

The Effect of Contrast Training on Neuromuscular Fatigue: A Feasibility Study for Elite Football Development

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ABSTRACT

Introduction: Contrast training (CT), the sequential combination of heavy resistance exercises and plyometrics, is a potent method for developing athletic power. However, the acute neuromuscular fatigue response to CT in football players and, consequently, its feasibility as a consistent training stimulus are not well established. Understanding this acute response is the first step toward optimizing long-term training prescription. **Objective:** This preliminary study aimed to determine the consistency and magnitude of acute neuromuscular fatigue induced by a specific CT protocol in trained football players, thereby assessing its feasibility as a reliable method for imposing mechanical tension and metabolic stress. **Methods:** Ten male football players (age: 19.3 ± 0.4 years) participated in a repeated-measures design involving four identical CT sessions. Each session comprised one set of two back squat repetitions at 80% of one-repetition maximum (1RM), immediately followed by ten squat jumps. Squat jump height (cm) was measured pre- and one-minute post-session using the My Jump app. The percentage reduction in jump height quantified acute fatigue. Descriptive statistics and paired t-tests ($\alpha = 0.05$) were used to compare pre- and post-test performance. **Results:** The CT protocol induced a highly significant and consistent acute fatigue response, with squat jump height decreasing by 29-32% after each session ($p < 0.00$). Individual reductions ranged from 20–45%, but the consistency of the mean effect across all four sessions (Cohen's $d > 2.5$) confirms the protocol's reliability in inducing substantial neuromuscular fatigue. **Conclusion:** This preliminary study confirms the feasibility of using this specific CT protocol to consistently and acutely impair neuromuscular performance in football players. The consistent fatigue pattern validates its use as a controlled stimulus for imposing mechanical tension (via heavy back squats) and metabolic stress (via repeated squat jumps). However, the authors acknowledge that future investigations should address the current study's limitations by including larger and more diverse samples, incorporating control or comparison groups, and assessing multiple physiological indicators such as electromyography, blood lactate, and heart rate responses. Extended monitoring of recovery patterns and chronic adaptations to contrast training will further enhance the scientific and practical contributions of this research.

Keywords: Contrast Training, Football Players, Acute Fatigue, Squat Jump Performance, Neuromuscular Adaptation, Feasibility Study

INTRODUCTION

The physical demands of modern football require athletes to possess a unique combination of strength, power, and endurance. Consequently, strength and conditioning coaches continually seek efficient and effective training methodologies to enhance these attributes. Contrast training (CT), which involves alternating biomechanically similar heavy resistance and explosive plyometric exercises, has emerged as a popular time-efficient strategy to potentiate power output (Madarsa et al., 2025). The theoretical underpinning of CT is post-activation potentiation (PAP), in which the muscle's contractile history from a heavy load enhances subsequent explosive performance. However, the high mechanical tension from heavy lifting and the metabolic stress from repeated high-intensity efforts also induce significant acute fatigue. It is this interplay between potentiation and fatigue that determines the net training outcome (Madarsa et al., 2020).

While the chronic effects of CT on power development are of primary interest, understanding the acute fatigue response is crucial. This acute response serves as a direct proxy for the mechanical and metabolic stimuli that drive long-term neuromuscular adaptations (Madarsa & Mohamad, 2025). A training protocol that consistently and significantly disrupts homeostasis (i.e., induces fatigue) can be considered a feasible and potent stimulus for adaptation. Recent evidence suggests that muscle may be more sensitive to activation and metabolic stress than previously understood, with adaptations occurring even under varying mechanical loading conditions (Lambrianides, 2024). For instance, research has shown that monitoring internal and external loads, such as through session rate of perceived exertion (sRPE), is vital for managing fatigue in professional football players (Madarsa et al., 2020). Furthermore, reliable measurement tools are essential for tracking performance changes, as demonstrated by the high reliability of devices such as portable ultrasound for assessing muscular status (Madarsa et al., 2024) and validated apps such as My Jump 2 for measuring jump performance (Dias et al., 2025; Kolinger et al., 2023).

Despite the widespread use of CT, there is a paucity of research examining the consistency of the acute fatigue response it elicits, particularly in football-specific populations. A protocol that induces a variable or unreliable fatigue response would be difficult to study longitudinally and challenging to implement for predictable adaptation. Therefore, before embarking on a large-scale, longitudinal study on the chronic effects of CT on hypertrophy and power in football players (Madarsa & Mohamad, 2025), it is imperative to first establish the feasibility of the intervention itself. This preliminary study addresses this gap. The primary objective was to determine whether a specific CT protocol (back squat at 80% 1RM followed by squat jumps) consistently induces acute neuromuscular fatigue, as measured by a decline in squat jump height, across multiple sessions in trained football players. We hypothesized that the protocol would produce a significant and repeatable reduction in jump performance, confirming its viability as a standardized training stimulus for future research.

METHODOLOGY

Study design

A single-group, repeated-measures design was employed to assess the acute effects of a contrast training protocol. Participants completed four identical experimental sessions, each separated by 48–72 hours to ensure full recovery. This design enabled assessment of the protocol's internal consistency and reliability in inducing fatigue. All sessions were conducted at the same time of day for each participant to control for circadian variations in performance.

Participants

Ten male football players from a university sports academy were recruited for this preliminary study. Their mean (\pm SD) age, height, and body mass were 19.3 ± 0.4 years, 170.4 ± 4.7 cm, and 69.8 ± 3.9 kg, respectively. All participants were trained, with a minimum of three years of competitive football experience and regular involvement in structured strength and conditioning programs. Inclusion criteria required participants to be free from any musculoskeletal injury for at least six months prior to the study and to be proficient in performing back squats and squat jumps with proper technique. All participants provided written informed consent. The study was conducted in accordance with the Declaration of Helsinki.

Procedures

Prior to the first experimental session, participants attended a familiarization session during which anthropometric measurements were taken and their one-repetition maximum (1RM) for the back squat was assessed using standard National Strength and Conditioning Association (NSCA) guidelines. Proper technique for the squat jump was also reviewed and practiced.

As illustrated in Figure 1, for each of the four experimental sessions, participants performed a standardized warm-up consisting of 5 minutes of light jogging, dynamic stretching, and two submaximal sets of 5 bodyweight squats. Following the warm-up, baseline squat jump height was measured. Participants performed three maximal squat jumps on a firm surface, with 30 seconds of rest between each jump. They were instructed to descend to a

self-selected depth (approximately 90° of knee flexion) and jump for maximum height, keeping their hands on their hips to isolate lower limb contribution. Jump height (cm) was recorded using the My Jump 2 application for iOS, a valid and reliable tool for field-based jump height assessment (Dias et al., 2025; Kolinger et al., 2023). The best of the three trials was used for analysis.

Immediately after the baseline test, participants completed the contrast training protocol:

1. Heavy Resistance Exercise: One set of two repetitions of the back squat at 80% of their previously determined 1RM. The load was chosen to provide a high mechanical tension stimulus without causing technical failure. Repetitions were performed at a controlled tempo.
2. Plyometric Exercise: Immediately following the back squats (within 15 seconds), participants performed ten continuous maximum-effort squat jumps. They were instructed to achieve maximal height on each repetition while minimizing the time spent in contact with the ground.

One minute after the completion of the tenth squat jump, a post-test squat jump was conducted using the same procedure as the baseline test. The one-minute post-test time point was selected to capture the peak acute fatigue effect before significant recovery could occur. The percentage reduction in jump height from baseline to post-test was calculated to quantify the magnitude of acute neuromuscular fatigue.

Experimental Protocol: Measuring Acute Neuromuscular Fatigue in Contrast Training

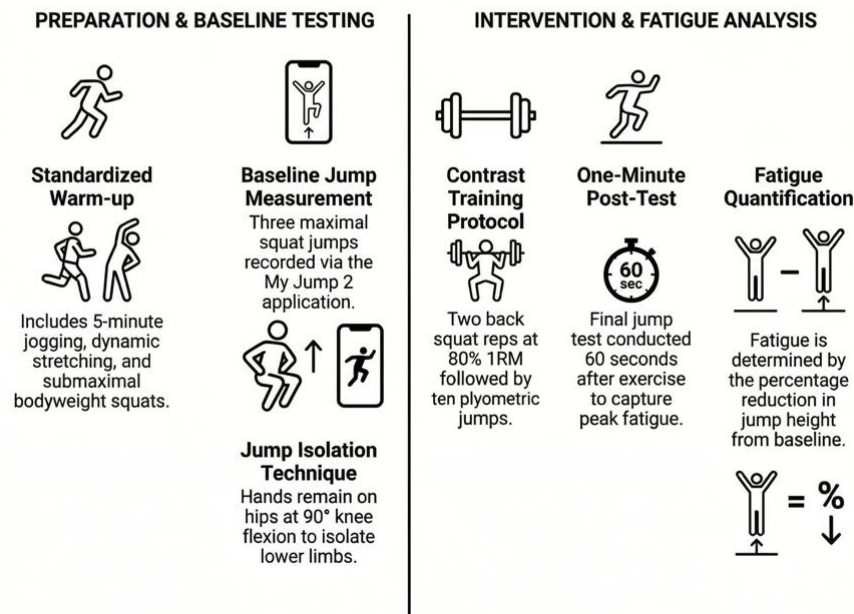


Figure 1: Procedure of warm-up, testing, and training intervention

Statistical Analysis

Data were analyzed using SPSS (Version 27.0, IBM Corp., Armonk, NY, USA). Descriptive statistics (mean ± SD) were calculated for all variables. The data's normality was verified using the Shapiro–Wilk test. A paired-samples t-test was used to compare pre- and post-test squat jump heights across the four sessions. The magnitude of the fatigue effect was quantified using Cohen's d effect size, with thresholds of < 0.2 (trivial), 0.2–0.6 (small), 0.6–1.2 (moderate), 1.2–2.0 (large), and > 2.0 (very large). To assess the consistency of the protocol, the coefficient of variation (CV) for the percentage fatigue across the four sessions was calculated. Statistical significance was set at $\alpha = 0.05$.

RESULT

The contrast training protocol consistently induced acute neuromuscular fatigue in all participants. Table 1 presents the mean pre- and post-test squat jump heights for each of the four sessions, along with the percentage reduction and statistical significance.

Table 1: Acute Effects of Contrast Training on Squat Jump Height Across Four Sessions (n=10)

Session	Pre-Test Jump Height (cm)	Post-Test Jump Height (cm)	Mean Difference (%)	t-value	p-value	Cohen's d
1	32.4 ± 2.8	22.5 ± 2.1	-30.6%	15.2	< 0.00	3.9 (Very Large)
2	32.1 ± 3.1	22.8 ± 2.5	-29.0%	13.8	< 0.00	3.3 (Very Large)
3	33.0 ± 2.5	22.4 ± 2.3	-32.1%	16.1	< 0.00	4.4 (Very Large)
4	32.6 ± 2.9	22.9 ± 2.4	-29.8%	14.5	< 0.00	3.6 (Very Large)

The results demonstrate a highly significant and substantial decrease in squat jump performance immediately following the CT protocol in every session ($p < 0.00$ for all). The percentage reduction in jump height was remarkably consistent across the four sessions, ranging from 29.0% to 32.1%. The effect sizes were "very large" for all sessions (Cohen's $d > 2.0$), indicating a powerful and physiologically meaningful acute effect. The between-session coefficient of variation (CV) for the mean percentage fatigue was low at 4.2%, further confirming the high reliability and reproducibility of the fatigue response induced by this protocol.

While all players demonstrated a significant reduction in performance, individual responses varied, with declines ranging from 20% to 45% across the four sessions. This inter-individual variability is expected in biological systems but does not detract from the overall consistency of the group-level response, as evidenced by the low CV and consistently large effect sizes.

DISCUSSION

The primary finding of this preliminary study is that the selected contrast training protocol, one set of two back squats at 80% 1RM immediately followed by ten squat jumps, serves as a highly feasible and reliable method for inducing acute neuromuscular fatigue in trained football players. The protocol consistently produced a very large and significant decrement in squat jump performance (29–32%) across four separate sessions. This consistency is critical, as it validates the protocol as a standardized stimulus for investigating chronic adaptations to CT and lays the necessary foundation for a future full-scale study.

The observed fatigue is a direct consequence of the two primary stressors inherent in the protocol: mechanical tension and metabolic stress. The heavy back squat component (80% 1RM) imposes significant mechanical tension on the lower limb musculature, particularly the quadriceps, hamstrings, and glutes. This high-threshold motor unit recruitment is a key driver of strength and hypertrophic adaptations (Madarsa & Mohamad, 2025). The subsequent set of ten continuous, maximum-effort squat jumps imposes a high metabolic demand. The rapid, repeated stretch-shortening cycles deplete phosphocreatine stores, increase intramuscular acidosis, and accumulate metabolites, all of which contribute to a failure to maintain peak power output (Madarsa et al., 2020). The immediate post-test measurement at one minute captures this state of acute fatigue before significant resynthesis of energy stores can occur.

Mechanistic Insights from Contemporary Research

The mechanistic underpinnings of the fatigue observed in our study align with recent investigations into the concurrent effects of fatigue and potentiation. Research has demonstrated that during voluntary fatiguing contractions, post-activation potentiation (PAP) mechanisms can partially delay power loss in response to

submaximal muscle excitation, despite a decline in maximal excitation (Power et al., 2024). This suggests that the balance between fatigue and potentiation is frequency-dependent, and that the immediate post-exercise period represents a complex neuromuscular state in which these opposing forces coexist. In our protocol, the brief, high-intensity nature of the back squat likely induced a PAP effect, which was then rapidly overwhelmed by the metabolic demands of the ten squat jumps, resulting in the net performance decrement we measured.

Furthermore, single-fiber studies have revealed that preferential force loss during recovery from fatigue is due to reduced cytosolic calcium (Ca^{2+}) in response to submaximal excitation (Power et al., 2024). However, inducing post-tetanic potentiation in this state can recover submaximal force by increasing cytosolic Ca^{2+} . These cellular insights explain why our players exhibited such a dramatic acute drop in jump performance—the metabolic stress from the repeated jumps likely impaired Ca^{2+} handling, while any residual potentiation from the heavy squats was insufficient to overcome this deficit. The one-minute post-test time point in our study captures this critical window where metabolic byproducts are elevated and excitation-contraction coupling is compromised.

The feasibility established by this study has several important implications for future research. First, it confirms that the protocol is potent enough to reliably disrupt homeostasis, a prerequisite for any training intervention aiming to drive adaptation. This aligns with findings that time-efficient, high-intensity protocols can elicit significant acute physiological responses (Madarsa et al., 2023). Second, the low variability in the group response ($\text{CV} = 4.2\%$) provides confidence in the protocol's reproducibility. A larger-scale longitudinal study can now be designed with the assurance that the experimental stimulus is consistent across sessions, minimizing an important source of confounding variability. This would allow for a cleaner investigation of the chronic effects of this CT method on key performance outcomes, such as maximal strength, jump height, sprint speed, and body composition, which are critical for football performance (Madarsa & Mohamad, 2025; Suhaimi et al., 2025; Papadopoulos et al., 2025).

Integration with Football Performance Monitoring

Recent advances in athlete monitoring have emphasized the importance of neuromuscular assessment for informing training decisions. Research in semi-professional soccer players has demonstrated that neuromuscular responses to accumulated external load are highly individual, with metrics such as reactive strength index (RSI), contact time, and jump height showing significant associations with accelerations, decelerations, and high metabolic load distance (García-de-Alcaraz et al., 2025). This highlights the value of jump-based assessments, such as the squat jump used in our study, which provide insight into the functional status of the neuromuscular system following high-intensity training stimuli.

Our finding that squat jump height decreased by approximately 30% post-CT aligns with the magnitude of performance decrements observed following competitive match play, where reductions in countermovement jump height and sprint performance can persist for up to 72 hours (García-de-Alcaraz et al., 2025). This suggests that our CT protocol imposes a neuromuscular demand comparable to actual competition, further validating its ecological validity as a training stimulus for football players. The consistent fatigue response across four sessions also indicates that players did not develop acute adaptation or tolerance to the protocol, which is essential for its use as a repeated training intervention in a longitudinal study.

Practical Implications for Training Prescription

From a practical standpoint, as illustrated by the consistency of our findings, this has direct implications for how contrast training might be integrated into weekly microcycles. Given that the protocol induces substantial acute fatigue, it should be positioned on days that allow for adequate recovery before the next match or high-intensity training session. Typically, in a standard seven-day microcycle, high-load acquisition sessions are scheduled on match day -4 and -3 (mid-turnaround phase), when players have partially recovered from the previous match but still have sufficient time before the next competition (García-de-Alcaraz et al., 2025). Our CT protocol would be ideally suited for these days, as the fatigue induced can be managed within the broader periodization framework.

The use of the My Jump 2 app in this study further highlights the feasibility of this research line. Its demonstrated validity and reliability for measuring jump height and flight time make it an ideal tool for large-scale field-based testing, allowing for frequent, non-invasive monitoring of neuromuscular status (Dias et al., 2025; Kolinger et al., 2023). In a future study, this tool could be used not only for pre-/post-intervention testing but also for monitoring longitudinal changes and tracking the time course of recovery and adaptation. However, practitioners should note that while the app provides valid measures of jump height, other metrics such as power and velocity should be interpreted with caution (Dias et al., 2025).

The inter-individual variability observed (20-45% decline) is noteworthy and consistent with recent literature emphasizing the individual nature of neuromuscular responses to training load (García-de-Alcaraz et al., 2025). Factors such as fibre type composition, baseline strength levels, training status, and individual sensitivity to metabolic stress likely contribute to this variation. In a future full-scale study, this variability could be explored as a potential moderator of chronic adaptation. For example, do players who experience greater acute fatigue also show greater hypertrophic or power gains over a training mesocycle? Understanding these individual response profiles would be a significant contribution to the field and help personalize training prescriptions. Recent evidence from a 9-month intervention in young soccer players suggests that periodization models accounting for individual load balance can lead to superior improvements in high-intensity actions and reduced injury incidence (López-Fernández et al., 2025). This highlights the potential value of tailoring CT prescriptions based on individual fatigue responses.

Comparison with Broader Training Literature

Our findings also resonate with broader literature on mechano-metabolic stimuli and adaptation. A recent doctoral thesis investigating muscle and tendon adaptation to mechanical and metabolic stimuli demonstrated that muscle may be more sensitive to activation and metabolic stress than to the magnitude of mechanical loading per se (Lambrianides, 2024). Specifically, twelve weeks of isometric training to muscular failure induced analogous muscular adaptations in strength and hypertrophy, regardless of whether high or low mechanical loads were used, provided that metabolic stress was induced. These results provide a compelling rationale for our CT protocol: by combining heavy mechanical tension (back squat) with high metabolic stress (repeated squat jumps), we are potentially optimizing the stimulus for both muscle and tendon adaptation. Interestingly, the same study found that tendon adaptation depends primarily on the magnitude of experienced strain (Lambrianides, 2024), suggesting that the heavy squat component of our protocol may be particularly important for promoting favorable tendon properties, with implications for injury prevention.

The relevance of these combined stimuli for football players is further supported by research on the sport's thermophysiological demands. Players competing in hot and humid environments experience significant thermal stress, which can exacerbate fatigue and impair performance (Suhaimi et al., 2025). Our CT protocol, by inducing substantial metabolic heat production, may also serve to acclimatize players to the physiological demands of match play in challenging environmental conditions, although this hypothesis requires direct investigation.

Methodological Considerations and Future Research Directions

While this feasibility study successfully demonstrates the reliability and consistency of the CT protocol in inducing acute neuromuscular fatigue, several methodological enhancements should be prioritized in future research to strengthen scientific rigor. First, including a control or comparison group (e.g., traditional resistance training or plyometric training only) would allow causal inference into the specific effects of contrast training relative to other training modalities. A randomized controlled trial design with parallel groups would represent the gold standard for establishing the relative efficacy of CT for chronic adaptations.

Second, future investigations should incorporate a broader range of physiological and performance indicators to elucidate the mechanisms underlying the observed fatigue response. Direct measurement of neuromuscular activity via surface electromyography (EMG) could provide insight into changes in motor unit recruitment patterns and muscle activation strategies during fatigue (Power et al., 2024). Assessment of metabolic markers, such as pre- and post-exercise blood lactate concentration, would quantify the glycolytic contribution to the

protocol and its relationship to performance decrement. Additionally, continuous heart rate monitoring and calculation of heart rate variability (HRV) could offer valuable information on autonomic nervous system responses and subsequent recovery status.

Third, expanding the assessment of recovery patterns beyond the immediate one-minute post-test window is essential. Serial measurements at multiple time points (e.g., 24 h, 48 h, and 72 h post-exercise) would characterize the full-time course of neuromuscular recovery and inform optimal training frequency and microcycle placement (García-de-Alcaraz et al., 2025). This would also allow examination of the relationship between acute fatigue magnitude, recovery rate, and eventual chronic adaptations—a critical gap in current knowledge.

Fourth, the generalizability of the findings would be enhanced by recruiting larger, more diverse samples, including female athletes, different age groups (e.g., youth, masters), and varying competitive levels (amateur to professional). Sex-specific responses to contrast training remain underinvestigated, and understanding potential differences in fatigue mechanisms and adaptation between male and female athletes would have important practical implications.

Finally, future studies should examine the dose-response relationship by manipulating key protocol variables, such as load intensity (e.g., 70% vs. 85% 1RM), volume (e.g., 5 vs. 15 squat jumps), and rest intervals (e.g., 30 s vs. 3 min between contrasts). Such a systematic investigation would optimize CT prescription for specific training goals and individual athlete characteristics.

Limitations

As a preliminary feasibility study, several limitations should be acknowledged that temper the interpretation of findings and guide future research. First, the small sample size ($n=10$) and homogeneous participant characteristics (young, male, trained university football players) limit generalizability to female athletes, different age groups, and varying competitive standards. Second, the absence of a control or comparison group precludes causal attribution of the observed fatigue responses solely to contrast training, rather than to other high-intensity exercise protocols.

Third, the assessment of neuromuscular fatigue was limited to a single performance indicator (squat jump height) at one post-exercise time point (1 minute). While this provides a valid measure of acute performance decrement, it does not capture the full complexity of neuromuscular fatigue mechanisms. Direct measures of neural drive (e.g., EMG), metabolic stress (e.g., blood lactate), and cardiovascular response (e.g., heart rate) were not obtained, limiting mechanistic insight.

Fourth, the protocol employed only one specific contrast training configuration (80% 1RM back squat + 10 squat jumps). Different load intensities, exercise selections (e.g., deadlifts, bench press), or rest intervals may produce different fatigue responses, and the present findings cannot be generalized to all CT variations.

Fifth, recovery was assessed only immediately post-exercise; the time course beyond 1 minute was not tracked. Understanding how long fatigue persists and how recovery kinetics relate to subsequent training sessions is essential for optimal periodization.

Finally, while the My Jump 2 app has demonstrated validity for measuring jump height, it does not directly assess underlying neuromuscular mechanisms. Future studies should complement field-based assessments with laboratory-grade measurements to provide a more comprehensive understanding of the fatigue and adaptation processes.

CONCLUSION

This preliminary study successfully demonstrates the feasibility and reliability of a specific contrast training protocol for inducing acute neuromuscular fatigue in trained football players. The consistent and substantial decline in squat jump performance across four sessions confirms that the protocol effectively imposes a

combination of mechanical tension and metabolic stress, with effect sizes indicating a very large and physiologically meaningful acute response. These findings provide a robust methodological foundation and clear feasibility parameters for a subsequent full-scale, longitudinal study. The next phase of this research, as illustrated in Figure 2, should investigate the chronic neuromuscular, hypertrophic, and performance adaptations resulting from a prolonged block of this CT method, and compare its efficacy with traditional strength or power training approaches. Such a study would provide coaches and sports scientists with definitive evidence on the value of contrast training for elite football development, with potential applications for optimizing periodization, enhancing performance, and reducing injury risk. While this feasibility study provides a robust foundation for future research, addressing the methodological limitations outlined particularly through larger and more diverse samples, inclusion of control groups, and multi-dimensional physiological assessment will be essential to advance scientific knowledge and optimize practical application of contrast training in elite football development.

Implications of the study

For practitioners, this study confirms that a simple, time-efficient CT protocol of heavy back squats and squat jumps can be used as a reliable tool to acutely stress the neuromuscular system. This acute stress can be a valuable tool for monitoring an athlete's readiness or fatigue state. For researchers, the study validates a specific protocol and measurement approach, paving the way for more complex longitudinal research designs. The demonstrated feasibility supports the use of this protocol in larger-scale investigations of chronic adaptation and performance enhancement.

Future directions

Building upon the feasibility established in this study, a comprehensive research agenda is proposed to advance understanding of contrast training in football populations. A full-scale, longitudinal investigation should employ a randomized controlled trial design with three parallel groups comprising contrast training (as described in this protocol), traditional strength training only (heavy resistance), and plyometric training only, with a fourth non-training control group to establish baseline changes, as this design would enable direct comparison of training methods and isolate the unique contributions of contrast training to chronic adaptations.

The intervention should span 8-12 weeks with periodic testing at mid-point and post-intervention, as well as follow-up assessment after a detraining period of approximately four weeks to examine retention effects, with outcome measures encompassing neuromuscular performance (including 1RM strength, countermovement jump and squat jump height, reactive strength index, sprint times over 5 m, 10 m, and 30 m, and change-of-direction ability such as the V-cut test and Illinois agility test), physiological mechanisms (including surface EMG of lower limb muscles during maximal voluntary contractions, blood lactate concentration pre-, post-, and during recovery, heart rate and heart rate variability, and hormonal responses including testosterone, cortisol, and growth hormone), morphological adaptations (including muscle architecture of the vastus lateralis and rectus femoris using portable ultrasound, and body composition via DXA or bioelectrical impedance), recovery kinetics through serial testing at 24 h, 48 h, and 72 h post-training sessions to characterize recovery profiles and identify factors predicting slow versus fast recovery, and individual response analysis investigating athlete characteristics that moderate acute fatigue magnitude and chronic adaptation to enable personalized training prescription (Madarsa et al., 2024; Lambrianides, 2024; López-Fernández et al., 2025).

Furthermore, research should explore the optimal integration of CT within weekly microcycles in ecologically valid settings, including studies examining how CT can be combined with football-specific skill practice on the same day or within the same microcycle to provide valuable practical guidance for coaches (Khan & Yadav, 2025), while comparative effectiveness research against other emerging periodization models such as integral periodization (López-Fernández et al., 2025) would establish the relative efficacy of CT for improving match performance and reducing injury risk. Finally, multicenter trials involving collaborations across institutions, leagues, and countries would enhance sample diversity and generalizability, ultimately providing the evidence base needed to inform practice in elite football development.

Complex Training (CT) Protocol: Current Implications & Future Directions

Practical & Research Implications



THE CT PROTOCOL:
Heavy Back Squats

EFFECTIVE NEUROMUSCULAR STRESS TOOL
Heavy back squats combined with squat jumps reliably assess athlete readiness and fatigue.

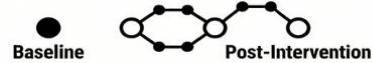


Followed by
Squat Jumps

RESEARCH VALIDATION
Validates the feasibility of this specific protocol for large-scale, chronic adaptation studies.

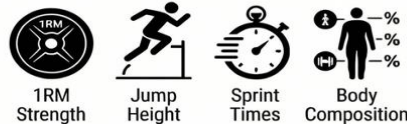
ROADMAP FOR FUTURE RESEARCH

8-12 WEEK LONGITUDINAL TRIALS



Transitioning to randomized controlled trials to investigate chronic performance effects.

MULTI-DIMENSIONAL OUTCOME TRACKING



PHYSIOLOGICAL MECHANISM ANALYSIS



PORTABLE ULTRASOUND and **HORMONAL TRACKING**
Utilizing portable ultrasound and hormonal tracking to understand underlying adaptive processes.

Figure 2: Implication of the study and future research direction

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Ethical Approval

All procedures performed were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments.

Conflict Of Interest

The authors declare that they have no conflict of interest.

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