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Effect of Core Stability Training on Throwing Accuracy and Bat Swing Mechanics in Competitive Pakistani Baseball Players: A Randomized Controlled Trial

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ABSTRACT

Background: Core stability is fundamental to kinetic chain efficiency in overhead throwing and rotational hitting sports. Despite its well-established role in athletic performance, no study has examined core stability training (CST) effects on baseball-specific skill outcomes in Pakistani players.

Objective: To determine the effect of an eight-week structured CST program on throwing accuracy and bat swing mechanics in competitive Pakistani male baseball players.

Methods: A randomized controlled trial was conducted with 80 competitive male baseball players (mean age: 21.4 ± 2.7 years) affiliated with the Pakistan Baseball Federation. Participants were randomly allocated to a Core Stability Training Group (CSTG; $n = 40$) or a Control Group (CG; $n = 40$). The CSTG completed a progressive, four-phase CST program (3 sessions/week, 8 weeks), while the CG continued standard training. Primary outcomes were throwing accuracy (mean radial error) and bat swing velocity, assessed using three-dimensional motion capture (Vicon Nexus, 200 Hz), radar measurement, and a target accuracy grid protocol. Core stability was assessed via the McGill Core Endurance Battery and Pressure Biofeedback Unit (PBU) test. Between-group differences were analyzed using ANCOVA (controlling for baseline), with Cohen's d effect sizes reported.

Results: The CSTG demonstrated significantly greater improvements than the CG in mean radial error (−31.2%; $d = 1.54$; $p < 0.001$), bat swing velocity (+10.2%; $d = 1.27$; $p < 0.001$), and hip-to-shoulder separation angle (+14.6°; $d = 2.40$; $p < 0.001$). McGill Composite Score and PBU scores were the strongest independent predictors of post-intervention throwing accuracy ($\beta = -0.54$) and bat swing velocity ($\beta = 0.49$), respectively. All between-group differences were statistically significant ($p < 0.001$).

Conclusion: An eight-week structured CST program produces large-magnitude improvements in throwing accuracy and bat swing mechanics in competitive Pakistani baseball players. These findings support the integration of progressive core stability work into evidence-based training programs within the Pakistani baseball ecosystem.

Keywords: *core stability training; baseball; throwing accuracy; bat swing mechanics; biomechanics; Pakistani athletes; randomized controlled trial*

INTRODUCTION

Baseball demands exceptionally precise integration of neuromuscular coordination, rotational power, and positional stability across the entire kinetic chain. The two performance

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metrics most central to competitive success throwing accuracy and bat swing velocity share a common mechanical foundation: the core musculature. The lumbo pelvic-hip complex serves as the pivotal link through which ground reaction forces generated by the lower limbs are transmitted, amplified, and directed toward the upper extremities. Deficits in core stability therefore compromise the efficiency of both throwing and hitting, regardless of upper-limb skill level (Kibler et al., 2006; Panjabi, 1992).

Core stability encompasses the coordinated activation of local stabilizers the transverses abdominis (TrA), multifidus, pelvic floor, and diaphragm and global stabilizers including the rectus abdominals, oblique's, erector spine, and gluteal complex (Bergmark, 1989; Hodges & Richardson, 1996). The critical function of these muscles extends beyond spinal protection; they collectively create the mechanical stiffness and neuromuscular control necessary for efficient rotational power transfer (McGill, 2010). The TrA, in particular, activates approximately 20–100 milliseconds before voluntary limb movements as a feed forward postural stabilizer, pre-stiffening the lumbar spine in anticipation of distal limb forces (Hodges & Richardson, 1997). Disruption of this anticipatory mechanism whether from inadequate training, fatigue, or injury — directly impairs throwing and hitting precision.

In baseball throwing, the six-phase kinematic sequence (wind-up, early cocking, late cocking, acceleration, deceleration, and follow-through) is critically dependent on lumbo pelvic stability throughout the acceleration and release phases (Fleisig et al., 1995). Release point inconsistency, a primary determinant of throwing error, has been attributed in large part to inadequate trunk control during the acceleration phase (Feltner & Dapena, 1986). In batting, hip-to-shoulder separation the differential rotation between pelvis and thorax during the swing load phase is the dominant biomechanical predictor of bat head speed, accounting for up to 62% of velocity variance (Fortenbaugh et al., 2011). This separation mechanism is entirely contingent on sufficient core stability to resist premature trunk rotation while the hips drive forward (Welch et al., 1995).

Pakistan's baseball landscape has undergone meaningful expansion since the Pakistan Baseball Federation (PBF) intensified grassroots development initiatives in collaboration with the World Baseball Softball Confederation (WBSC) during 2015-2022. As of 2023, the sport is played across 23 districts with an estimated 15,000-20,000 registered players (PBF Annual Report, 2023). Despite this growth, the sport's biomechanical and conditioning science foundations in this population remain critically understudied. Pakistani players frequently enter baseball programs with cricket backgrounds, providing pre-existing rotational movement competencies but also sport-specific musculoskeletal adaptations that may differ meaningfully from North American or East Asian baseball populations (Iqbal & Hussain, 2018). Uncritical extrapolation of international CST research to this context is therefore methodologically problematic.

Randomized controlled trials have demonstrated that six-to-twelve-week CST programs produce significant improvements in trunk endurance, neuromuscular activation timing, and functional athletic performance across diverse sports (Prieske et al., 2016; Reed et al., 2012; Hibbs et al., 2008). In overhead sport athletes, CST has improved throwing velocity and accuracy in handball players (Saeterbakken et al., 2011) and bat swing performance in softball players (Chu et al., 2009). However, no empirical study has examined these outcomes in Pakistani baseball players using gold-standard three-dimensional biomechanical assessment. This study addresses that gap through a rigorously designed RCT, testing the hypothesis that an eight-week structured CST program produces significantly greater improvements in throwing accuracy and bat swing mechanics compared to standard training in competitive Pakistani male baseball players.

METHODS

Research Design

A two-group, parallel randomized controlled trial (RCT) was employed, following CONSORT 2010 guidelines (Schulz et al., 2010). The study received ethical approval from the Institutional Review Board of the University of Sports Sciences, Lahore (Approval No. USS-IRB-2021-034) and was conducted in accordance with the Declaration of Helsinki. The trial was registered with the Pakistan Medical Research Council Clinical Trials Registry (No. PMRC-CTR-2021-1342) prior to participant recruitment.

Participants

A total of 104 competitive male baseball players registered with PBF-affiliated clubs in Punjab, Sindh, and Khyber Pakhtunkhwa were screened for eligibility. Eighty players met all inclusion criteria age 18–28 years, minimum two years of competitive experience, active league participation in the preceding six months, and absence of current musculoskeletal injury and provided written informed consent. Exclusion criteria included recent injury history (< 6 months), history of lumbar spine surgery, neurological conditions affecting motor control, and concurrent participation in another exercise intervention study. Sample size was determined a priori using G*Power 3.1 ($\alpha = 0.05$, power = 0.80, effect size $d = 0.70$), yielding a minimum of 34 participants per group; 40 per group were recruited to account for 15% anticipated attrition.

Randomization and Blinding

Block randomization (block size = 4), stratified by province and playing position, was performed using a computer-generated sequence by an independent statistician. Allocation was concealed using sealed opaque envelopes. Blinding of participants to group allocation was not feasible given the nature of the intervention; however, all outcome assessors were blinded to group allocation throughout the study period.

Intervention

The Core Stability Training Group (CSTG) completed a supervised, progressive eight-week program (three sessions per week, 60–75 minutes per session) delivered by NSCA-CSCS certified specialists at three provincial venues. The program was structured across four two-week

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phases: Phase I (motor learning and deep core activation), Phase II (global muscular endurance), Phase III (dynamic stability under load), and Phase IV (sport-specific functional integration). Phase I emphasized TrA and multifidus motor control through pressure biofeedback-guided drawing-in maneuvers, bird dogs, and dead bugs. Phase II introduced McGill endurance exercises (plank, side bridge, Sorensen hold) and anti-rotation patterns. Phase III progressed to loaded carries, TRX training, and Copenhagen planks. Phase IV incorporated medicine ball rotational throws, cable chops, and bat swing simulations with resistance bands.

Session load was monitored using the Borg CR10 Rating of Perceived Exertion scale, with a minimum acceptable compliance threshold of 80% of planned sessions (≥19 of 24). The Control Group (CG) maintained their standard physical conditioning routine comprising baseball skill practice and general cardiovascular conditioning without structured CST.

Outcome Measures

Pre- and post-intervention assessments were conducted within 72 hours of the first and final training sessions, respectively, at standardized times of day (08:00–12:00 h).

Core stability was assessed using (a) the McGill Core Endurance Battery (Flexion, Extension, dominant and non-dominant Side Bridge tests; ICC = 0.89–0.95; McGill et al., 1999) with a composite time-in-position score, and (b) the Pressure Biofeedback Unit (PBU; Chattanooga Group) for deep core activation using the standardized abdominal drawing-in maneuver (ADIM) protocol (ICC = 0.82; Richardson et al., 1999), with the maximal pressure decrease (mmHg) recorded without compensatory global muscle substitution.

Throwing accuracy was quantified as mean radial error (cm) across 10 standardized overhand throws from 18.44 meters to a 60 × 60 cm target grid. A JUGS Sports radar gun (accuracy ±0.5 mph) simultaneously recorded throwing velocity. Three-dimensional kinematics of both throwing and batting trials were captured using a 14-camera Vicon Nexus motion capture system (Oxford Metrics, UK; 200 Hz) with a 39-marker full-body set. Kinematic variables extracted from throwing included peak trunk angular velocity and release point variability. Bat swing variables included bat head velocity at contact, hip-to-shoulder separation angle (maximum), trunk rotation angular velocity, launch angle, and swing plane deviation, assessed across 15 tee-swing trials. Ground reaction forces during batting were measured using a Kistler force plate (1000 Hz).

Statistical Analysis

All analyses were conducted in IBM SPSS Version 27.0 and R 4.2.0 ($\alpha = 0.05$). Data normality was confirmed via Shapiro-Wilk tests. Between-group baseline equivalence was assessed using independent samples t-tests. The primary inferential analysis was ANCOVA, with post-intervention scores as dependent variables and pre-intervention scores as covariates, to control for potential baseline differences (Vickers & Altman, 2001). Within-group changes were evaluated using paired t-tests. Effect sizes were reported as Cohen's d (within-group) and partial eta squared (η^2p; between-group). Pearson correlations examined relationships between core stability change scores and performance outcomes. Multiple linear regression identified independent predictors of post-intervention throwing accuracy and bat swing velocity. The intention-to-treat principle governed primary analyses, with missing data managed through multiple imputations (20 datasets).

RESULTS

Participant Flow and Baseline Characteristics

Of 80 enrolled participants (CSTG: n = 40; CG: n = 40), two CSTG participants withdrew mid-intervention (one ankle injury, one relocation). Intention-to-treat analyses were performed for all 80 participants. Groups were comparable at baseline across all demographic, anthropometric, and performance variables ($p > 0.05$ for all; Table 1). Mean age was 21.3 ± 2.6 years (CSTG) and 21.5 ± 2.8 years (CG). Approximately 72% of CSTG and 70% of CG participants reported a cricket background. Mean training compliance in the CSTG was 91.4% of planned sessions.

Table 1

Baseline Demographic and Anthropometric Characteristics by Group (Mean ± SD)

Variable	CSTG (n = 40)	CG (n = 40)	p-value
Age (years)	21.3 ± 2.6	21.5 ± 2.8	0.72
Height (cm)	173.4 ± 5.8	172.9 ± 6.1	0.68
Body mass (kg)	68.2 ± 7.4	67.8 ± 7.9	0.81
BMI (kg/m²)	22.7 ± 1.9	22.6 ± 2.1	0.89
Playing experience (years)	5.4 ± 2.2	5.2 ± 2.0	0.63
Cricket background (%)	72.5	70.0	0.79
Pitcher/Infielder (%)	55.0	52.5	0.82

Note. CSTG = Core Stability Training Group; CG = Control Group; BMI = Body Mass Index.

Core Stability Outcomes

The CSTG demonstrated markedly greater improvements than the CG in all core stability measures following the eight-week intervention (Table 2). The McGill Composite Endurance Score increased by 46.1% in the CSTG (426.6 ± 73.4 s to 623.3 ± 65.1 s; $d = 2.72$; $p < 0.001$), compared to a non-significant 3.2% increase in the CG ($d = 0.18$; $p = 0.31$). ANCOVA revealed a highly significant between-group effect ($F [1,77] = 102.4$, $p < 0.001$, $\eta^2p = 0.57$). PBU-measured deep core activation improved substantially in the CSTG, with mean pressure decrease during ADIM increasing from 4.2 ± 1.1 mmHg to 7.8 ± 0.9 mmHg shifting from below to within the criterion range for effective TrA contraction (6–10 mmHg). The proportion of ADIM trials showing compensatory global muscle substitution fell from 34.6% to 8.4% in the CSTG, indicating meaningful improvements in motor control specificity. The CG showed negligible and non-significant changes in all core measures.

Table 2

McGill Core Endurance Battery and PBU Scores: Pre- and Post-Intervention by Group (Mean ± SD)

Measure	CSTG Pre	CSTG Post	CG Pre	CG Post	F (ANCOVA)	p	d (CSTG)
Flexion endurance (s)	148.4 ± 31.2	214.6 ± 28.7	150.1 ± 33.4	155.8 ± 34.1	F(1,77) = 64.3	< 0.001	2.11
Extension endurance (s)	112.3 ± 24.6	158.9 ± 22.1	113.7 ± 26.1	116.4 ± 25.8	F(1,77) = 58.7	< 0.001	1.96
Side bridge – dominant (s)	87.6 ± 18.4	131.2 ± 17.9	88.2 ± 19.1	91.4 ± 18.6	F(1,77) = 71.4	< 0.001	2.42
Side bridge – non-dominant (s)	78.3 ± 17.2	118.6 ± 16.4	79.1 ± 17.8	81.3 ± 17.5	F(1,77) = 68.9	< 0.001	2.37
McGill composite (s)	426.6 ± 73.4	623.3 ± 65.1	431.1 ± 78.2	444.9 ± 76.0	F(1,77) = 102.4	< 0.001	2.72
PBU score (mmHg)	4.2 ± 1.1	7.8 ± 0.9	4.1 ± 1.0	4.3 ± 1.1	F(1,77) = 91.3	< 0.001	3.64

Note. ANCOVA = Analysis of Covariance controlling for pre-intervention scores; d = Cohen's d for within-CSTG change; PBU = Pressure Biofeedback Unit.

Throwing Accuracy and Velocity

Throwing accuracy improved significantly in the CSTG relative to the CG (Table 3). Mean radial error decreased by 31.2% in the CSTG (18.6 ± 4.2 cm to 12.8 ± 3.1 cm; $d = 1.54$; $p < 0.001$), while the CG showed a non-significant 3.8% improvement ($d = 0.16$; $p = 0.43$). ANCOVA confirmed a significant between-group difference ($F [1,77] = 48.3$, $p < 0.001$, $\eta^2p = 0.39$). Throw-to-throw consistency, measured as the within-session standard deviation of radial error, improved substantially in the CSTG ($d = 1.81$; $p < 0.001$), indicating enhanced neuromuscular control of the release point across consecutive trials. The proportion of throws landing in Zone 1 (≤10 cm from center) more than doubled in the CSTG (12.4% to 28.6%).

Throwing velocity increased by 8.1% in the CSTG (72.4 ± 5.8 mph to 78.3 ± 5.4 mph; $d = 1.06$; $p < 0.001$), compared to a non-significant 1.0% increase in the CG ($p = 0.57$). Peak trunk angular velocity during the throwing motion increased by 18.9% in the CSTG (1082 ± 143 °/s to 1287 ± 128 °/s; $d = 1.47$; $p < 0.001$), consistent with the kinetic chain model predicting that improved core stability enables more efficient and explosive trunk rotation during the acceleration phase.

Table 3

Throwing Accuracy, Velocity, and Kinematic Outcomes: Pre- and Post-Intervention by Group (Mean ± SD)

Variable	CSTG Pre	CSTG Post	CG Pre	CG Post	p (ANCOVA)	d (CSTG)
Mean radial error (cm)	18.6 ± 4.2	12.8 ± 3.1	18.3 ± 4.4	17.6 ± 4.2	< 0.001	1.54
SD of radial error (cm)	5.8 ± 1.4	3.4 ± 1.1	5.7 ± 1.5	5.5 ± 1.4	< 0.001	1.81
Zone 1 accuracy (%, 0–10 cm)	12.4 ± 5.1	28.6 ± 7.4	12.8 ± 5.3	13.7 ± 5.6	< 0.001	2.58
Throwing velocity (mph)	72.4 ± 5.8	78.3 ± 5.4	72.1 ± 6.1	72.8 ± 6.0	< 0.001	1.06
Peak trunk angular velocity (°/s)	1082 ± 143	1287 ± 128	1078 ± 151	1092 ± 147	< 0.001	1.47

Note. SD = standard deviation of individual trial radial errors within session; Zone 1 = within 10 cm of target centre.

Bat Swing Mechanics

The CSTG demonstrated statistically significant and practically meaningful improvements across all bat swing variables (Table 4). Bat swing velocity increased by 10.2% (74.3 ± 6.1 mph to 81.9 ± 5.8 mph; $d = 1.27$; $p < 0.001$), compared to a non-significant 1.6% increase in the CG ($d = 0.19$; $p = 0.29$). Hip-to-shoulder separation angle showed the largest improvement in the CSTG, increasing by an absolute 14.6° (24.6 ± 6.3° to 39.2 ± 5.8°; $d = 2.40$; 59.3% improvement; $p < 0.001$), versus a non-significant 2.1° increase in the CG ($p = 0.19$). Between-group ANCOVA for hip-to-shoulder separation was highly significant ($F[1,77] = 56.3$, $p < 0.001$, $\eta^2 p = 0.42$).

Trunk rotation angular velocity at contact increased by 19.8% in the CSTG ($d = 1.64$; $p < 0.001$). The timing of hip rotation peak to contact shortened significantly (186 ± 24 ms to 162 ± 21 ms; $d = 1.07$; $p < 0.001$), indicating more efficient exploitation of the stretch-shortening mechanism during the swing. Launch angle improved toward the optimal performance range (3.8 ± 4.1° to 7.4 ± 3.6°; $d = 0.92$; $p < 0.001$), and swing plane deviation decreased substantially (9.4 ± 3.2° to 5.8 ± 2.7°; $d = 1.24$; $p < 0.001$). The CG demonstrated negligible and non-significant changes in all batting variables.

Table 4

Bat Swing Mechanics Outcomes: Pre- and Post-Intervention by Group (Mean ± SD)

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Variable	CSTG Pre	CSTG Post	CG Pre	CG Post	F (ANCOVA)	p	d (CSTG)
Bat swing velocity (mph)	74.3 ± 6.1	81.9 ± 5.8	74.1 ± 6.4	75.3 ± 6.2	F(1,77) = 39.8	< 0.001	1.27
Hip-to-shoulder sep. angle (°)	24.6 ± 6.3	39.2 ± 5.8	24.9 ± 6.7	27.0 ± 6.5	F(1,77) = 56.3	< 0.001	2.40
Trunk rot. angular velocity (°/s)	678 ± 84	812 ± 76	681 ± 89	692 ± 87	F(1,77) = 44.2	< 0.001	1.64
Time hip peak → contact (ms)	186 ± 24	162 ± 21	184 ± 26	182 ± 25	F(1,77) = 12.4	< 0.001	1.07
Launch angle (°)	3.8 ± 4.1	7.4 ± 3.6	3.9 ± 4.3	4.2 ± 4.1	F(1,77) = 14.9	< 0.001	0.92
Swing plane deviation (°)	9.4 ± 3.2	5.8 ± 2.7	9.2 ± 3.4	8.8 ± 3.2	F(1,77) = 21.6	< 0.001	1.24

Note. Sep. = separation; rot. = rotation; hip peak → contact = time from peak hip rotation angular velocity to contact.

Ground Reaction Forces During Batting

Force plate analysis revealed significant modifications in batting GRF characteristics in the CSTG. Peak vertical GRF on the lead foot increased from 14.8 ± 2.4 to 17.6 ± 2.1 N/kg ($d = 1.22$; $p < 0.001$), time to peak GRF decreased from 118 ± 18 ms to 98 ± 15 ms ($d = 1.19$; $p < 0.001$), and GRF impulse during the weight transfer phase increased from 8.2 ± 1.4 to 10.4 ± 1.2 N·s/kg ($d = 1.66$; $p < 0.001$). These findings indicate that CST enhanced not only trunk neuromuscular function but also the magnitude and timing of lower-body force production during the swing. The CG showed no significant GRF changes ($p > 0.05$ for all).

Regression and Subgroup Analyses

Multiple regression for post-intervention throwing accuracy (Table 5) was highly significant ($R^2 = 0.71$; $F[5,74] = 36.4$; $p < 0.001$), with changes in McGill Composite Score ($\beta = -0.54$; $p < 0.001$) and PBU Score ($\beta = -0.38$; $p < 0.001$) emerging as the strongest independent predictors alongside baseline accuracy. For bat swing velocity ($R^2 = 0.74$; $F[4,75] = 53.6$; $p < 0.001$), changes in hip-to-shoulder separation angle ($\beta = 0.49$; $p < 0.001$) and McGill Composite Score ($\beta = 0.44$; $p < 0.001$) were the primary predictors. Players with cricket backgrounds demonstrated modestly greater bat speed gains ($\beta = 0.21$; $p = 0.013$).

Subgroup analyses indicated that pitchers and infielders achieved greater CST-induced improvements in throwing accuracy (Δ radial error: −7.2 ± 2.4 cm vs. −4.9 ± 2.1 cm for outfielders/catchers; $p = 0.012$) and velocity (Δ: +7.4 ± 2.2 mph vs. +4.6 ± 1.9 mph; $p = 0.009$), likely reflecting the greater position-specific precision demands of these roles. No significant between-position differences were detected for batting outcomes.

Table 5

Multiple Regression: Predictors of Post-Intervention Throwing Accuracy (Radial Error, cm) and Bat Swing Velocity

Predictor	B	SE B	β	t	p
Panel A: Throwing Accuracy (R^2 = 0.71, F[5,74] = 36.4, p < .001)					
Baseline radial error	0.68	0.09	0.61	7.56	< 0.001
ΔMcGill composite score	−0.018	0.004	−0.54	−4.50	< 0.001
ΔPBU score	−0.72	0.18	−0.38	−4.00	< 0.001
Playing experience (years)	−0.34	0.14	−0.18	−2.43	0.018
Group (CSTG = 1)	−3.46	0.82	−0.42	−4.22	< 0.001
Panel B: Bat Swing Velocity (R^2 = 0.74, F[4,75] = 53.6, p < .001)					
Baseline bat swing velocity	0.74	0.10	0.64	7.40	< 0.001
ΔHip-to-shoulder sep. angle (°)	0.48	0.11	0.49	4.36	< 0.001
ΔMcGill composite score	0.008	0.002	0.44	4.00	< 0.001
Cricket background (Yes = 1)	1.84	0.72	0.21	2.56	0.013

Note. Δ = change score (post − pre); sep. = separation; all VIF < 2.5, indicating acceptable multicollinearity.

DISCUSSION

This randomized controlled trial provides the first empirical evidence that an eight-week structured CST program produces large-magnitude, statistically significant improvements in throwing accuracy and bat swing mechanics in competitive Pakistani male baseball players. The findings extend the international CST-baseball literature to a previously unstudied South Asian population and carry direct implications for strength and conditioning practice within the Pakistani baseball ecosystem.

The 31.2% reduction in mean radial throwing error (d = 1.54) observed in the CSTG aligns with the theoretical prediction that enhanced core stability improves release point consistency by providing a more stable proximal platform during the arm acceleration phase. This effect size substantially exceeds the moderate effects (d = 0.67–0.98) reported by Saeterbakken et al. (2011) in handball a population with broadly comparable throwing mechanics and may reflect the relatively greater baseline core instability evident in Pakistani players compared to the

Scandinavian elite athletes studied by those authors. The McGill Composite baseline scores in the present sample (approximately 427 s) fell considerably below normative values documented for North American collegiate baseball players by McGill et al. (1999), suggesting that inadequate core conditioning represents a more prevalent and severe performance limitation in this population, thereby creating a larger magnitude of improvability through targeted training. The concurrent increases in throwing velocity (d = 1.06) and peak trunk angular velocity (d = 1.47) support the kinetic chain model's prediction that improved lumbopelvic stability enables more complete and efficient transfer of rotational energy from the lower limbs through the trunk to the throwing arm (Kibler et al., 2006).

The 59.3% improvement in hip-to-shoulder separation angle (d = 2.40) is the most notable finding of this study and represents a mechanistically coherent outcome given the intervention's emphasis on progressive core rotational loading. Fortenbaugh et al. (2011) identified hip-to-shoulder separation as the primary predictor of bat speed, and the 10.2% gain in bat swing velocity observed in the CSTG (d = 1.27) is directly consistent with this biomechanical relationship. The shortened time from peak hip rotation to contact (Δ = −24 ms; d = 1.07) suggests a more efficient stretch-shortening mechanism in the trunk musculature — an adaptation that is theoretically attributable to the progressive plyometric and medicine ball rotational training incorporated in Phase IV of the CST protocol. These findings are consistent with Szymanski et al. (2010), who reported moderate bat speed improvements (d = 0.67) following a twelve-week trunk rotation training program in collegiate players, and with Chu et al. (2009), who documented significant hitting improvements following combined core and hip strength training in softball players.

The force plate data offer mechanistic insight beyond the trunk adaptations captured by motion analysis. The significant increases in peak vertical GRF (d = 1.22) and GRF impulse during weight transfer (d = 1.66) in the CSTG indicate that CST modified ground force characteristics proximal to the trunk, suggesting that the lumbo pelvic-hip training enhanced the quality of lower-body drive during the batting weight transfer phase. This finding aligns with the theoretical model of Putnam (1993), who demonstrated that effective kinetic chain summation begins with adequate lower-extremity force generation, and extends prior CST literature by documenting GRF-level adaptations not previously examined in baseball-specific intervention studies.

The regression analyses provide important mechanistic support for the proposed neuro mechanical pathway model. The identification of McGill Composite Score as the strongest independent predictor of post-intervention throwing accuracy (β = −0.54) suggests that global core endurance adaptations — rather than local stabilizer activation improvements alone are the primary neuromuscular substrate underlying improved throwing precision. The positive relationship between ΔPBU score and throwing accuracy improvement (β = −0.38) further indicates that enhanced specificity of deep core motor control contributes independently to release point consistency, consistent with Hodges and Richardson's (1997) feed forward activation model. For bat swing velocity, hip-to-shoulder separation angle improvement emerged as the strongest predictor (β = 0.49), confirming the primacy of this kinematic variable as the biomechanical conduit through which core stability enhancements translate into batting performance gains.

The positive effect of cricket background on CST-induced bat speed improvement (β = 0.21) is a practically significant finding with implications for PBF talent identification strategies. Pakistani cricketers possess established rotational movement patterns from batting particularly the weight transfer and body rotation mechanics of pull shots and drives that may provide a pre-existing neuromuscular foundation facilitating faster acquisition of the hip-to-shoulder separation mechanism during CST. This finding suggests that cricket-to-baseball conversion programs may be particularly effective for batting positions and that the large cricket-playing talent pool in Pakistan represents an underutilized resource for baseball development.

The greater CST responsiveness of pitchers and infielders compared to outfielders and catchers for throwing outcomes is consistent with the position-specific throwing demands of these roles, where precision at standardized distances from set positions is particularly performance-critical. These players may derive greater functional benefit from the release point consistency improvements associated with CST because their game performance is more immediately contingent on throwing accuracy metrics that directly correspond to the outcome measures employed in this study.

Limitations

Several limitations require consideration. First, the restriction to competitive adult males limits generalizability to female and youth players. Second, the eight-week observation window precludes conclusions about long-term adaptation or the durability of improvements following program cessation. Third, the absence of electro-myographic assessment means that the proposed neuro mechanical mechanisms remain inferential. Fourth, participant blinding was not feasible, and Hawthorne effects cannot be fully excluded. Fifth, dietary intake and sleep quality were not systematically monitored as potential confounders. These limitations notwithstanding, the rigorous RCT design, gold-standard biomechanical assessments, and high ecological validity of the Pakistani baseball sample represent meaningful methodological strengths.

CONCLUSION

An eight-week structured, progressive core stability training program produced large-magnitude improvements in throwing accuracy, throwing velocity, bat swing velocity, hip-to-shoulder separation angle, trunk rotation angular velocity, launch angle, and ground reaction force characteristics in competitive Pakistani male baseball players. These improvements were substantially greater than those observed in players undergoing standard conditioning and were mechanistically linked to enhancements in global core endurance and deep core motor control specificity. The intervention is feasible and scalable within Pakistani provincial baseball contexts, relying on equipment readily accessible to most domestic academies. These findings strongly support the integration of periodized, position-sensitive core stability training into the annual preparation plans of Pakistani competitive baseball players, with immediate implications for the PBF's national conditioning curriculum.

PRACTICAL IMPLICATIONS

Strength and conditioning specialists working with Pakistani baseball players should incorporate the four-phase CST protocol described in this study into pre-season preparation (8–12 weeks). Practitioners are advised to establish baseline core stability benchmarks using the McGill Battery and PBU test, with players achieving composite scores below 350 seconds prioritized for intensive CST intervention. Phase progression should be gradual, with Phases I and II motor control and endurance foundations consolidated before introducing the dynamic loading and rotational power stimuli of Phases III and IV.

The Pakistan Baseball Federation is encouraged to: (a) incorporate the McGill Core Endurance Battery into standard pre-season fitness monitoring for all national and provincial academy players; (b) develop position-specific CST Phase IV modules targeting the kinematic priorities of pitching, infield, outfield, and catching roles; (c) integrate core stability training theory and practice into Level 2 and Level 3 coaching certification curricula; and (d) establish a longitudinal core stability assessment database to enable population-level performance monitoring across competitive cohorts.

Future research should investigate: (a) long-term adaptation trajectories and maintenance of performance gains at 3–12 months post-intervention; (b) CST effects in female and adolescent Pakistani baseball players; (c) EMG-based verification of the feed forward neuro mechanical mechanisms proposed in this study; (d) position-specific CST protocol comparisons; and (e) the prospective effect of CST on throwing arm injury incidence in this population.

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