



# Effects of Plyometric Training on Different Surfaces: Differential Impacts on Jump Height and Reactive Strength in Adolescent Soccer Players

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## Abstract

Plyometric training (PT) is a well-established method for enhancing explosive performance in youth athletes. However, the influence of training surface on the quality of neuromuscular adaptation—beyond mere performance outcomes—remains incompletely understood. This review synthesizes recent evidence, with a focus on a key 2026 randomized controlled trial comparing 4-week PT programs performed on four surfaces (concrete, sand, synthetic turf, natural grass) in adolescent male soccer players [1]. All firm surfaces (concrete, turf, grass) produced comparable improvements in jump height (squat jump: +11.1–13.0%; countermovement jump: +11.8–14.9%), sprint time, and reactive strength index (RSI), accompanied by significant reductions in ground contact time. In contrast, sand-based training improved jump height but unexpectedly reduced RSI (–29.7%) and increased contact time (+32.1%) when tested on a firm surface [1]. This dissociation demonstrates that equivalent gains in jump performance can arise from fundamentally

different neuromuscular adaptations. The review explores the biomechanical mechanisms underlying these surface-specific adaptations, discusses the principle of training specificity, and provides evidence-based recommendations for surface selection in youth soccer training. Monitoring mechanistic indices such as RSI alongside traditional performance measures is essential when training surfaces differ from competition conditions.

**Keywords:** reactive strength index, plyometric training, training surface, adolescent athletes, stretch-shortening cycle, soccer

## 1. Introduction

Explosive lower-body power, typically measured by vertical jump height and sprint acceleration, is a critical determinant of competitive success in soccer. It directly influences performance in aerial duels, rapid changes of direction, high-intensity sprints, and decisive match actions [2,3]. For adolescent players, this developmental period represents a crucial window for neuromuscular adaptation; appropriately designed training can yield substantial athletic benefits while establishing foundations for long-term athletic development [4].

Consequently, optimizing training methodologies to enhance explosive capacities in youth soccer populations remains a central research priority in sports science and strength and conditioning.

Plyometric training (PT), which harnesses the stretch-shortening cycle (SSC) to augment rate of force development and neuromuscular efficiency, has been consistently shown to be an effective intervention for improving explosive performance in youth athletes [5].

The SSC involves an eccentric contraction immediately followed by a concentric contraction, allowing storage and release of elastic energy in the musculotendinous unit and activation of the stretch reflex, thereby amplifying force production beyond what is possible with isolated concentric actions.

Recent systematic reviews and meta-analyses have confirmed that PT significantly improves jump height, sprint speed, and change-of-direction ability in young soccer players [6,7].

Despite the established efficacy of PT, it remains unclear how programming variables such as training surface influence the adaptive process. The training surface is a critical environmental factor that fundamentally alters the biomechanical context of each jump and landing, affecting ground contact time, joint stiffness, force attenuation characteristics, and elastic energy return [8]. Surface compliance influences running mechanics and energetics, with decreased surface stiffness reducing metabolic rate and increasing leg stiffness [9]. Recent studies have shown that surfaces with different hardness values lie on a continuum of mechanical stimuli, with implications for lower-limb loading patterns and injury risk [10].

Despite the theoretical importance of surface selection, current evidence guiding practical decision-making remains inconclusive. Previous studies comparing PT on different surfaces in youth populations have typically been limited to binary comparisons (e.g., firm vs. sand) and have often concluded that different

surfaces yield similar performance improvements [11,12].

However, these studies have almost exclusively focused on performance outcomes such as jump height and sprint time, implicitly assuming that equivalent performance gains reflect equivalent physiological adaptations.

This assumption may be overly simplistic. An identical increase in jump height could arise from enhanced concentric strength, improved SSC efficiency, or altered neuromuscular coordination—distinct adaptive pathways with different implications for long-term athletic development, injury risk, and transfer to sport-specific movements [13].

The quality of adaptation can be assessed through mechanistic indices such as the reactive strength index (RSI) and ground contact time (CT) during drop jumps. RSI, calculated as jump height divided by contact time, reflects SSC efficiency and has been associated with athletic performance, change-of-direction ability, and injury risk in youth athletes [14,15].

Therefore, if jump height improves but SSC function declines, the adaptation is qualitatively different and may be undesirable for sport-specific performance. Understanding how different training surfaces influence these mechanistic indices is essential for designing effective and safe training programs.

The primary purpose of this review is to synthesize recent evidence—with a focus on a key 2026 randomized controlled trial by Kim et al. [1]—comparing the effects of a standardized 4-week PT program performed on four ecologically valid surfaces (concrete, sand, synthetic turf, natural grass) on both performance outcomes and SSC-specific mechanistic indices in adolescent male soccer players. Secondary objectives include discussing the biomechanical mechanisms underlying surface-specific adaptations, examining the principle of training specificity and its implications for transfer to competition conditions, and providing practical, evidence-based guidelines for surface selection in youth soccer training.

## **2. Biomechanical Basis: Surface Properties and the Stretch-Shortening Cycle**

### **2.1 The Stretch-Shortening Cycle and Plyometric Training**

The effectiveness of PT relies heavily on the efficient utilization of the SSC. The SSC consists of three phases: the eccentric phase (pre-stretch), the amortization phase (transition), and the concentric phase (shortening). During the eccentric phase, elastic energy is stored in the musculotendinous unit, and muscle spindles are activated, generating a reflex potentiation. The amortization phase represents the time between eccentric and concentric actions; shorter amortization times are associated with greater SSC efficiency. During the concentric phase, stored elastic energy is released and the stretch reflex contributes to enhanced force production [16].

The mechanical properties of the training surface influence each phase of this cycle. Surface hardness determines the magnitude and rate of impact forces, which affect the degree of muscle stretch, the rate of eccentric loading, and the timing of the subsequent concentric action. Optimal SSC function requires rapid

eccentric loading followed by immediate concentric action; surfaces that delay this transition or alter the loading pattern may affect training adaptations. The amortization phase is particularly sensitive to surface characteristics, as any delay in the transition from eccentric to concentric action reduces the contribution of stored elastic energy to the subsequent movement.

## 2.2 Quantifying Surface Mechanical Properties

Surface mechanical properties can be quantified using the coefficient of restitution (COR), which represents the ratio of rebound velocity to impact velocity and reflects energy return upon impact. This measure provides a standardized way to compare surfaces independent of the athlete's movement pattern. In Kim et al. [1], COR values were measured using a standardized tennis ball drop test from a height of 1.5 m, with high-speed video recording to determine rebound height. The measured COR values were: concrete ( $0.643 \pm 0.021$ ), synthetic turf ( $0.485 \pm 0.019$ ), natural grass ( $0.453 \pm 0.018$ ), and sand ( $0.134 \pm 0.015$ ). These values confirm that sand exhibits substantially higher energy absorption than the other surfaces, consistent with recent surface characterization studies [10,17].

Based on these COR values, surfaces with  $COR \geq 0.45$  (concrete, synthetic turf, natural grass) can be classified as “firm surfaces,” while sand ( $COR = 0.134$ ) is classified as a “compliant surface.” This classification is consistent with the mechanical continuum proposed in previous biomechanical research [9,18]. The substantial difference in COR between firm surfaces and sand (approximately 0.45–0.64 vs. 0.13) indicates that these surface types represent fundamentally different mechanical environments for plyometric training.

## 2.3 Biomechanical Responses to Surface Compliance

Firm surfaces (high COR) minimize energy loss upon landing, facilitating effective elastic energy return. This allows athletes to generate high rebound forces with short ground contact times, creating favorable conditions for improving SSC efficiency. On firm surfaces, the amortization phase can be minimized, allowing rapid transition from eccentric to concentric actions. The high energy return also reduces the muscular effort required for propulsion, potentially allowing athletes to focus on rapid force production rather than force generation per se. This mechanical environment encourages the development of neuromuscular patterns characterized by high stiffness, rapid force production, and efficient utilization of elastic energy.

In contrast, compliant surfaces such as sand (low COR) dissipate impact energy through surface deformation, limiting elastic energy return. Under these conditions, athletes must adopt alternative strategies to generate sufficient vertical impulse. These strategies include prolonged ground contact times, increased joint range of motion (particularly at the ankle and knee), and altered muscle activation patterns [17,18]. The increased contact time allows for greater force generation through concentric action, compensating for the reduced elastic contribution. Recent biomechanical studies have confirmed that jumping on sand increases ankle and

knee range of motion while reducing loading rates, indicating that surface characteristics directly affect joint loading patterns [19].

These kinematic and kinetic adaptations, while functional on compliant surfaces, may not optimize SSC efficiency when transferred to firm surfaces. The prolonged contact time and altered joint kinematics become ingrained through repetitive practice, potentially creating a movement pattern that is suboptimal for performance on firm competition surfaces.

### 3. Differential Adaptations to Surface-Specific Plyometric Training

#### 3.1 Study Design and Methodology

Kim et al. [1] employed a randomized controlled trial design with 75 adolescent male soccer players (age:  $15.2 \pm 0.8$  years) assigned to five groups: concrete (CEM), sand (SD), synthetic turf (ST), natural grass (NG), and a control group (CON).

Participants were required to have at least three years of systematic soccer training and no structured PT in the previous six months.

All training groups performed an identical progressive PT program twice weekly for four weeks, differing only in training surface.

The PT program incorporated progressive overload in both volume (total foot contacts increased from 72 to 104 over four weeks) and intensity (exercise complexity and hurdle height increased progressively). Exercises included squat jumps, countermovement jumps, pogo hopping, hurdle jumps, drop jumps, and rebound hops.

Pre- and post-intervention assessments were conducted on a standardized indoor tartan track to evaluate transfer of surface-specific adaptations to game-like conditions.

Assessments included squat jump (SJ), countermovement jump (CMJ), drop jump (DJ) height, ground contact time (CT), reactive strength index (RSI), and 20-m sprint time.

The control group did not receive PT during the intervention period but was offered the same training protocol after post-testing to ensure fairness.

All assessments were conducted by trained researchers blinded to group allocation.

#### 3.2 Adaptations to Firm Surface Training

All firm-surface groups (CEM, ST, NG) demonstrated significant improvements across all performance measures.

Squat jump height increased by 11.1–13.0% (CEM: +3.8 cm, ST: +3.5 cm, NG: +3.2 cm), countermovement jump height increased by 11.8–14.9% (CEM: +3.7 cm, ST: +3.4 cm, NG: +3.1 cm), and drop jump height increased by 9.2–10.7% (CEM: +3.1 cm, ST: +2.9 cm, NG: +2.8 cm). These improvements were statistically significant compared to the control group (all  $p < 0.001$ ), with large effect sizes (Cohen's  $d$  ranging from 0.86 to 1.20) [1].

The 20-m sprint time also improved significantly, with reductions of 3.8–4.9% across the firm-surface groups.

Critically, the firm-surface groups also demonstrated significant improvements in SSC-specific indices. Reactive strength index increased by 0.10–0.12 (18–24% improvement) in all three groups (CEM: +0.12, ST: +0.10, NG: +0.11), with concurrent reductions in ground contact time of 15–20 ms (11–14% reduction). These changes indicate that firm-surface PT improved both the ability to generate jump height and the efficiency of the SSC, as reflected by shorter contact times and higher RSI values.

The control group showed no significant changes in any variable, confirming that regular soccer training without targeted PT was insufficient to enhance explosive performance over four weeks [1].

### 3.3 The Dissociation in Sand Training

The sand group exhibited a pattern fundamentally different from the firm-surface groups. While SJ (+1.1 cm, +3.7%,  $p = 0.04$ ), CMJ (+1.3 cm, +4.0%,  $p = 0.03$ ), and DJ (+1.2 cm, +4.2%,  $p = 0.03$ ) heights improved significantly compared to the control group, these improvements were substantially smaller than those observed in firm-surface groups (approximately one-third the magnitude). More importantly, the quality of adaptation was qualitatively distinct.

Reactive strength index decreased markedly in the sand group ( $-0.28$ ,  $-29.7\%$ ,  $p < 0.001$ ), representing a large negative effect size (Cohen's  $d = -1.04$ ). Concurrently, ground contact time increased by 45 ms ( $+32.1\%$ ,  $p < 0.001$ ) [1].

This dissociation—improved jump height but reduced RSI and increased CT—demonstrates that sand training produced adaptations that were not only quantitatively different but qualitatively distinct from those induced by firm-surface training.

When assessed on a firm surface, sand-trained athletes exhibited SSC characteristics (prolonged contact time, reduced RSI) that were actually inferior to their pre-training values, despite improvements in jump height.

This finding has important implications for coaches and practitioners who may use sand training with the assumption that it will improve performance on firm competition surfaces.

### 3.4 Mechanisms Underlying the Jump Height-RSI Dissociation

Several interconnected mechanisms may explain the divergent adaptation observed with sand training.

Surface-specific motor learning. Training on a highly compliant surface necessitates prolonged contact times and altered lower-limb kinematics to generate sufficient vertical impulse against a yielding substrate.

The sand surface deforms under load, requiring athletes to extend the contact phase to achieve adequate impulse.

This strategy, while effective on sand, becomes ingrained through repetitive practice. When athletes are subsequently tested on a firm surface, these learned movement patterns persist, resulting in inappropriately long contact times and consequently lower RSI values.

This interpretation aligns with the principle of training specificity: neuromuscular adaptations are optimized for the conditions under which training is performed [20].

This mechanism suggests that the observed RSI decline reflects a transfer deficit rather than a global deterioration of SSC function.

Shift in adaptive mechanisms. The energy-absorbing nature of sand may differentially affect the relative contribution of various adaptive pathways.

Sand training may preferentially enhance concentric strength, accounting for the observed jump height improvements, while providing a reduced stimulus for the neural and tendinous adaptations that underpin rapid force production and elastic energy utilization.

The reduced elastic energy return on sand diminishes the need for high tendon stiffness and rapid neuromuscular activation, potentially leading to adaptations that are less favorable for SSC function on firm surfaces. Konrad et al. reported that training on compliant surfaces may be less effective for increasing Achilles tendon stiffness compared to firm surfaces [21], supporting this interpretation.

Neuromuscular control adaptations. Unstable surfaces require greater co-contraction of agonist and antagonist muscles for joint stabilization. While this enhances joint stability on the training surface, it may interfere with the rapid reciprocal inhibition patterns characteristic of efficient SSC function. The increased co-contraction can prolong the amortization phase and reduce the efficiency of force transmission. The increased CT observed in the sand group may partially reflect this heightened stabilization requirement [19,22].

It is important to note that the RSI decline observed when testing on a firm surface does not necessarily indicate a global deterioration of SSC function. Rather, it suggests that adaptations to sand training are surface-specific and may not transfer optimally to performance on firm surfaces. Whether the sand group would have demonstrated superior RSI if tested on sand remains unknown, as all post-tests were conducted on a standardized firm surface to simulate game conditions. This highlights the critical role of testing specificity in interpreting training outcomes [14,23].

### 3.5 Comparisons Among Firm Surfaces

No statistically significant differences were observed among concrete, synthetic turf, and natural grass groups for any outcome variable (SJ, CMJ, DJ, RSI, CT, or sprint time) [1]. This suggests that, within the limits of the study, these three surfaces produced broadly similar adaptive responses. However, post-hoc sensitivity analysis indicated that the study was powered to detect only large effects (Cohen's  $f \geq 0.40$ ). Therefore, while no differences were detected, the possibility of smaller, potentially meaningful differences among firm surfaces cannot be excluded. Some recent studies have suggested subtle biomechanical differences between natural and synthetic turf, particularly in terms of rotational resistance and shock absorption [10,17].

Larger-scale investigations with greater statistical power are needed to determine whether sport-specific surfaces offer advantages over concrete for soccer-specific tasks.

#### 4. Integration with Previous Research

The findings of Kim et al. [1] help resolve apparent contradictions in the literature regarding surface effects on PT adaptations. Marzouki et al. reported comparable improvements across firm and sand surfaces in schoolchildren and concluded that surface type did not differentially affect outcomes [12].

However, that study did not assess SSC-specific indices such as CT and RSI and therefore could not detect the qualitatively distinct adaptive patterns observed in the 2026 trial.

This highlights the importance of incorporating mechanistic measures in training studies to capture the full spectrum of adaptation.

Ramirez-Campillo et al. compared PT on grass versus sand in youth soccer players and found similar improvements in jump height and sprint time, but noted a non-significant trend for reduced RSI in the sand group [11]. While the difference did not reach statistical significance in that study, the direction of effect is consistent with the dissociation reported by Kim et al. [1].

The consistency of the trend across studies strengthens the conclusion that sand training may have differential effects on SSC function.

Impellizzeri et al. reported comparable jumping improvements between sand and grass training in soccer players but observed greater muscle soreness with sand training, suggesting altered mechanical demands [24].

The increased muscle soreness may reflect greater eccentric loading or different muscle activation patterns, consistent with the biomechanical differences between sand and firm surfaces.

Recent systematic reviews have emphasized the importance of RSI as a monitoring tool in youth athletes. Eccher et al. and Jarvis et al. highlighted that RSI is associated with both performance and injury risk, and recommended its routine use in athletic development programs [14,15].

The evidence from surface-specific PT studies further supports this recommendation, as RSI captured qualitative differences in adaptation that were not reflected in jump height alone.

The collective evidence suggests that focusing exclusively on performance outcomes such as jump height may provide an incomplete picture of training adaptations, particularly when training surfaces deviate from competition conditions.

#### 5. Practical Applications

The synthesized evidence supports the following evidence-based guidelines for surface selection in adolescent soccer training.

For developing power and reactive strength on firm competition surfaces, concrete, synthetic turf, and

natural grass appear similarly effective based on current data.

Coaches can select among these surfaces based on availability, convenience, and facility constraints without compromising the quality of adaptation. This flexibility allows for practical scheduling and resource allocation while maintaining training effectiveness.

Sand-based plyometrics should be used strategically when the primary goal is to improve firm-surface reactive strength. While sand training improves jump height, these gains may not transfer optimally to RSI on firm surfaces.

However, sand training may be valuable for other objectives, including concentric strength development during off-season preparatory phases, eccentric overload and muscle conditioning, active recovery sessions where reduced joint impact is desired, providing variety and psychological freshness within a periodized program, and reducing cumulative impact loading during periods of high training volume.

A periodized approach combining surfaces may optimize outcomes across the annual training cycle. During pre-season and competitive phases, firm surfaces (grass, turf, or concrete) should be used to maximize SSC transfer to competition conditions and maintain specificity.

During off-season and preparatory phases, sand training can be employed to build strength base, provide eccentric overload, and reduce cumulative impact loading while maintaining training volume. Transition phases may utilize a mix of surfaces to maintain adaptability.

Practitioners should monitor RSI alongside jump height to obtain a comprehensive view of adaptive quality. A player who improves jump height but shows declining or stagnant RSI on firm surfaces may be developing strength without corresponding improvements in reactive capacity—a pattern that may warrant program adjustment.

Regular monitoring (every 4–6 weeks) can help detect such patterns early. Simple field tests using contact mats or smartphone applications can provide reliable RSI measurements without requiring expensive laboratory equipment.

If sand training is employed, periodic testing on firm surfaces (every 2–3 weeks) can help detect whether adaptations are transferring appropriately.

If RSI declines on firm surfaces during a sand-training block, it may be prudent to incorporate firm-surface sessions to maintain specificity or to adjust the volume or intensity of sand training.

A hybrid approach, combining both sand and firm-surface sessions within a training week, may help maintain specificity while gaining the benefits of reduced impact loading.

## 6. Future Research Directions

Several important gaps remain that warrant investigation. Longer intervention periods (8–12 weeks) are needed to determine whether continued sand training eventually induces SSC enhancement through gradual adaptation or whether the observed dissociation persists.

Direct biomechanical measurements using force plates, motion capture systems, and electromyography would allow a more mechanistic understanding of how surface compliance modulates neuromuscular adaptation.

Surface-specific testing protocols that include post-tests on each training surface would help distinguish between true physiological adaptation and testing-specific transfer effects.

Diverse populations including female athletes, younger children, and athletes from different sports are needed to determine generalizability.

Injury surveillance is required to examine whether observed SSC changes translate to altered injury risk during subsequent sport participation. Finally, dose-response research examining different volumes, intensities, and frequencies of surface-specific training would help establish optimal dosing guidelines.

## 7. Conclusion

This review demonstrates that four weeks of plyometric training on firm surfaces (concrete, synthetic turf, natural grass) effectively enhances both jump performance and reactive strength in adolescent soccer players.

Within the limits of current evidence, no differential effects among these firm surfaces were detected, suggesting that coaches can select among them based on practical considerations without compromising adaptation quality.

In contrast, sand-based training, while improving jump height, leads to reduced reactive strength index and increased ground contact time when transferred to a firm surface.

This dissociation—improved performance outcome but impaired mechanistic function—underscores the importance of monitoring quality indices such as RSI alongside traditional performance measures.

Equivalent gains in jump height can arise from fundamentally different neuromuscular adaptations, with potentially different implications for sport-specific performance and long-term athletic development.

Coaches and practitioners should consider the principle of specificity when designing plyometric programs.

Training surfaces that closely match competition conditions optimize transfer of SSC adaptations.

When non-specific surfaces such as sand are employed, they should be used strategically with appropriate monitoring to ensure that desired adaptations are achieved.

Regular assessment of RSI on firm surfaces can help detect whether adaptations are transferring appropriately, allowing timely program adjustments.

Future research should employ longer intervention periods, incorporate direct biomechanical measurements, utilize surface-specific testing protocols, and include diverse populations to fully characterize the long-term implications of surface-specific training adaptations.

Such investigations will further refine evidence-based guidelines for surface selection in youth athletic development.

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