14.4% of the total variance and was primarily associated with the flexion-extension of the left knee (Fig. 5, panel E). Post-AOT repetitions displayed less flexion during the 180° rotation around the right foot, and a greater flexion during the final pushing phase. Finally, the third principal component explained 11.6% of the total variance. The biomechanical joint with the highest weight was the left elbow flexion-extension (Fig. 5, panel F), for which a more consistent pattern was observed across the entire movement, with reduced flexion during the final 180° rotation phase around the right foot, and increased flexion during the pushing and

Fig. 5 Biomechanical characterization of the Hesitation Jump Shot and Spin Move. Panels A-C show, from left to right, the joints' angular variations explaining most of the variance as emerged from the PCA relative to the HJS. Panels D-F show the angular variations explaining most of the variance of the SM. Light red and light blue curves represent individual pre- and post-AOT repetitions, respectively, while the corresponding bold curves indicate the average trajectories. Black asterisks indicate time points with significant pre- vs. post-AOT differences. Dashed vertical lines separate, from left to right, the dribbling, loading, and pushing phases for the HJS (top panels) and the spinning and pushing phase for the SM (bottom panels). Below each set of angular-variation trajectories, and temporally aligned with them, the SE across repetitions is shown for pre-AOT (red line) and post-AOT (blue line) trials over the entire movement execution.



shooting phase. Overall, SM execution became notably more stable. Following the AOT period, the SE decreased substantially (lower sections of panels D, E, and F in Fig. 5), particularly during the spinning phase, diminishing up to three times its Pre-AOT value.

Discussion

Motor learning research increasingly recognizes that effective skill acquisition depends not only on physical practice but also on cognitive and neural processes that support the formation and refinement of motor representations^{32–34}. Within this framework, AOT has emerged as a promising approach, as the combined use of action observation, motor imagery, and physical execution can facilitate the establishment of new movement patterns¹⁰. Nevertheless, the major limitation of the existing AOT literature is the low ecological validity of most protocols and the scant evidence on long-term effects in real-world performance environments. Although previous studies have reported encouraging outcomes, they have been conducted predominantly in controlled laboratory settings and have relied on standardized, non-personalized stimuli see⁴. These limitations open a debate about whether AOT can be feasibly integrated into everyday practice and whether its influence extends, beyond controlled tasks, to actions performed under realistic constraints. Using sports as a privileged scenario, the present study designed a personalized AOT protocol directly within the athlete's typical training setting in order to evaluate its potential impact under conditions that closely reflect actual sport practice. The findings indicate that implementing a personalized AOT protocol in a real-world training environment is feasible and was associated with biomechanical and behavioral changes observed during the intervention period.

One relevant aspect of this study concerns the feasibility of delivering AOT in a fully ecological setting. Previous sport-related AOT research has often relied on controlled laboratory settings, third-person or non-individualized models^{22,35}, whereas the present protocol integrated 360° self-modeling directly into the athlete's habitual training context. The use of individualized recordings of the athlete's best executions repeatedly exposed him to an optimized version of his own movement pattern, in line with theoretical proposals suggesting that slightly more skilled models can serve as effective references for driving motor refinement^{9,14,36}. The feasibility and acceptability of on-court AOT suggest that this personalized training can be integrated into regular technical training without altering established routines, an important prerequisite for scalability in high-performance sport.

The AOT intervention was associated with systematic modifications in movement organization. Across all three gestures, post-training executions showed more compact trajectories as evident from the reduced range of motion for several joints, and more consistent kinematic organization, particularly at the shoulder, elbow, and knee, i.e., the joints that are known to be key contributors to the organization of basketball shooting actions^{37,38} and in coordinating force transfer along the kinetic chain^{39–42}. These refinements suggest changes in the underlying structure of the movement.

During the ball-pickup phase of the jump shot, reduced right-shoulder excursion and lower elbow flexion angles resulted in a more compact and controlled preparatory posture, whereas the loading and shooting phases remained largely unchanged, suggesting that the primary adaptations involved the organization of the preparatory sequence rather than the release mechanics themselves. A comparable refinement emerged in the hesitation jump shot, where post-training executions showed more stable flexion-extension trajectories of the right shoulder and elbow. The gesture showed greater knee flexion during the final loading phase and larger elbow extension at ball release after AOT, indicating, respectively, a more forceful propulsion strategy culminating in a higher ball release point. Interestingly, these kinematic factors were already documented as decisive differentiators between missed and made jump shots in basketball players³⁹. Finally, although the spin move differed from the other movements in biomechanical features, its execution appeared adapted after AOT, with a more compact initial shooting posture, reduced left-knee flexion during rotation, and lower, more stable elbow positioning throughout the spin. These modifications yield a more coherent and economical rotational pattern, with fewer unnecessary oscillations and more efficient phase transitions. Across the three gestures, these kinematic refinements point to

a reorganization of movement structure rather than isolated adjustments, consistent with the possibility that AOT contributed to stabilizing and optimizing complex motor patterns.

These kinematic observations were accompanied by behavioral differences between the pre- and post-training periods. As a first step, we deliberately tested whether AOT affects the athlete's ability to recruit trained gestures in demanding, real-world contexts. Indeed, most sport-science studies assessing skill-training interventions rely on accuracy-based metrics see⁴³, often measured in low-pressure or standardized tasks. While increasing accuracy is undoubtedly a desirable outcome, focusing exclusively on accuracy risks capturing only the *tip of the iceberg*. If motor training effectively induces kinematic refinement, the primary expectation is that the athlete should be able to recruit the improved motor pattern more frequently during competitive play, where execution is modulated by situational variables such as defensive pressure, spacing, and game dynamics. Guided by this rationale, we did not limit the analysis to shooting accuracy during training (TSP) and matches (MSP), but also quantified the number of attempts per match for each specific gesture. The observed pattern was consistent with our working hypothesis: shooting accuracy remained relatively stable, but the number of attempts increased consistently across all trained movements. Despite their preliminary nature, these findings suggest that accuracy alone may be insufficient to capture the full spectrum of training-related changes—particularly when the intervention targets kinematic attunement—and that one behavioral manifestation of these changes may be an increased use of the trained gestures during competition. Whether a longer training period could subsequently influence shooting percentage remains an open question that warrants investigation in larger cohort studies.

Finally, a critical question concerns the durability of the observed changes, as determining whether training-induced improvements persist over time is a central issue in motor learning. Although several studies have documented short-term benefits of AOT in accuracy or movement efficiency, evidence for long-term retention remains limited e.g.^{20,44}. The present study provides preliminary indications that some effects may extend beyond the immediate post-training period. Six months after the intervention, and in the absence of any further AOT exposure, the trained gestures continued to be performed in official matches with comparable or higher frequency. This behavioral persistence was accompanied, for the Jump Shot, by a stable biomechanical organization, as the follow-up jump-shot trials clustered closely with the post-training executions, especially with respect to the joints that had shown the most substantial modifications during the intervention. Such convergence is consistent with the possibility that self-modelled AOT contributed to the stabilization of the movement pattern beyond the immediate post-training assessment, although this observation is limited to the Jump Shot⁴⁵.

In light of these results, personalized immersive AOT appears to be a feasible approach for implementation in ecological elite-sport settings and may be associated with biomechanical refinements and behavioral changes compatible with transfer to competitive performance.

Limitations

The present study should be interpreted within the boundaries of a single-case design conducted in an ecological elite-sport context. While this approach does not allow population-level generalization or strong causal inference, it enables a detailed longitudinal characterization of behavioral and biomechanical changes within a real training environment. Within this same ecological framework, the absence of a control or comparative condition should also be considered. Because the intervention was embedded within the athlete's ordinary training routine, its contribution cannot be fully separated from the broader training context, which included ongoing technical work, strength development, and competitive exposure. Similarly, the comparison across two seasons offers a valuable longitudinal perspective on the evolution of the athlete's behavior over time, but also requires caution when attributing the observed changes to a single factor in isolation. Competitive contextual factors, including tactical adjustments, role evolution, opponent behavior, playing opportunities, and seasonal differences, may also have influenced the match scouting outcomes.

A related limitation concerns the interpretation of the mechanisms potentially underlying the observed changes. The study focuses on the characterization of behavioral and biomechanical changes associated with the

intervention, rather than the direct assessment of specific cognitive components. Variables such as motor imagery engagement, confidence, or other cognitive mechanisms were not directly assessed. Therefore, these processes should not be treated as direct explanatory mechanisms, but rather as possible contributors within the broader set of factors potentially involved in the observed changes.

Finally, the long-term biomechanical follow-up was available only for the Jump Shot, thereby defining the scope of the retention analysis. Within this context, however, the follow-up provides evidence that the post-training motor organization observed for that gesture was still detectable six months later. While this observation cannot be extended to all trained movements, it nonetheless supports the interpretation that at least part of the observed changes was not limited to the immediate post-training phase.

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Data availability Raw data were generated at IN-CNR. Derived data supporting the findings of this study are available from the corresponding author Maddalena Fabbri-Destro on request.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval The study was conducted in accordance with the Declaration of Helsinki. Procedures have been approved by the CNR research ethics and integrity committee (project QUASAR, dated 22 September 2022) and informed consent was obtained from the athlete.

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Authors and Affiliations

P. Presti^{1,2} · A. Ciraolo² · S. Bizzozzi³ · A. Marallo¹ · P. Avanzini² · Fabbri-Destro Maddalena² 

✉ Fabbri-Destro Maddalena
maddalena.fabbridestro@cnr.it

¹ Department of Movement, Human and Health Sciences, Foro Italico University of Rome, piazza Lauro de Bosis, 15, Rome 00135, Italy

² Istituto di Neuroscienze, Consiglio Nazionale delle Ricerche (CNR), via Volturno, 39- E, Parma 43125, Italy

³ Pallacanestro Fulgor Fidenza, via Palmiro Togliatti, 42, Fidenza (PR) 43036, Italy