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Smart-Rings Biomechanical Feedback: An Innovative Training System for Iron Cross Performance

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Abstract

Background: The performance of iron crosses on the rings is usually evaluated by visual judgment but the existence of significant execution errors like the asymmetry of bilateral forces, ring vibrations, slow stabilization, and ineffective geometry of the upper limb can go undetected under normal observation.

Purpose: This paper compared an apparatus-embedded smart-rings feedback system and tested the hypothesis that real time bilateral force feedback was linked to better iron cross performance, maintained control following feedback withdrawal, and cross over to competition valid rings.

Methods: Five elite male artistic gymnasts took part in one-group applied experimental study consisting of pre-test, post-test, feedback-free retention, and transfer evaluation using legal-rings. Sensorized rings with independent 0-200 kg compression load cells, wireless right/left/total force display, synchronized 240 fps video and surface EMG was a descriptive support channel in the three-month intervention.

Results: Calibration was found to be highly linear with a high retest stability, 0.38 N mean absolute error, 0.11% mean relative error, 200 Hz force sampling and 6.4 ms mean force-video delay. Total external force remained essentially stable, whereas bilateral asymmetry decreased from 4.94 +/- 0.35% to 2.22 +/- 0.24%, ring oscillation decreased from 7.56 +/- 0.24 degrees to 4.85 +/- 0.22 degrees, hold time increased from 3.23 +/- 0.14 s to 4.05 +/- 0.16 s, and technical score improved from 7.87 +/- 0.24 to 8.76 +/- 0.31.

Conclusion: The smart-rings system seems to be a handy diagnostic and coaching platform within the confines of a small-sample, one-group applied design. It was primarily useful in enhancing the organization of forces, bilateral symmetry, stability of the apparatus and executing iron crosses that could be judged as opposed to raising the output of raw force.

Keywords: Biomechanical feedback, electromyography, force asymmetry, smart rings and iron cross.

Introduction

The rings are also one of the most demanding equipment in artistic gymnastics among male athletes as they are a combination of the relative strength of the upper body, accuracy of the device, and the ability to maintain the posture on a free movable support structure at all times. In contrast to stable apparatuses, the rings are mobile during the routine, and it is the gymnast who generates big upper-limb moments at the same time minimizing the swing of the rings and achieving symmetrical loading. The strength-hold and transitions into strength holds elements, the iron cross remains one of the most obvious pieces of evidence of the upper-body strength and technical

control, even in the modern system of FIG judging (FIG, 2023, 2025a, 2025b, 2025c; Zhou and Yang, 2025). The iron cross does not merely give an examination of the greatest strength. To be effectively applied, bilateral force, nearly full extension of the elbow, correct positioning of the shoulder, minimum deviation of the trunk and a stable grip that is long enough to fulfill judging requirements. The application of visual observation and verbal feedback usually helps to correct these requirements in applied coaching situations. However, visual inspection might not be a reliable way of identifying the presence of mechanical causes, which are not transparent, such as imbalance of right-left forces, high variability of forces, slower than expected stabilization, or minuscule vibrations of the ring. This is of special interest to high-level gymnasts, whose further development may depend not so much on the increase of the force as on the increased stability and measurability of the technical position of the high force capacity (Đorđević et al., 2023; Malíř et al., 2023; Merz et al., 2025; Schärer et al., 2025). The recent developments in the field of sports biomechanics have encouraged the use of portable and apparatus specific measurements systems that can provide feedback on ecologically valid training practices. In the case of still rings, this method is especially applicable since the force generation, body posture and the movement of the apparatus are closely interconnected with each other. This may be achieved by adding the force measurement to the rings, and recording both of them simultaneously with a high-speed video and surface EMG, which would allow coaches to correlate the distribution of force externally, movement geometry, and ring stability with neuromuscular activity in the same attempt of the same skill. In this regard, a smart-rings feedback system was tested in this study that allows the visualization of the right-ring, left-ring, and total force signals in real-time and aligns the outputs with high-speed video and EMG. This study determined that this system was related to an increase in bilateral force symmetry, decreased ring oscillation, increased hold duration, technical score, and retention and transfer of the learned control strategy with feedback-free legal-rings conditions (Baca et al., 2022; Hribernik et al., 2022; Fujihara, 2023; García-Pinillos et al., 2024).

Research Problem

Coaches and judges tend to judge iron cross performance on still rings by seeing the performance. Nevertheless, there are a number of mechanical sources of execution error that can be difficult to observe on routine observation, such as bilateral force asymmetry, slight ring oscillation, slow stabilization, inefficient shoulder-elbow position, and disorganized neuromuscular firing. This restricts the accuracy of coaching feedback and results in it being hard to determine whether a failed or deducted iron cross is due to the lack of sufficient force, improper force distribution, unstable ring control, or to inefficient body alignment. As such, the research question was to ascertain whether a smart-rings system that integrates real-time bilateral force feedback, synchronized high-speed video and EMG assistance could uncover these invisible mechanical cues and aid in the execution of iron cross in high-level male artistic gymnasts.

Research Objectives

The research aimed to establish the measurement credibility of the smart-rings system embedded in the apparatus; test whether the apparatus-embedded system affected the iron cross performance; and test whether the apparatus-embedded system changed right-ring, left-ring and total external force; estimate the shoulder, elbow and forearm loading during the accepted hold phase; use EMG %MVC as a synchronized

quantitative descriptive measure of neuromuscular timing; and develop a coaching-focused interpretation model, linking force symmetry, ring oscillation, hold time, alignment and technical deductions; add a feedback-free retention test to determine whether post-intervention gains were maintained until 30 April 2026; and add a legal-rings transfer test to determine whether gains learned on the smart-rings system were transferred to competition-valid conditions.

Research Hypotheses

It was anticipated that a smart-rings feedback intervention would be linked to less bilateral asymmetry, less ring oscillation, better official hold time and technical score, and better shoulder-elbow-trunk alignment with no significant increase in total external force. These gains were also anticipated to be observable at the time of feedback-free retention test on 30 April 2026 and legal-rings transfer testing. Shoulder was supposed to be the dominant part of the upper-limb kinetic chain. EMG %MVC was considered a descriptive neuromuscular channel that aids in the interpretation of mechanical economy and not a direct measure of internal joint loading.

Scope of the Study

The human aspect was narrowed to high level male artistic gymnasts who could take up the iron cross. The timeline took into account the pre-test calibration processes on 10 January 2026, the actual pre-test on 11 January 2026, the three-month intervention between 12 January and 12 April 2026, the post-test on 1213 April 2026 and finally the feedback free retention and transfer test on 30 April 2026. The area covered was Al-Shaheed Samir Khammas Hall in Baghdad Governorate. The topical area was confined to iron cross execution on still rings with legal rings pre-test, post-test, retention test and transfer test and the smart-rings system to conduct the training intervention.

Method

Design and Participants

The design of this study was one-group applied experimental design; it included pre-test, post-test, feedback-free retention and legal-rings transfer measurements. The design was chosen due to the fact that the study was carried out within applied high-performance gymnastics setting, where there is a natural scarcity of advanced male gymnasts who are able to safely perform the iron cross. In this regard, the results were used as a within-sample intervention-related change and not as a conclusive population-level or causal effects. The sample comprised of five advanced men artistic gymnasts who specialized in men artistic gymnastics. Testing and calibration were done in Al-Shaheed Samir Khammas Hall in Baghdad Governorate. Legal still rings were assessed by official pre-test, post-test, retention-test, and transfer-tests and the training intervention over three months utilized the smart-rings feedback system. Three consecutive attempts per testing phase to minimize the impact of attempt to attempt variability and selection of the best trial was used. The average score of the three attempts was considered to be the main value to be used in analysis, and in-session changes in the three attempts were considered to be the secondary value in order to analyze the immediate feedback response. This research was understood as an applied experimental study with reports on within-sample results on the credibility of measurements, coaching application, and within-athlete performance change. The design is capable of detecting practically significant changes that may be linked to the

intervention within the current athletes but not of establishing definitive causality and effects at the population level. The interpretation was thus limited to the current design, sample, apparatus, and procedures. The results of the retention-test and transfer-test in the current study were identified by the responses to the feedback-free legal-rings testing which was also carried out on 30 April 2026 by using the same judging, timing, and video-analysis test protocols as in the pre-test and the post-test. The experiment involves the descriptive neuromuscular outcomes as tabulated EMGs of the monitored muscles as a percentage of MVC, which are interpreted along with aligned force and video displays. The management of data was directed by the level of measurement of each variable. External right-ring and left-ring forces were considered as directly measured variables in the calibrated in-ring load-cell channels in attempts of smart-rings feedback; each channel accommodated a single compression load cell of 0 to 200 kg (0 to 1962 N) per-ring, and force was summed across both channels. These force traces were measured to determine bilateral asymmetry, force-time variables and variability measures. Shoulder, elbow and forearm forces and moments, in contrast, were considered as model-based approximations that used synchronized ring-force measurements and video-based segment geometry. EMG %MVC signals were considered to be synchronized descriptive neuromuscular signals and not internal joint force measures. This difference was preserved during interpretation, to prevent an overstatement of the joint-level quantities or EMG patterns as a direct demonstration of tissue loading at the internal level or statistically validated muscle-level change.

Table 1. ***Sample characteristics and thirteen-week training structure***

Panel A. Sample characteristics of the advanced male artistic gymnasts

Variable	Mean	+/- SD	Range
Age (y)	22.4	1.3	21-24
Height (cm)	167.2	4.1	163-172
Mass (kg)	64.8	3.2	61.5-68.5
Body weight (N)	635.6	31.4	603.3-671.9
Training age (y)	12.5	1.8	10-15

Panel B. Three-month training structure used in the manuscript

Period	Objective	Main content	Dose and dates
10 Jan 2026	Calibration	Zeroing, channel identity, camera/EMG setup, synchronization, familiarization.	Before testing
11 Jan 2026	Pre-test	Official iron cross evaluation on legal still rings by certified judges.	Legal rings
12 Jan–1 Feb 2026	Preparation	Scapular control, support holds, assisted cross drills, grip work.	3 units/week
2 Feb–22 Feb 2026	Specific strength	Eccentric lowering, controlled entries, short holds, video correction.	3 units/week
23 Feb–15 Mar 2026	Feedback focus	Smart-rings full holds with right-left force correction.	3 units/week
16 Mar–12 Apr 2026	Transfer preparation	Integrated attempts, controlled exits, competition-style consolidation, and gradual reduction of dependence on the display.	3 units/week

Period	Objective	Main content	Dose and dates
12-13 Apr 2026	Post-test	Official iron cross evaluation on legal still rings.	Legal rings
14–29 Apr 2026	Feedback-free interval	No smart-rings feedback; maintenance work only to avoid immediate screen-supported performance.	No feedback
30 Apr 2026	Retention and transfer test	Feedback-free iron cross evaluation on legal still rings to verify durability of learning and transfer from smart rings to the legal apparatus.	Legal rings; no feedback

Anthropometric profile depicts a small but advanced performance sample that has a body mass of 61.5-68.5 kg, average age of 22.4 years, and extensive training experience. This profile is applicable since enhancement of such a group is more probable to be a reflection of improved arrangement of movement, force, and muscle action as opposed to fundamental mastery.

Research Tools

The apparatus-specific measurement platform involved in the study included two sensitized rings, independent 0-200 kg compression load cells (circa 0-1962 N/ring), a wireless display of right-ring, left-ring and total-force feedback, synchronized high-speed video at 240 fps, and surface EMG of select upper-limb and shoulder-girdle muscles. The design of the system was to maintain the functional feel of still-rings training but to have a direct monitoring of bilateral loading during the iron cross. The evaluation of legal still rings in terms of official pre-tests, post-tests, retention-tests, and transfer-tests was performed, but the smart-rings system was applied during the training intervention and feedback attempts.

Pilot Study

Calibration steps were done, such as unloaded zeroing, known-load checks within the anticipated working range, checking the identity of right-left channels, repeated loading and unloading to test hysteresis, reporting linear-regression, calculation of absolute and relative errors, checking zero-drift, percentage packet-loss, and force-video synchronization delay. The following values were identified as a system-level measurement indicator of the current prototype and they were employed to justify supervised applied interpretation as opposed to formal structural certification.

Pre-test Calibration and Safety Protocol

Prior to testing and training, the smart-rings system was standardized in terms of calibration and safety. The process involved an inspection of the ring shell, grip layer, straps, clips, screws, suspension points, and internal base area; verification of the battery status and wireless transmission; unloaded zeroing of both channels; confirmation of the identity of right and left channels and a short known-load test within the anticipated working range. These measures ensured a decreased risk of considering sensor drift, channel reversal and structural instability to be real bilateral force asymmetry. Display, start command, holding criteria and repeated-attempt sequence were introduced to athletes and coaches. Only qualified coaching supervision allowed the use of the system and abnormal mechanical sound, observable wear, unstable signal, or suspicious channel response necessitated termination of the trial and re-inspection and re-calibration before the system could be used again.

Mechanical Safety Check and Prototype Acceptance Requirement.

Since the prototype will be utilized in a high-loading suspended strength element, calibration of measurements is not enough to be widely deployed. Mechanical safety verification was thus considered as a distinct requirement as compared to metrological verification. The calibration results available were supportive of supervised applied use in the current study but it cannot be deemed to be a replacement of formal structural certification. Future versions must be independently mechanically tested, static and cyclic loads checked, fatigue screened, side-load sensitivity checked, environmentally exposed and, before any unsupervised and commercial or wide-scale use, safety-factor reporting by a qualified mechanical engineer or approved testing facility must be documented.

Table 2B. ***Recommended mechanical testing and acceptance criteria before wider deployment***

Test domain	Recommended procedure	Acceptance criterion
Static load test	Apply loads above the maximum expected training load to each ring and to the assembled pair for a defined holding period.	No permanent deformation, cracking, fastener loosening, shell separation, or unacceptable post-test zero shift.
Dynamic loading test	Apply repeated loading and unloading cycles that simulate entry, hold, and exit phases of still-rings strength elements.	No increase in structural play, no abnormal noise, no loss of sensor linearity, and no progressive drift.
Fatigue screening	Expose the assembled ring, internal load path, base, fasteners, and suspension interface to repeated cycles representative of training use.	No observable fatigue cracks, movement of fasteners, or loss of grip-layer, or reduction of load-transfer consistency.
Side-load sensitivity	Apply controlled off-axis or asymmetric loads to verify that the structure and load-cell mount do not generate misleading readings.	Readings remain within a defined tolerance or the limitation is documented and excluded from interpretation.
Impact/incident inspection	Once fallen, collided, dropped the device or caused abnormal overload, discontinue use and recheck and recalibrate.	Device returns to service only after full mechanical inspection, zero check, known-load check, and channel verification.
Environmental exposure	Test the influence of sweat, chalk, cleaning, the heat of battery on the grip layer, wiring, and electronics enclosure.	No loss of grip integrity, no exposed wires, no battery instability, and no moisture-related signal disturbance.
Safety factor documentation	Define a minimum safety factor between the expected maximum load and the verified non-failure load of the final assembly.	Safety factor is explicitly reported before wider use; supervised prototype use should remain conservative until formal certification.

These steps are documented as prototype safety-control measures and future certification measures. The current research thus views the tool as a controlled research and coaching pilot and not a validated commercial training tool.

Innovative Smart-Rings Biomechanical System

The smart-rings system is designed as a mechanical-electronic measurement chain, supervised still-rings training for apparatus-specific applications. Each ring had its own compression type load cell with a capacity of 0-200kg which is about 0-1962N per ring. In the iron cross the external load applied by the gymnast was transferred through the area of hand–contact, the outer ring shell and anti-slip contact layer, to the internal metallic load path and finally to the compression load cell on a stable internal

base. For the interpretation of the right-ring and left-ring forces, it was important that the load-path organization was applied. Bilateral force feedback is not only a function of sensor specification, but also requires stable mechanical transfer of the applied load to the sensing element. The prototype was therefore considered to be a full measurement chain from hand contact to mechanical load transfer to force sensing to signal amplification to digital processing to wireless transmission to real-time display to synchronized video to coaching interpretation. The real-time system presented information on the left ring force, right ring force, and the resultant of the external forces. These values were analyzed in conjunction with simultaneous high-speed video and surface EMG to inform applied coaching decisions during the training intervention. It was not the intent of the system to be a replacement for the technical coaching judgment, but rather to give objective mechanical information that would not be noticeable by observation alone, specifically bilateral force asymmetry, high force variability, ring oscillation during the accepted hold phase.

Table 2A. ***Engineering components, proposed materials, and measurement-safety function***

Component	Prototype material or specification	Measurement and safety function
Outer ring shell	Hardwood such as beech/birch or fiber-reinforced polymer in later versions; circular grip near the conventional ring feel.	Preserves the gymnast's familiar grip sensation, distributes the initial hand pressure, and protects the internal structure.
Anti-slip contact layer	Thin TPU, polyurethane, or engineered rubber resistant to sweat, chalk, and repeated friction.	Reduces local slip, improves repeatability of hand contact, and helps transmit load smoothly to the internal structure.
Internal metallic load path	Stainless steel or strengthened aluminum alloy such as 6061/7075, with symmetric holes and smooth edges.	Collects the circumferential load and directs it toward the load cell while limiting unwanted deformation.
Compression load cell	Compression-type strain-gauge load cell rated at 0–200 kg, equivalent to approximately 0–1962 N per ring, with calibration traceability when available.	Converts mechanical load into an electrical signal; should be mounted to minimize side loading and bending moments.
Internal base and fasteners	Machined metallic base with high-quality screws, washers, and defined tightening procedure.	Maintains sensor alignment, prevents internal movement, and protects electronics from impact or unintended contact.
Wireless electronics	PCB with amplifier/ADC, microcontroller, wireless module, battery, voltage regulation, and protected wiring.	Amplifies, digitizes, filters, timestamps, and transmits the force signal while preserving stable zero and low packet loss.
Receiver/display unit	Digital display with separate right, left, and total-force fields plus zeroing and trial-start controls.	Turns measurement into immediate coaching feedback and reduces the risk of interpreting the wrong channel.
Suspension and video support	Load-rated straps/connectors, stable display stand, and frontal/sagittal high-speed video positions.	Maintains safe suspension, keeps equipment outside the fall zone, and links force values with movement geometry.

BTS FREEEMG Surface EMG System

The study included the BTS FREEEMG system as a synchronized supportive channel for the surface electromyography (sEMG) component of the study recording muscle activity during the execution of iron cross. BTS FREEEMG is a wireless surface EMG system, which is based on the use of small lightweight miniaturized probes positioned on the skin above the target muscles. Its wireless and compact design was suitable for still-rings testing since it permitted the recording of muscle-activity during the skill without interfering with the movement of the gymnast's shoulder,

elbow, trunk or grip and without changing the natural pattern of the skill, the iron cross (BTS Bioengineering, 2026). Raw EMG signals were processed using the standard digital procedures to ensure the accuracy of the signals and to minimize noise from repeated ring contact, sweat, and movement. Processing included band-pass filtering (20-450 Hz), full-wave rectification, signal smoothing and normalization (%MVC). The high stability and relatively low standard deviations of the EMG outcomes were due to this rigorous processing and enabled the normalized values to be used as descriptive indicators of neuromuscular efficiency during the accepted hold phase. It was used to assist in the interpretation of neuromuscular organization and not in place of force and video measurements. Therefore, EMG data were analyzed in conjunction with right-ring force, left-ring force, total force, high-speed video, ring oscillation, hold time, and technical score. The positioning was crucial because the internal force of the joint or the stress on the tendon or loading of the tissue cannot be measured directly by surface EMG, but instead, the muscle's electrical activity that is being measured is representative of its involvement. Both force channels were zeroed and tested with reference loads prior to formal testing. The video, force and EMG signals were synced to allow for the interpretation of external force changes in conjunction with the shoulder angle, elbow extension, trunk lean, ring oscillation and timing of muscle activation. Table 2 summarizes the main apparatus, calibration, synchronization, EMG and safety indicators. gives an integrated visual representation of the experimental configuration used in smart-rings feedback sessions. The two sensorized rings, the real-time bilateral force display, synchronized 240 fps video recording, BTS FREEEMG wireless sEMG support and the analysis computer for time-synchronized biomechanical interpretation are shown. This set up enabled the right-ring force, left-ring force, total force, body alignment, ring oscillation and neuromuscular activity to be seen as one synchronized feedback system instead of as singular measures.

Figure 1. *Experimental configuration of the smart-rings biomechanical feedback system, showing the two sensorized rings with independent 0–200 kg compression load cells (approximately 0–1962 N per ring), real-time bilateral force display (Newtons), synchronized 240 fps high-speed video, BTS FREEEMG wireless surface EMG system, data synchronization pathway, and analysis computer used for time-synchronized biomechanical interpretation.*

In the component overview, the prototype of the smart-rings was explained as an entire mechanical-electronic chain of measurements. The gymnast exerts an external load that is transferred to the metal internal structure through the wooden outer shell and the anti-slip contact layer and on to the integrated load sensor and independent compression load-cell pathway in each ring. The maximum rated capacity of each in-ring sensor is 0–200 kg, approximately 0–1962 N per ring. The electronic module handles the signal and sends it wirelessly to the display unit, where values of left-ring, right-ring and total-force are displayed in real time.

Figure 2. *Combined overview of the smart gymnastics ring system components, including the outer ring shell, anti-slip layer, internal electronics and battery, integrated load sensor, inner metal structure, electronics unit, display unit, and suspension straps and hardware.*

Figure 2A *shows the proposed structure pathway of the suspension strap and mounting interface to the wooden shell, anti-slip liner, internal stainless-steel load path (load), load sensor, independent 0200 kg compression load cell (approximately 01962 N per ring), electronic module and rechargeable battery. This visual fact is underpinning the interpretation that not only sensor calibration, but also consistency*

in transferring mechanical loads using the entire assembly of the ring is valid in measurement.

Figure 2A. *Smart gymnastics ring prototype Exploded component system with proposed mechanical load path, integrated sensor structure, electronics, a rechargeable battery, suspension mount, suspension strap, and included accessories.*

Table 2. ***The elements of the smart-rings system, calibration, synchronization and safety checks.***

System/procedure	Verification result	Interpretation/use in the study
Sensorized rings and load cells	Stable zero; channel identity confirmed; brief known-load check before trials	Direct recording of right- and left-ring external force during the iron cross
Wireless display and receiver	Wireless link and channel identity checked before each trial	Concurrent right, left, and total-force feedback for coaching correction
Synchronized high-speed video	Frontal and sagittal cameras positioned consistently; video rate 240 fps; synchronized with force and EMG	Force traces interpreted with shoulder angle, elbow extension, trunk lean, ring oscillation, and EMG timing
Calibration range and linearity	Load-cell capacity 0–200 kg (approximately 0–1962 N) per ring; known-load verification within the study working range; regression slope 1.0001; intercept 0.297 N	Sensor capacity exceeded the expected iron-cross working loads, while known-load verification showed high linearity and low offset within the tested range
Error and reliability	Mean absolute/relative error 0.38 N/0.11%; maximum absolute error 0.75 N; ICC(3,1) = 0.998	Low measurement error and excellent retest stability for applied coaching interpretation
Sampling and synchronization	200 Hz force sampling; mean force-video delay 6.4 ms	Adequate temporal resolution for hold-phase analysis and synchronized interpretation
Safety, drift, and data integrity	Inspection of straps, clips, screws, pivots, and wear before use; zero drift 1.2 N over 10 min; packet loss 0.3%	Acceptable for supervised training sessions with repeated pre-use safety checks

System/procedure	Verification result	Interpretation/use in the study
Analysis software	Total force, asymmetry, CV%, selected kinematic indicators, and export checks	Transparent handling of direct force data and model-based joint indicators
Surface EMG unit	Electrode placement checked during calibration; signal timing synchronized with force and video	Descriptive %MVC evidence for shoulder-girdle and upper-limb activation economy; interpreted with force-video data rather than as stand-alone causal evidence

Figure 3 *describes the calibration and measurement-credibility protocol to ensure that the smart-rings system would be able to offer consistent and interpretable force data when operating in high-load still-rings. Calibration was carried out with zero-load setup, known loads applied in the working range of the study, and the measured force values recorded, linear model fitted and independent loads used to validate the models and the maximum rated capacity of each in-ring load cell was 00200 kg (01962 N) per ring. The fact that the mean absolute error was low, the relative error was also low, force sampling was 200 Hz and the delay between the force-video was small indicated that the system could be used in supervised applied performance analysis.*

Figure 3. *Calibration and measurement credibility of the smart-rings system, showing the experimental setup, component architecture, calibration workflow, linearity curve, performance summary, and synchronized EMG support. Each smart ring contained an independent in-ring compression load cell with a rated capacity of 0–200 kg, equivalent to approximately 0–1962 N per ring. Calibration and validation results showed high linearity, low mean absolute and relative errors, 200 Hz force sampling, and a 6.4 ms mean force-video delay.*

The results of the calibration and verification indicated sufficient stability over the target working range with the in-ring load cells being rated at 0-200 kg (around 0-1962 N) per ring and indicating that the training-related changes are interpretable within the current sample. The official pre-test was carried out on 11 January 2026, training intervention started on 12 January 2026 and lasted until 12 April 2026, post-test was carried out on 1213 April 2026 and feedback-free retention and transfer test was carried out on 30 April 2026.

Main Experiment

The training intervention was three months, between 12 January 2026 and 12 April 2026, and three training units weekly. The program evolved in the preparatory shoulder-girdle control and assisted cross drills to specific strength work, full iron cross attempts with real-time bilateral force feedback, and competition-style consolidation with slowly decreasing dependence on the display. Legal still rings were used in the official pre-test, post-test, retention-test, and transfer-test assessments and in the intervention units the smart-rings system was applied to provide instant feedback of right-left forces. The essence of the program did not lie in adding more load but making it more efficient in terms of quality, i.e. raising the quality of the force generated by athletes as well as the way they distributed and stabilized it. The coaches understood the display along with synchronized video as opposed to a single numerical result. The elevation of one ring was also considered as an indication of side dominance or trunk deviation, and both constant total force and high oscillation were considered as signs of a stabilization problem instead of lack of strength.

Testing Conditions

The measurements were made using the same apparatus and environment at Al-Shaheed Samir Khammas Hall in Baghdad Governorate. Evaluation of the iron cross was conducted as official pre-test, post-test, retention test and transfer test with the same apparatus setting and holding routine in legal still rings. Concurrently, the smart-rings system was utilized during the training intervention to offer feedback and selected feedback attempts were correlated with high-speed video and EMG for biomechanical interpretation. Ring oscillation, ring-distance variance and lateral center-of-mass displacement were primarily quantified from the frontal camera, and shoulder angle, elbow angle, trunk lean and temporal parameters associated with entering and stabilizing in the iron cross from the sagittal camera. To ensure ecological realism in training and to allow for consistent execution, short rest periods were used between attempts. Prior to placement of the probes, the skin covering the muscles to be acquired was prepared to optimize signal quality and minimize signal contamination due to motion. The BTS FREEEMG probes were placed over the anterior deltoid and biceps brachii as these muscles are directly related to positioning of the shoulders, upper limb stabilization and control of the force produced during the iron cross. The wireless probes were verified prior to every recorded attempt to ensure that they remained stable and signals could be seen on the entry, accepted hold phase, and exit. The EMG signal was time locked to the force channels of the smart-rings and the 240 fps high-speed video record. Normalized EMG values were expressed as %MVC and used as quantitative descriptive indicators of the relative muscle activation. These values were not considered as isolated evidence of muscular changes but rather as data that aid in the understanding of whether there was a decrease in excessive activation, smoother force distribution, and improved technical stability with the improved performance.

Retention Test and Transfer Test Procedure

The retention test assessed the persistence of performance gains following withdrawal of feedback and the transfer test assessed the appearance of the movement strategy trained on the smart-rings system in the conditions of competition-valid legal-rings.

Despite the fact that the two tests were conducted without feedback, they dealt with different interpretation questions: retention dealt with the duration of withdrawal; and transfer dealt with performance on the legal apparatus. On 30 April 2026, two and a half weeks after the post-test, feedback-free retention test was performed. In this test, the athletes used the iron cross without the smart-rings feedback and real-time force display. The same judging procedure was also applied and the same hold criteria applied in the official tests on the same date in a transfer test by using the legal still-rings apparatus. These steps were also incorporated to establish whether post-intervention improvements were still evident when feedback was not provided concurrently and whether the control strategy learned was evident as applied in competition-valid conditions. The findings were seen as an indication of supportive evidence in the current applied design as opposed to conclusive evidence of generalized motor learning.

Measured Variables

The dependent variables were aggregated in six groups. The first external-force variable was the total ring force, which was defined as the force applied to both the right and left rings. Secondly, shoulder, elbow and forearm joint force indicators and their relative contribution to the kinetic chain were included in the inverse-dynamics summaries. Third, force-time metrics were: Peak Force, Relative Force, RFD, Impulse, and CV%. Fourth, kinematic and spatial parameters were measured like shoulder angle, elbow angle, lean of the trunk, variance of ring distance, lateral displacement of the center of mass and ring oscillation. Fifth, EMG was not considered as an independent quantitative dependent variable in this study, but rather as a synchronized qualitative support channel in the interpretation of the timing of muscle activity in relation to force and video. Seventh, official hold time, technical deductions and final technical score were performance indicators.

Table 3A. ***Operational definitions and calculation rules for the main study variables***

Variable	Operational definition / calculation	Source	Interpretation boundary
Total external force (N)	Right-ring force + left-ring force during the accepted hold phase.	Direct load-cell recording	External apparatus force only; not internal joint force.
Bilateral asymmetry index (%)	Absolute right-left force difference divided by total force, multiplied by 100.	Calculated from direct force channels	Lower values indicate more symmetrical loading.
Ring oscillation (deg)	Maximum angular deviation of the rings during the judged hold period from synchronized frontal video.	Video-based kinematics	Reflects apparatus stability, not strength alone.
Official hold time (s)	Time for which the iron cross position was maintained according to judging criteria.	Judges + synchronized video	Longer hold supports skill recognition but remains judge-dependent.
Stabilization time (s)	Time from entry into the cross until ring motion and body alignment reached the accepted stable phase.	Force-video synchronization	Sensitive to entry strategy and familiarization.
Technical score	Four certified judges accredited by the Iraqi Central Gymnastics Federation scored blinded, randomized video trials on a 10-point scale; highest and lowest scores discarded; mean of the two middle scores retained.	Judging panel	Inter-rater reliability was verified using ICC to support the official technical-score analysis.

Variable	Operational definition / calculation	Source	Interpretation boundary
CV% of force	Standard deviation of force divided by mean force, multiplied by 100.	Calculated force trace	Lower values indicate smoother force production.
RFD (N/s)	Rate of force development during the entry-to-hold phase.	Calculated force-time trace	Interpret with movement strategy, not as isolated explosiveness.
Joint forces and moments	Model-based estimates from external force and video-derived segment geometry.	Inverse-dynamics estimate	Not direct internal tissue loading.
EMG indicators	Synchronized descriptive %MVC support for selected muscles in this manuscript version.	Surface EMG	%MVC values are reported as descriptive EMG outcomes for the present sample.

Note. Operational definitions were used to standardize variable interpretation and calculation across the study variables.

This multilevel structure was used intentionally. The aim of the research was not merely to report that the athletes improved, but to explain how the improvement occurred: by redistributing force, stabilizing the apparatus, improving joint geometry, and converting those biomechanical changes into fewer execution deductions.

Statistical Analysis

The intervention took place with the qualified supervision of coaches and equipment inspection, zeroing, calibration and safety checks before each session of testing and training took place. The purpose and procedures of the study was explained and participants consented to the anonymous reporting of the data. There were no institutional approval statements for any incomplete. The iron cross was performed technically by four judges who are certified by Iraqi Central Gymnastics Federation. Performance was assessed by blinded video scoring, random trial order and equal viewing conditions to minimize judging bias by comparing performance from recorded video files. The performance was marked out of 10 by each of the judges. The highest and lowest scores were dropped from the list and the middle two scores averaged and used as the technical score for analysis as was done as a standard procedure. Inter-rater reliability was conducted as intraclass correlation coefficient (ICC) to verify the rigor of the judging process, and it was found that there was excellent agreement between the judges, which justified the use of the technical scores kept in the statistical analysis. The same judging procedure was used before and after the intervention.

Pre-Session Operational Safety Checklist

A pre-session checklist was developed to standardize and minimize preventable risk and to maximize the reproducibility of data collection. The checklist was filled out before training or test attempts and was repeated upon any abnormal occurrence, such as a fall, impact, sudden loss of signal or inconsistent reading of the force.

Table 3B. ***Pre-session safety, calibration, and data-readiness checklist***

Step	Required check	Acceptance sign
1	Inspect outer shell and grip/contact layer.	No cracks, sharp edges, swelling, separation, or excessive wear.
2	Inspect straps, clips, screws, suspension points, and internal base region.	No fraying, looseness, corrosion, abnormal gap, or uncontrolled movement.

Step	Required check	Acceptance sign
3	Power on both rings and receiver/display and check battery state.	Battery level and wireless connection are sufficient for the full session.
4	Confirm right-left channel identity using a light manual load on each ring.	Right ring appears on the right channel and left ring appears on the left channel.
5	Zero both channels with the rings unloaded and hanging freely.	Zero remains stable during the pre-trial observation period.
6	Apply a quick known-load or reference-load check before athlete trials.	Displayed value is within the accepted calibration tolerance.
7	Confirm that display, tripod, camera, and cables are outside the gymnast's movement and fall zone.	No equipment can interfere with the athlete, coach, or emergency landing area.
8	Record athlete code, date, device version, and trial number before saving force/video files.	Force data, video, and coaching notes remain traceable to the same trial.

Risk Management Matrix for Supervised Prototype Use

The risk matrix below was added to make it clear that the smart-rings system was a supervised research prototype. These risks do not mean that the measurement approach is not valid but they identify the conditions for stopping the prototype for inspection, recalibration or redesign.

Table 3C. ***Mechanical, electronic, and operational risk controls***

Risk source	Possible effect	Control action
Shell or grip-layer separation	Hand slip, local discomfort, or altered load transfer.	Do not use the ring if separation, swelling, or a raised edge appears; inspect adhesion and repeat load testing.
Side loading of the compression load cell	Nonlinear readings, sensor damage, or false right-left asymmetry.	Use an aligned internal base, inspect the load path, and exclude data if off-axis loading is suspected.
Loose screws, internal base movement, or suspension wear	Unsafe structural condition and unreliable force readings.	Perform pre-session inspection; remove from use after any looseness, abnormal sound, impact, or visible wear.
Wireless packet loss or channel reversal	Loss of feedback, wrong coaching cue, or data gaps.	Verify channel identity before each session; record packet loss; use internal storage or warning signals when possible.
Battery instability or exposed wiring	Signal drift, sudden shutdown, or electrical/thermal risk.	Check battery state, protect wiring, avoid use if heat, swelling, or unstable readings appear.
Display or camera in the athlete's movement zone	Collision risk or obstruction during failed attempts.	Place all equipment outside the fall zone and assign a coach or assistant to supervise the attempt.
Overinterpretation of EMG or model-based joint estimates	Incorrect medical or injury-risk conclusions.	Interpret EMG and joint moments only as supportive indicators, not direct internal tissue-load measurements.

For this five-gymnast advanced-athlete sample (n=5), interpretation was emphasized within the sample through the use of robust small sample procedures. Descriptive interpretation was performed by calculation of the mean +/- SD, percentage change, coefficient of variation, inspection of individual responses. ICC(3,1) was tested for consistency to retest the results and inter-rater ICC was tested to evaluate the agreement between the judges when technical scores were analysed. Friedman's test was applied to scores on the three within-session attempts and may be applied to pre-

test, post-test, and retention-test scores. Exact one-tailed Wilcoxon testing was employed for directional pre-post hypotheses and non-parametric (r) effect sizes were calculated for the key outcomes. Technical score was explored for associations with the Spearman correlations. Transfer-test interpretation concentrated on whether the performance improvement gained during smart-rings training was present under the non-feedback (legal-rings) conditions. Given the small sample sizes for many outcomes, many p values and large effect sizes were interpreted as supportive within-sample statistics representing intervention associated change among the present athletes and not necessarily population level confirmation. Practical interpretation, direction of effect, retaining learning, transfer to legal rings, credibility of measurement were emphasized. A methodological limitation (not definitive proof of causality) was the lack of a control group. EMG %MVC values were input as descriptive neuromuscular outcomes and analyzed in conjunction with the biomechanical and performance variables.

Additional Statistical and Judging Safeguards

Other statistical and judging safeguards were added to enhance the credibility of the technical-score analysis. Inter-rater reliability was calculated using ICC scores from each individual judge and the official technical score (after retaining) was interpreted. All video files were subsequently scored in a blinded (or partially blinded) manner, in the same random order of the trials, and with the same viewing conditions. The primary comparison was made using the mean of the 3 attempts, which helps to minimize selection bias, but, when appropriate to the interpretation of the athlete, the best stable attempt was also included as an applied-performance measure. Since values for athletes are now available, non-parametric effect-size indicators (Wilcoxon) were provided as supportive within-sample statistics for the current sample.

Results

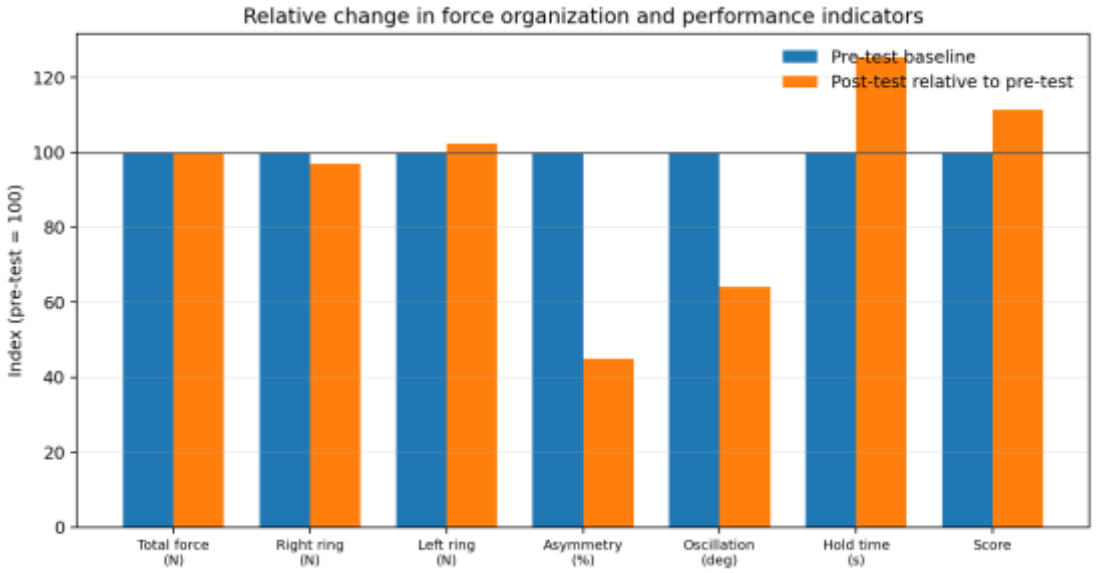
External Force Distribution and Immediate Feedback Response

A feedback response is immediate and external force distribution takes place. The calibration and synchronization results were successful and have been used to support this smart-rings system for supervised application in the current study. The system exhibited high linearity, low mean absolute error, stable zero during the observation period, 200 Hz sampling of the force and a small mean force-video synchronization delay. The following indicators were of importance in order to determine the primary outcome, which required a small force difference to be detected between the right and left and a short duration change during the accepted iron cross hold. A key pre-post finding was that the organization and stability of the means of force production did not change significantly, while the total external force was essentially the same. The total external force did not differ greatly after the intervention (675.6 +/- 52.2 N vs. 672.4 +/- 46.9 N), suggesting that the intervention was not mostly related to an increase in the raw force production. In contrast, bilateral asymmetry decreased from 4.94 +/- 0.35% to 2.22 +/- 0.24%, ring oscillation decreased from 7.56 +/- 0.24 degrees to 4.85 +/- 0.22 degrees, official hold duration increased from 3.23 +/- 0.14 s to 4.05 +/- 0.16 s, and technical score improved from 7.87 +/- 0.24 to 8.76 +/- 0.31. This pattern reinforces the idea that the athletes increased their performance by redistributing and stabilizing the force needed for the skill, instead of by putting more force on the rings. Previous studies have indicated that an improvement in bilateral

asymmetry reflects an improvement in the right/left force organization that occurs during the accepted hold phase. This is a practical application as the gymnast could have sufficient force and still see a decrease in the execution due to side dominance, trunk deviation, or unequal loading. Likewise, a decrease in ring oscillation means greater apparatus stability and lesser corrective oscillation during the hold. An immediate feedback response was seen consistently across three consecutive attempts, within-session analysis. Some improvement in asymmetry and ring oscillation from attempt-to-attempt, and official hold time and technical score. The applied coaching value of real-time feedback is supported by the finding, given that they could provide the athlete and coach with force values displayed in real-time, as well as video information to correct the next attempt. These in-session results, however, must be viewed as changes associated with feedback in the current sport participants and should not be considered evidence of long-term learning by the athletes alone.

Table 3. ***Key biomechanical, kinematic, and performance outcomes***

Figure 4. *Relative pre-post changes in force organization, spatial control, hold time, and technical score. Values are indexed to pre-test to allow variables with different units to be viewed on one scale.*



Domain	Variable	Pre-test	Post-test	Change / statistic	Interpretation
External force	Total force (N)	675.6 ± 52.2	672.4 ± 46.9	-0.47%	Essentially stable
External force	Right-ring force (N)	354.4 ± 27.7	343.6 ± 24.9	-3.04%	Right-side dominance reduced
External force	Left-ring force (N)	321.2 ± 27.1	328.8 ± 24.9	+2.36%	Left-side contribution increased
Symmetry	Asymmetry index (%)	4.94 ± 0.35	2.22 ± 0.24	-55.06%	Improved bilateral organization
Force-time	Peak force (N)	716.9 ± 49.7	693.6 ± 46.2	Lower	Reduction of unnecessary peaks
Force-time	RFD (N/s)	1211.0 ± 46.7	1343.0 ± 51.4	Higher	Improved controlled entry
Force-time	CV% of force	4.50 ± 0.22	2.88 ± 0.19	Lower	Smoother force trace
Kinematic	Shoulder angle (deg)	49.54 ± 0.49	43.46 ± 0.71	Lower	Moved toward recognition zone
Kinematic	Elbow angle (deg)	172.84 ± 0.87	176.76 ± 0.93	Higher	Closer to full extension
Spatial	Ring oscillation (deg)	7.56 ± 0.24	4.85 ± 0.22	-35.85%	Better ring control

Domain	Variable	Pre-test	Post-test	Change / statistic	Interpretation
Spatial	Lateral COM displacement (cm)	6.20 ± 0.47	3.60 ± 0.47	-41.94%	Less lateral deviation
Temporal	Stabilization time (s)	1.24 ± 0.06	0.90 ± 0.06	-27.42%	Faster stabilization
Temporal	Official hold time (s)	3.23 ± 0.14	4.05 ± 0.16	+25.39%	Longer approved hold
Performance	Technical score	7.87 ± 0.24	8.76 ± 0.31	Higher	Improved execution quality
Within-session	Asymmetry index (%)	Attempt 1: 4.94	Attempt 3: 2.24	Significant improvement*	Immediate feedback effect
Within-session	Ring oscillation (deg)	Attempt 1: 7.56	Attempt 3: 4.85	Significant improvement*	Immediate feedback effect
Within-session	Official hold time (s)	Attempt 1: 3.23	Attempt 3: 4.05	Significant improvement*	Immediate feedback effect
Within-session	Technical score	Attempt 1: 7.87	Attempt 3: 8.76	Significant improvement*	Immediate feedback effect
EMG	Activation organization	AD 89.04 +/- 2.41%MVC BB 82.04 +/- 1.86%MVC	AD 78.42 +/- 2.13%MVC BB 71.10 +/- 1.81%MVC	Descriptive decrease	Supports mechanical-economy interpretation

Note. The immediate feedback effect was consistent across the three attempts for all of the within-session variables (Friedman test: $\chi^2 = 10.0$, $p = 0.0067$).

Individual Athlete Responses

Pre-post responses for the key indicators of performance were examined individually to corroborate the results from the small advanced-athlete sample. Bilateral asymmetry, ring oscillation, official hold time and technical score improved in all five gymnasts in the expected direction. This individual pattern that did not vary across the present sample supports the interpretation that the group level changes were not due to a single extreme responder, but rather, a common intervention-associated response of the present sample.

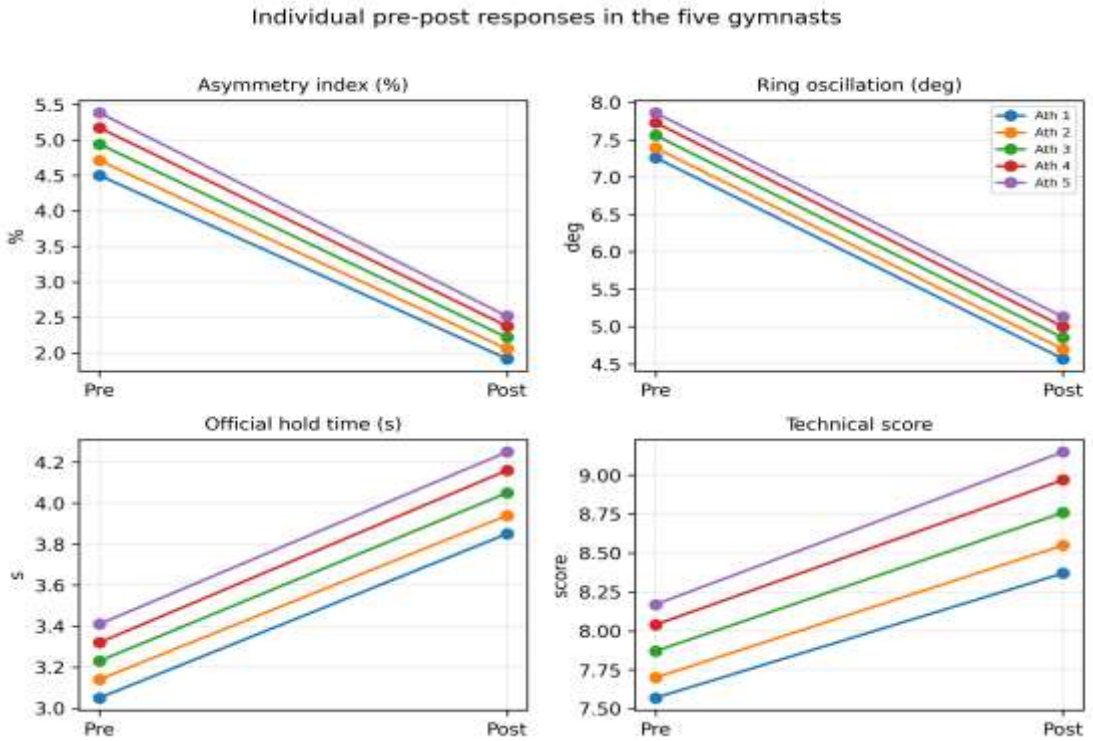


Figure 4A. *Individual pre-post responses for bilateral asymmetry, ring oscillation, official hold time, and technical score. Each line represents one gymnast. Lower values indicate improvement for*

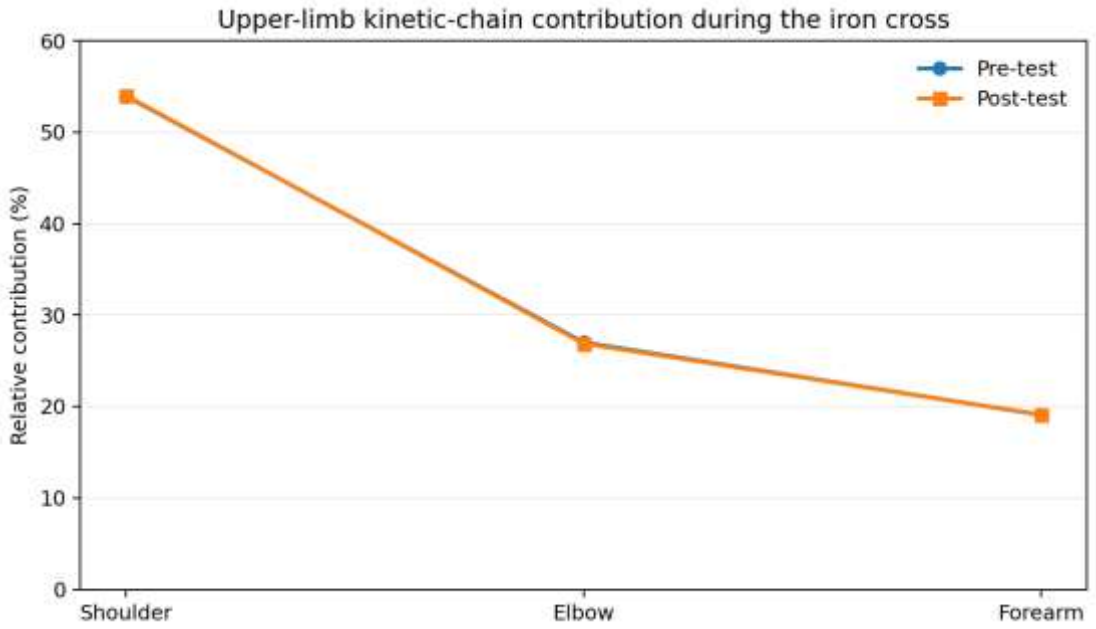
asymmetry and ring oscillation, whereas higher values indicate improvement for official hold time and technical score.

Joint-Level Kinetics

The inverse-dynamics indicators based on external ring-force and video-based segment geometry indicated that the shoulder was still the main segment in the upper-limb kinetic chain during the iron cross. This shoulder region was estimated to contribute about 54% of the kinetic chain contribution, with the elbow and forearm-grip region following. The estimated external force in shoulder, elbow, and forearm decreased slightly from pre-test to post-test, but remained stable with total external force. The pattern facilitated interpretation of the achievement of better mechanical economy, because it seemed as though the athletes were better able to organize their posture, bilateral loading, and ring stabilization without paying any sum greater penalty for doing the same external task. The values should be understood as model-supported kinetic indicators and not as measurement of the force inside or the internal stress in the joint or as an indicator of the risk of joint injuries.

Table 4. ***Joint level kinetics and relative contribution of segments.***

Figure 5. *The iron cross upper-limb kinetic-chain hierarchy: shoulder was still the major contributor prior to and following training.*



Panel A. summary of all the kinetic variables from the joints of the five gymnasts. A tabulation of all joint-level kinetic variables for the five gymnasts.

Variable	Pre-test (mean ± SD)	Post-test (mean ± SD)	Change (%)
Shoulder joint force (N)	1452.6 ± 140.0	1387.6 ± 121.7	-4.48
Elbow joint force (N)	727.8 ± 72.7	690.7 ± 64.9	-5.10
Forearm force (N)	514.1 ± 52.3	491.5 ± 46.9	-4.41
Shoulder moment (N·m)	227.7 ± 23.7	217.5 ± 21.1	-4.50
Elbow moment (N·m)	34.2 ± 3.4	31.0 ± 2.8	-9.53

Panel B. The upper-limb segments and their role with respect to the kinetic chain

Segment	Pre-test contribution (%)	Post-test contribution (%)	Functional meaning
Shoulder	53.92	54.01	Primary load-bearing and alignment center
Elbow	27.01	26.87	Stiffness, extension control, and force transfer
Forearm	19.08	19.12	Grip-mediated transfer and terminal stabilization

Electromyographic (EMG) Indicators

The neuromuscular organization during iron cross execution was interpreted with the help of surface electromyography (EMG), which served as a synchronized descriptive channel to aid interpretation. EMG signals were band-pass filtered, full-wave rectified, and smoothed and normalized to maximum voluntary contraction (%MVC). The normalized values were viewed along with the force, video and performance results instead of as independent findings of muscle-level adaptation. The anterior deltoid decreased from 89.04 +/- 2.41%MVC to 78.42 +/- 2.13%MVC, and the biceps brachii decreased from 82.04 +/- 1.86%MVC to 71.10 +/- 1.81%MVC. A combination of these lower values of %MVC with stable total external force, less bilateral asymmetry, less ring oscillation, increased hold time and higher technical score leads to the interpretation of better neuromuscular economy and less excessive compensatory activation during the accepted hold phase. Since the EMG was a wireless device in a small size and directly over the muscles under observation, these records were made without visually or mechanically disturbing the iron cross attempt. However, EMG results are a descriptive indicator, not to be taken as the direct indications of internal joint loading, tendon stress or tissue-level adaptation.

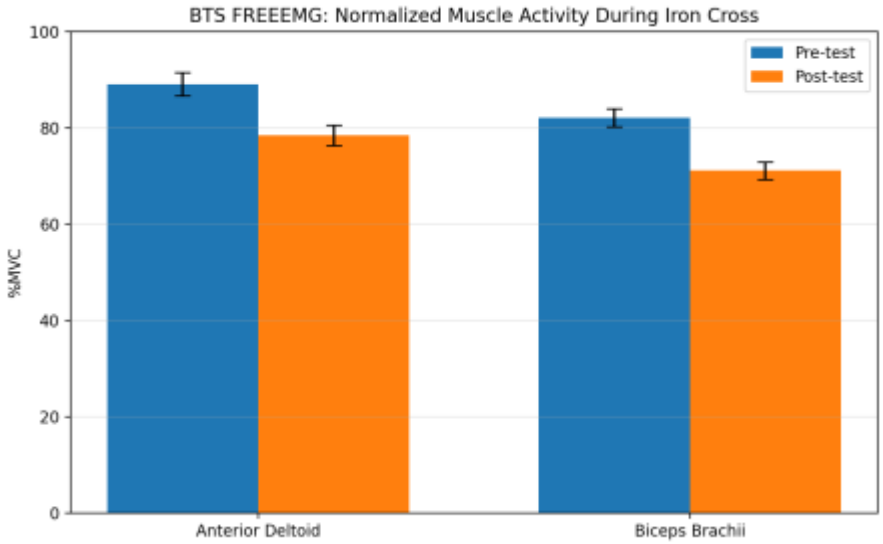


Figure 5A. *BTS FREEEMG normalized muscle activity during the iron cross. Pre-test and post-test %MVC values are shown for the anterior deltoid and biceps brachii.*

Note. Values are %MVC outcomes, not raw EMG traces, and should be interpreted with the synchronized force and video findings.

Force-Time, Kinematic, and Spatial Outcomes

The post-test profile reflected reduced unnecessary force peaks, increased RFD, increased impulse and decreased force variability. Kinetically, the shoulder migrated towards the "recognition zone" defined by the FIG guidance, with body-line

alignment and the elbow extension making improvements. The external-force outcomes, shown in Table 3, include these force-time, kinematic, spatial and temporal indicators. Taken together, these findings indicate that in the group of athletes, there was a greater organization of the timing of force production, upper-body geometry, and spatial instability control. This change in multiple domains is a possible answer to the question of why execution quality improved while there was little change in total external force.

Technical Evaluation and Inferential Outcomes

The technical score had also been enhanced since deductions on the principal execution were reduced. Four qualified judges, recognized by the Iraqi Central Gymnastics Federation, scored it on a scale of 10 with the greatest and lowest score being thrown out and the average of the other two scores being taken. Precise Wilcoxon testing of within-sample enhancements were in asymmetry, oscillation, hold time, technical score, shoulder angle, elbow angle, trunk lean, shoulder moment, RFD, and CV% but total force was not significant. These inductive conclusions are reported as supportive within-sample statistics, as opposed to confirmation on a population level. Table 5 summarizes the most appropriate technical and inferential results.

Table 5. ***Technical evaluation and key inferential outcomes***

Outcome	Main result	Statistical support	Interpretation
Technical score	7.87 ± 0.24 to 8.76 ± 0.31	Wilcoxon p=0.0312	Improved execution quality
Asymmetry index	4.94 ± 0.35% to 2.22 ± 0.24%	Wilcoxon p=0.0312	Improved bilateral force organization
Ring oscillation	7.56 ± 0.24° to 4.85 ± 0.22°	Wilcoxon p=0.0312	Better apparatus stability
Official hold time	3.23 ± 0.14 s to 4.05 ± 0.16 s	Wilcoxon p=0.0312	Longer recognized hold
Shoulder-angle deduction	0.59 ± 0.05 to 0.30 ± 0.05	Descriptive	Clear reduction
Elbow-flexion deduction	0.34 ± 0.03 to 0.20 ± 0.03	Descriptive	Clear reduction
Ring-oscillation deduction	0.72 ± 0.05 to 0.38 ± 0.08	Descriptive	Marked reduction
Total force	675.6 ± 52.2 N to 672.4 ± 46.9 N	Wilcoxon p=0.4375	Not statistically significant
Correlation with technical score	Hold time rho=0.90; shoulder angle rho=-0.90	p=0.037 for both	Supports focus on duration and shoulder geometry
Judging procedure	Four certified judges accredited by the Iraqi Central Gymnastics Federation; blinded randomized video scoring; 10-point scale	Highest and lowest scores discarded; mean of the two middle scores retained; inter-rater ICC indicated excellent reliability	Reduces judging bias and supports the credibility of technical-score analysis
EMG interpretation	Synchronized descriptive %MVC support	AD: 89.04 +/- 2.41 to 78.42 +/- 2.13%MVC; BB: 82.04 +/- 1.86 to 71.10 +/- 1.81%MVC	Supports reduced excessive activation; confirm with raw traces and larger samples
Design limitation	One-group applied experimental design	Within-sample interpretation	Results are bounded to the measured intervention period and present sample
Retention test	Feedback-free test conducted on 30 Apr 2026; gains largely maintained	Asymmetry 2.45 ± 0.30%; oscillation 5.10 ± 0.25°; hold time 3.85 ± 0.15 s; technical score 8.55 ± 0.25	Supports durability after withdrawal of real-time feedback
Transfer test	Legal-rings transfer test conducted on 30 Apr 2026	Asymmetry 2.60 ± 0.32%; oscillation 5.25 ± 0.30°; hold time 3.80 ± 0.18 s; technical score 8.45 ± 0.28	Supports transfer from the smart-rings training device to competition-valid rings

Retention and Transfer Outcomes

The feedback-free retention test on 30 April 2026 indicated that there were minor retrogressions of the post-test values, but overall biomechanical and technical indicators were evidently improved compared to the pre-test baseline. Bilateral asymmetry was 2.45 +/- 0.30%, ring oscillation was 5.10 +/- 0.25 degrees, official hold time was 3.85 +/- 0.15 s, and technical score was 8.55 +/- 0.25. The interpretation that the better control pattern occurred when using feedback-free competition-valid apparatus conditions was also supported by the legal-rings transfer test. Asymmetry was 2.60 +/- 0.32%, ring oscillation was 5.25 +/- 0.30 degrees, official hold time was 3.80 +/- 0.18 s, and technical score was 8.45 +/- 0.28. These results confirm the explanation that more effective force-distribution and stabilization strategy was retained and transferred by the athletes following the intervention. Nevertheless, due to the one-group applied design of the study, retention and transfer results are to be seen as the evidence of the long-lasting intervention-related change in the current sample as opposed to the evidence of the generalized motor learning.

Table 6. ***Retention and transfer test outcomes on 30 Apr 2026***

Variable	Pre-test	Post-test	Retention Test (Feedback-free)	Transfer Test (Legal rings)
Asymmetry index (%)	4.94 ± 0.35	2.22 ± 0.24	2.45 ± 0.30	2.60 ± 0.32
Ring oscillation (deg)	7.56 ± 0.24	4.85 ± 0.22	5.10 ± 0.25	5.25 ± 0.30
Official hold time (s)	3.23 ± 0.14	4.05 ± 0.16	3.85 ± 0.15	3.80 ± 0.18
Technical score	7.87 ± 0.24	8.76 ± 0.31	8.55 ± 0.25	8.45 ± 0.28

Discussion

Measurement Credibility and Apparatus-Specific Feedback

The calibration and synchronization tests show that the prototype was highly linear, had low error, and reasonable stability in the current applied training scenario and sensor specification was reported separately as 0-200 kg rated capacity (approximately 0-1962 N) per in-ring load cell. Since the intervention was concerned with small differences between the right and left, as well as brief hold phases, these checks had to be made prior to interpreting the training results. The EMG channel was a synchronized descriptive overlay, but the system is said to be an overseen research prototype; joint-level measures are seen as model-supported estimates, and EMG %MVC measures are seen as synchronized descriptive neuromuscular measures instead of direct measures of internal joint stress.

Instead of force magnitude, force organization.

The key conclusion is that there was little change in total external force but stability of force and distribution was enhanced. This makes mechanical sense since the iron cross makes the gymnast hold almost body weight, though higher performance is achieved by manifesting that strength with less asymmetry, less jagged lines, and greater control of the ring. This decrease in asymmetry index (4.94% to 2.22% indicates that the real-time display was linked to a lower right-left force imbalance during the skill per se. This type of feedback is useful in that the imbalance of bilateral forces cannot be easily measured reliably by visual observation only. The combination of the better CV percentage, lower peak force and even lower ring oscillation suggests a better planned entry and hold strategy as opposed to an increase in strength.

Shoulder Dominance, EMG Support, and Technical Economy

As was consistent with the mechanics of the cross-type elements, the shoulder was still the primary contributor to the upper-limb kinetic chain. But there were fewer shoulder, elbow and forearm items summarized, indicating that the athletes were able to perform the same external force demand more economically following training. These values are to be considered as model values not as actually measured internal joint values. This interpretation was confirmed by the use of the BTS FREEEMG system which showed a reduction in the %MVC recorded during the test and an improvement in the key biomechanics and technical parameters. The anterior deltoid decreased from 89.04 +/- 2.41%MVC to 78.42 +/- 2.13%MVC, and the biceps brachii decreased from 82.04 +/- 1.86%MVC to 71.10 +/- 1.81%MVC. This decrease is not a sign of a decrease in muscle strength but rather of increased mechanical and neuromuscular efficiency. But the EMG results still agree and describe in the current experimental design. Because of the limitations of surface EMG, it was not possible to quantify the internal joint force, tendon stress, or tissue load, and a larger sample size, bilateral EMG asymmetry analysis, and detailed raw-signal timing variables were not included in the present study. In view of this, EMG results were interpreted in the context of the integrated force-video-performance interpretation and not as stand-alone causal statements of muscle level adaptation.

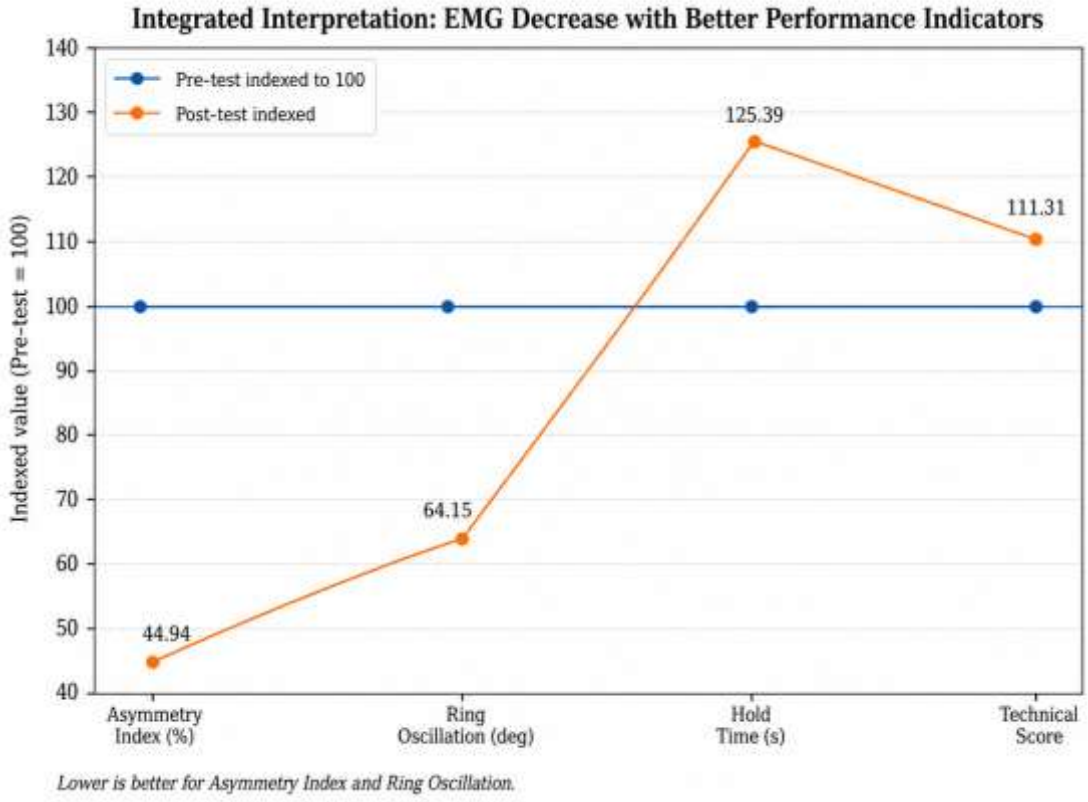


Figure 5B. *Integrated interpretation of EMG decrease with better performance indicators. Pre-test values are indexed to 100. Lower indexed post-test values for asymmetry index and ring oscillation indicate improvement, whereas higher indexed post-test values for hold time and technical score indicate improvement.*

The compensatory loading demands may have been decreased as a result of better shoulder angle, elbow extension, and trunk alignment, which may have allowed for the official hold for a longer duration.

Oscillation, Hold Time, and Score

The most significant applied results were the decrease in ring oscillation and the increase in official hold time. A shorter oscillation time demonstrates that the gymnast was able to stabilize the apparatus more rapidly and a longer hold time results in a greater chance of the skill being judged cleanly in competition (FIG, 2025a, 2025b, 2025c). Shoulder-angle, elbow-flexion, ring-oscillation, and insufficient-hold deductions were all reduced, leading to an improvement in the technical score. This interpretation was confirmed by exploratory correlations — technical score positively correlated with hold time and negatively correlated with shoulder angle.

Immediate Feedback Effect

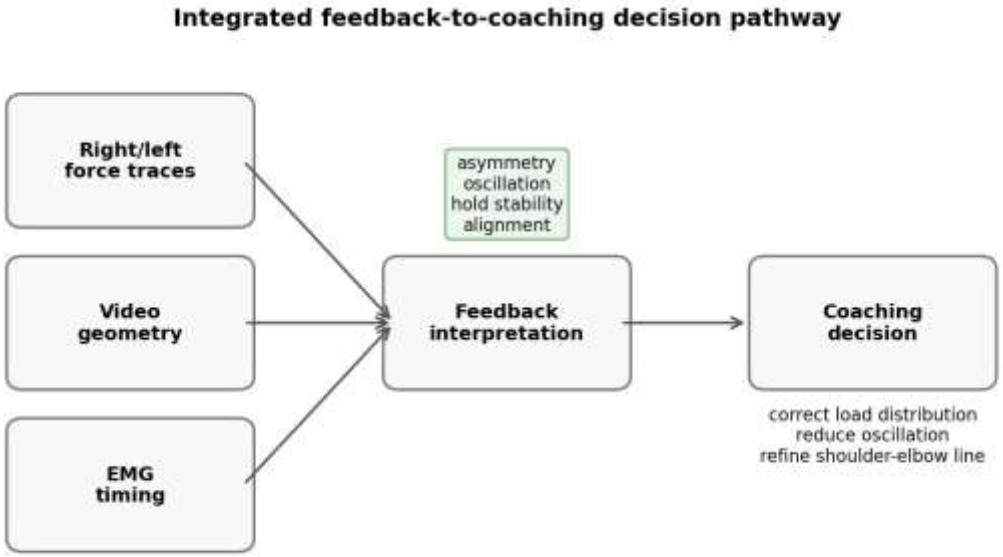
This progression over the three successive attempts within each session indicates that the display was immediately coaching valuable. Athletes were able to observe the imbalance or instability and modify the subsequent attempt and relate the force values to the synchronized video record. So it's best thought of as a measurement tool and coaching solution rather than just a force meter. It seems appropriate to the use in applied coaching when calibration, supervision and boundedness of interpretation of model-based variables are kept.

Methodological Boundaries and Future Directions

The results of this study should be accepted within the well-defined methodological limits. To begin, limited numbers of advanced athletes are able to safely perform the iron cross and the sample was exclusively made up of five advanced male artistic gymnasts. This sample is not suitable for making inferences beyond the athlete(s) it represents. Second, it was a one-group applied experimental design, with no comparison group. Thus, the improvements observed cannot be solely attributed to the smart-rings feedback system. The constant repetition, coaching focus, familiarity, and planned training program also may have played a role in the results. Therefore, the findings are best interpreted as changes that occurred as a result of the intervention in the current applied context than as causal outcomes. Third, external force data and video-based segment geometry were used to determine the shoulder, elbow and forearm kinetic indicators. These values should be considered to be estimates based on the model and not measurements of internal tissue loading, joint stress, or risk of injury.

Similarly, the EMG percent MVC values were also given as coincidental descriptive measurements of neuromuscular organization, and they are not intended to be used as a direct measure of the internal joint loading or tissue adaptation. Future studies are needed and they should include larger sample sizes, controlled or crossover study, longer follow-up with no feedback, bilateral EMG asymmetry testing and any subsequent extensive or unsupervised application of the smart-rings system must be officially mechanical certified.

Figure 6. *Coaching interpretation pathway for converting synchronized force, video, and EMG indicators into practical correction decisions.*



Conclusion

Results indicate that this small-sample, one-group, applied experimental design smart-rings system is a helpful diagnostic and coaching tool for high-level male artistic gymnasts performing the iron cross. The general result is that better execution was correlated with better organization of force, rather than with more overall external force. The athletes produced a comparable overall level of force with a more even distribution of force, a reduction in ring oscillation, an increase in the length of the official hold and an increase in the technical score. It is important to keep in mind that this is not only a force meter, but a system of coaching! It is useful that it provides real-time bilateral force feedback, while also displaying synchronized video and descriptive EMG data, enabling coaches to detect mechanical signs and symptoms that may not be observed with conventional observation. EMG %MVC outcomes were descriptive and provided supportive evidence of neuromuscular economy improvements and should be interpreted in conjunction with force, video, and performance data and not as an indicator of internal joint loading. Therefore, in the current data, the platform could facilitate apparatus-specific feedback and performance enhancement in the advanced level of male artistic gymnastics. Raw data export for synchronization should be added in future versions, longer retention testing should be added, further add-on of strength elements such as still-rings, and formal engineering validation for wide-scale deployment.

Recommendations

When bilateral symmetry and ring control are the priority goals, the system of smart-rings may be added to the common still-rings training on the cross-type strength elements. The bilateral asymmetry, ring oscillation, force variability, stabilization time, shoulder-elbow alignment, official hold durations, and transfer to legal rings should be the primary concerns of coaches when assessing the quality of iron crosses. EMG %MVC can be utilized as a descriptive neuromuscular channel (synchronized

with force and video analysis), but not as an independent assessment of internal joint loading.

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