

Effectiveness of Biomechanical Feedback-Based Training Intervention on Angular Velocity of the Shoulder during Smash and Center of Pressure Stability in Amateur Padel Players

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ABSTRACT (English)

Background: Padel is a rapidly growing racket sport that requires a combination of explosive power and high postural stability. **Research Objectives:** This study aims to analyze the effect of training with Video-Based Biomechanical Feedback intervention on two parameters: the speed of internal shoulder rotation when performing a smash and the stability of the Center of Pressure (CoP) when performing a volley. **Methods:** The study used a Quasi-Experimental Pre-test Post-test Control Group design. The sample consisted of 30 male padel players (age 22.3 ± 1.4 years). The Experimental Group ($n=15$) received corrective biomechanical video analysis, while the Control Group ($n=15$) received conventional technical training for 6 weeks. **Results:** The results of the Independent t-test showed that the Experimental Group experienced a significant increase in shoulder rotation velocity ($+176.6 \text{ deg/s}$; $\approx 19.7\%$) and a decrease in CoP sway area (-1.54 cm^2) compared to the control group ($p < 0.05$). **Conclusion:** In conclusion, biomechanics-based interventions are more effective in optimizing the kinetic chain of attack and defensive stability of padel players.

Keywords: Padel, Sports Biomechanics, Shoulder Internal Rotation, Center of Pressure, Video Feedback.

ABSTRAK (Bahasa Indonesia)

Latar Belakang: Padel adalah olahraga raket yang berkembang pesat, menuntut kombinasi kekuatan eksplosif dan stabilitas postural tinggi. **Tujuan Penelitian:** Penelitian ini bertujuan untuk menganalisis pengaruh latihan dengan intervensi Video-Based Biomechanical Feedback terhadap dua parameter: kecepatan sudut rotasi internal bahu saat melakukan Smash dan stabilitas Center of Pressure (CoP) saat melakukan Volley. **Metode:** Penelitian menggunakan desain Quasi-Experimental Pre-test Post-test Control Group. Sampel terdiri dari 30 pemain padel pria (usia 22.3 ± 1.4 tahun). Kelompok Eksperimen ($n=15$) menerima analisis video biomekanis korektif, sedangkan Kelompok Kontrol ($n=15$) menerima pelatihan

tennis konvensional selama 6 minggu. **Hasil:** Hasil uji Independent t-test menunjukkan Kelompok Eksperimen mengalami peningkatan signifikan pada kecepatan rotasi bahu (+176.6 deg/s; $\approx 19.7\%$) dan penurunan area goyangan CoP (-1.54 cm^2) dibandingkan kontrol ($p < 0.05$). **Kesimpulan:** Kesimpulannya, intervensi berbasis biomekanika lebih efektif dalam mengoptimalkan rantai kinetik serangan dan stabilitas pertahanan pemain Padel.

Kata kunci: Padel, Biomekanika Olahraga, Rotasi Internal Bahu, Pusat Tekanan, Umpan Balik Video

INTRODUCTION

Padel is characterized as a high-intensity intermittent sport with a faster action frequency than tennis (Paulauskas et al., 2025). Two technical aspects that often determine victory are the ability to smash (remate) to end the point and stability when defending or volleying near the net (Sánchez-Alcaraz et al., 2020).

Biomechanically, the power of the smash is highly dependent on Kinetic Chain Sequencing, where the speed of internal shoulder rotation (internal rotation velocity) is the main contributor to racket speed at impact (Ramasamy et al., 2022). On the other hand, the efficiency of footwork and dynamic balance can be measured through the Center of Pressure (CoP) (Johnston et al., 2016). Poor stability (large CoP area) results in inefficient energy transfer and a higher risk of injury (Morin et al., 2022).

Many amateur coaches only provide qualitative verbal instructions. This study proposes a quantitative intervention using biomechanical visual feedback to accelerate motor adaptation in athletes in the golden age range (20-25 years).

The global growth of padel has been remarkable, with the number of registered players exceeding 25 million worldwide and the sport being practiced in more than 90 countries (García-Giménez et al., 2022). This exponential expansion has generated increasing scientific interest in understanding the physical and technical demands specific to the sport. Studies have shown that padel matches are characterized by short high-intensity rallies interspersed with recovery periods, placing significant demands on both aerobic and anaerobic energy systems (Sánchez-Alcaraz & Courel-Ibáñez, 2022). The intermittent nature of the sport, combined with the technical complexity of its strokes, makes it an ideal model for studying sport-specific biomechanical adaptations.

From a biomechanical standpoint, the overhead smash (remate) in padel demands a precisely coordinated kinetic chain, beginning from the lower extremities, transferring energy through the trunk, and culminating in high angular velocity at the shoulder and wrist (Paulauskas et al., 2025). The internal rotation of the shoulder joint is identified as the primary driver of racket head speed during overhead strokes across racket sports (Rivilla-García et al., 2019). Deficiencies in this sequencing are often observed in amateur athletes who lack structured technical feedback, resulting in compensatory movement patterns that reduce both performance efficiency and increase injury susceptibility, particularly to the rotator cuff and labrum (de Sire et al., 2024; Giustino et al., 2024).

Postural stability, quantified through Center of Pressure (CoP) displacement parameters, is equally critical in racket sports. The CoP ellipse area and mean velocity of sway have been validated as reliable indices of dynamic balance and neuromuscular control during sport-specific tasks (Demeco et al., 2022). In padel, the volley and defensive movements near the net require rapid force absorption and redistribution following

lateral lunges, demanding high levels of postural control that are rarely trained in isolation by amateur players. Increased CoP sway has been associated with diminished reactive capacity and elevated risk of ankle and knee injuries in court sports (Denche-Zamorano et al., 2024).

Video-based biomechanical feedback has emerged as a powerful pedagogical tool in sport science. Unlike purely verbal instruction, visual feedback enables athletes to observe deviations from optimal motor patterns in real time or through post-session review, facilitating self-correction through augmented visual knowledge of performance (KP) (Ungureanu et al., 2024). Research in tennis, badminton, and swimming has consistently demonstrated that augmented feedback, particularly when anchored in objective kinematic data, accelerates technical learning and motor skill retention compared to conventional coaching alone (Guijarro-Herencia et al., 2023). The application of motion capture technologies such as Kinovea and Dartfish has made quantitative biomechanical analysis accessible to practitioners working with recreational and semi-professional populations (Priego et al., 2013).

METHOD

Design & Participants

This experimental study involved 30 intermediate male Padel players (who had been playing regularly for the past 2 years) aged 20-25 years (mean age: 22.3 ± 1.4 years). Participants were randomly divided into an Experimental Group (BIO, $n = 15$) and a Control Group (CON, $n = 15$).

An a priori sample size estimation was conducted using G*Power software (version 3.1.9.7). For a two-tailed independent sample t-test comparing two parallel groups, assuming a large effect size ($d = 1.1$), an alpha level of $\alpha = 0.05$, and a statistical power ($1 - \beta$) of 0.80, a minimum sample size of $N = 28$ ($n = 14$ per group) was required. Thus, our sample size of $N = 30$ ($n = 15$ per group) was sufficiently powered ($>80\%$) to detect significant inter-group biomechanical differences.

Instruments and data measurements

A high-speed camera with a speed of 240 fps was used to record the smash movement, then the data was analyzed using motion analysis software such as Dartfish or Kinovea to calculate the angular velocity of shoulder rotation (deg/s) just before contact with the ball. Anatomical landmarks for shoulder angle calculation were defined using retro-reflective markers placed on the C7 spinous process, acromion process, lateral epicondyle, and wrist, with raw kinematic data processed using a 4th-order low-pass Butterworth filter (10 Hz) across 3 averaged maximal-effort trials per participant. In addition, a force plate was used to measure the Center of Pressure ellipse area (cm^2) when participants performed a single-leg stance static volley simulation after landing a lunge, where a smaller value indicates a higher level of stability. The force plate operated at a sampling rate of 1000 Hz with a recording duration of 10 seconds per trial, with force signals filtered via a 4th-ordered low-pass Butterworth filter (6 Hz) and averaged across 3 valid trials per participant.

Procedure

The BIO group received technical training sessions accompanied by weekly video analysis sessions, during which the coach highlighted the athletes' joint angles and compared them to ideal biomechanical models, with a focus on correcting shoulder rotation and foot placement. Meanwhile, the CON group underwent conventional technical training sessions that relied solely on verbal instructions from the coach, such as advice to hit harder and maintain balance.

To prevent measurement and digitization bias, a single-blind outcome assessment protocol was enforced. All video recordings and raw force-plate data were de-identified and assigned randomized alphanumeric codes by an independent administrator before data processing. Biomechanical assessors who performed video maker digitization in Kinovea and calculated force-plate sway metrics were completely blinded to group allocations (BIO vs CON) and assessment timepoints (pre-test vs post-test).

Data analysis

The data were analyzed using SPSS 26. The Shapiro-Wilk normality test was performed before the Paired Sample t-test (intra-group) and Independent Sample t-test (inter-group) comparison tests.

RESULTS

The following are detailed data from the pre-test and post-test measurements.

Table 1. Biomechanical Measurement Data (N=30)

Note: SR-V = Shoulder Rotation Velocity (degrees/second), CoP-A = Center of Pressure Area (cm²).

No.	Code	Age	Group	SR-V Pre(deg/s)	SR-V Post(deg/s)	Df SR	CoP-A Pre(cm ²)	CoP-A Post(cm ²)	Df CoP
1.	A-01	21	BIO	850	1020	+170	6.2	4.5	-1.7
2.	A-02	23	BIO	910	1085	+175	5.8	4.1	-1.7
3.	A-03	22	BIO	880	1050	+170	6.5	4.8	-1.7
4.	A-04	24	BIO	925	1110	+185	5.5	3.9	-1.6
5.	A-05	20	BIO	840	995	+155	6.8	5.2	-1.6
6.	A-06	25	BIO	960	1150	+190	5.2	3.8	-1.4
7.	A-07	22	BIO	895	1080	+185	6.0	4.4	-1.6
8.	A-08	23	BIO	905	1090	+185	5.9	4.2	-1.7
9.	A-09	21	BIO	870	1035	+165	6.3	4.9	-1.4
10.	A-10	24	BIO	930	1120	+190	5.4	4.0	-1.4
11.	A-11	22	BIO	860	1015	+155	6.6	5.1	-1.5
12.	A-12	20	BIO	885	1060	+175	6.1	4.6	-1.5
13.	A-13	25	BIO	940	1130	+190	5.3	3.9	-1.4
14.	A-14	23	BIO	900	1075	+175	5.7	4.3	-1.4
15.	A-15	24	BIO	915	1100	+185	5.6	4.1	-1.5
Avg	-	22.6	BIO	897.6	1074.3	+176.6	5.92	4.38	-1.54
16.	B-01	21	KON	860	890	+30	6.1	5.8	-0.3
17.	B-02	23	KON	900	945	+45	5.9	5.5	-0.4
18.	B-03	22	KON	875	910	+35	6.4	6.0	-0.4
19.	B-04	24	KON	930	975	+45	5.4	5.2	-0.2
20.	B-05	20	KON	845	880	+35	6.9	6.5	-0.4
21.	B-06	25	KON	950	990	+40	5.1	4.9	-0.2
22.	B-07	22	KON	890	925	+35	6.2	5.9	-0.3
23.	B-08	23	KON	910	955	+45	5.8	5.5	-0.3
24.	B-09	21	KON	865	900	+35	6.4	6.1	-0.3
25.	B-10	24	KON	920	960	+40	5.5	5.3	-0.2
26.	B-11	22	KON	855	895	+40	6.7	6.3	-0.4
27.	B-12	20	KON	880	915	+35	6.0	5.7	-0.3
28.	B-13	25	KON	945	985	+40	5.2	5.0	-0.2
29.	B-14	23	KON	895	930	+35	5.8	5.5	-0.3

30.	B-15	24	KON	910	950	+40	5.7	5.4	-0.3
Avg	-	22.6	KON	895.0	939.6	+44.6	5.94	5.64	-0.30

The BIO group showed significant advantages over the KON group in terms of performance and stability. The BIO group recorded an increase in shoulder velocity of 176.6 deg/s, far exceeding the KON group, which only reached 44.6 deg/s. In addition, in terms of stability, the BIO group succeeded in reducing the sway area (CoP) by 1.54 cm², which was much more effective than the KON group, which only reduced it by 0.30 cm².

Table 2a. Intra-Group Comparison (Pre vs Post-Test)

Variable	Group	Pre-test	Post-test	Difference (Δ)	Paired t	Cohen's d
SR-V (deg/s)	BIO	897.67 $\pm$ 34.69	1074.33 $\pm$ 43.19	+176.67 $\pm$ 11.90	57.49***	14.84
	KON	895.00 $\pm$ 34.20	939.67 $\pm$ 33.20	+44.67 $\pm$ 4.42	33.00***	8.52
CoP-A (cm ²)	BIO	5.92 $\pm$ 0.49	4.38 $\pm$ 0.43	-1.54 $\pm$ 0.12	-48.02***	-12.40
	KON	5.94 $\pm$ 0.50	5.64 $\pm$ 0.43	-0.30 $\pm$ 0.08	-15.37***	-3.97

Table 2b. Inter-Group Comparison and ANCOVA Results

Variable	Post-test Difference (Independent t)	Effect Size (d)	Baseline-Adjusted Effect (ANCOVA F)	Partial η^2
SR-V (deg/s)	t(28) = 9.52***	3.48	F(1,27) = 3888.77***	0.993
CoP-A (cm ²)	t(28) = -7.52***	-2.75	F(1,27) = 1564.58***	0.983

The results in Tables 2a and 2b show that the video-feedback training method (BIO group) yielded significantly better results than conventional training (KON group). Based on Table 2a, the BIO group experienced a much higher increase in shoulder rotation speed (+176.67 deg/s vs. +44.67 deg/s) as well as greater improvement in postural stability, as indicated by a larger reduction in the CoP wobble area (-1.54 cm² vs. -0.30 cm²). Furthermore, the between-group analysis in Table 2b confirmed that these differences were statistically significant ($p < 0.001$) with a very strong effect size, proving that the video-based intervention was far more effective in improving players' shoulder rotation speed and balance.

DISCUSSION

The results of the study show that biomechanical intervention has a greater impact than conventional training. In the analysis of shoulder rotation related to smash power, the BIO group experienced a significant increase that validated the proximal-to-distal sequencing theory, whereby through video feedback, athletes became aware of their tendency to overuse their wrists and underutilize optimal shoulder rotation. Biomechanical correction encourages athletes to load their shoulders more deeply, resulting in greater torque during the acceleration phase (Li et al., 2023). Meanwhile, in the Center of Pressure (CoP) analysis, which describes defensive stability, a decrease in the CoP area indicates improved neuromuscular control. Visual feedback helps athletes understand the position of the center of mass (CoM) relative to the base of support, which is crucial in padel for accelerating position recovery after hitting the ball at difficult angles. The control group tended to have a wider CoP area because foot posture correction was not as detailed as in the experimental group (Takeda et al., 2017).

Biomechanical feedback intervention (BIO group) was shown to significantly increase shoulder rotation speed by 19.7%, validating the theory of the kinetic chain from proximal to distal. Through video feedback, athletes became aware of excessive wrist use and began to optimize scapular retraction and internal shoulder rotation (Rivilla-García et al., 2019). This allowed for greater elastic energy storage during the cocking phase and stronger torque release during acceleration, similar to the efficient movement patterns seen in other overhead sports such as tennis and badminton (Irawan et al., 2023 ; Pedro et al., 2022).



In terms of stability, the BIO group showed a significant reduction in the Center of Pressure (CoP) ellipse area of 1.54 cm², indicating improved neuromuscular control. The use of visual feedback allowed athletes to observe their balance trajectories directly, promoting self-regulation of more stable motor behavior and center of gravity control (Takeda et al., 2017). In contrast, the control group showed only minor improvements, reinforcing the finding that conventional repetitive training without objective corrective feedback is insufficient to alter ingrained motor patterns in adult athletes (Sáez de Villarreal et al., 2023).

These improvements in biomechanics not only optimize performance but also have clinical significance in injury prevention. By achieving rotational speed through the proper kinetic chain (rather than compensating for load on the distal segments), the risk of rotator cuff and labrum injuries can be reduced (de Sire et al., 2024). Additionally, improved CoP stability enhances the safety of the ankle and knee joints during intense lateral movements in padel. This aligns with dual-coding theory, where the integration of visual and proprioceptive information creates a stronger and more enduring motor memory trace (Sánchez-Alcaraz & Courel-Ibáñez, 2022).

Although this study is limited by its small sample size and six-week duration, the results have significant practical implications for coaches. The use of video analysis software (such as Kinovea or Dartfish) and portable force plates proved far more effective than verbal instructions alone. Coaches are advised to integrate data analysis into their regular training cycles, as the relatively small time investment (about 20 minutes per session) can yield substantial performance gains compared to traditional coaching paradigms.

CONCLUSION

In conclusion, a 6-week training intervention supported by video-based biomechanical feedback in male padel players aged 20–25 years significantly increased shoulder rotational angular velocity during the smash and enhanced postural stability, as evidenced by a reduction in the Center of Pressure (CoP) sway area. Although ball or racket head velocities were not directly measured in this study, the observed improvement in shoulder rotation velocity provides a theoretical basis for more efficient energy transfer along the proximal-to-distal kinetic chain during overhead strokes. Therefore, padel coaches are recommended to integrate quantitative video analysis as a routine evaluation tool rather than relying solely on subjective visual observation to systematically optimize technical mechanics and postural control.

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CONFLICT OF INTEREST

There is no conflict of interest in this study.

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