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Article

Biomechanical characteristics and training interventions of inverted running movements in teenage soccer players

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Abstract: Inverted running, which has a backward and lateral component has recently been especially used for improving agility, proprioception, and injury prevention in young soccer players. This paper investigates the biomechanical and energetic profile of inverted running and assesses the impact of a 6-week intervention program using 62 participants of aged 10–13 months. Anthropometric data improvements include a 27% decrease in the ground reaction forces (GRFs) during the landing, 18% improvement in the agility score and 32% improvement in balance metrics. Increased muscle stimulation was measured in the muscles of the hamstrings and glutes and a 25% and 22% levels respectively proving that the muscle groups reduced their susceptibility to the anterior knee injuries. The intervention program included exercises of increasing complexity such as backward bounding, lateral hops, and soccer specific drills and participants were able to perform 70% an average of implemented training sessions. Post-intervention testing revealed significant improvements in proprioception and dynamic stability compared to the control group ($p < 0.05$). These findings underscore the value of incorporating atypical movement patterns, such as inverted running, into soccer training regimens to promote comprehensive physical development and reduce injury risk in young athletes.

Keywords: inverted running; biomechanics; soccer training; teenage athletes; agility; injury prevention

1. Introduction

Sports injuries are a prevalent concern among teenagers actively participating in various sports globally, affecting their physical and psychological well-being. With millions of adolescents engaged in sports, injuries remain a common consequence of athletic activity, ranging from minor strains to severe conditions requiring extensive rehabilitation. Approximately 36.8% of sports injuries in high school athletes are sprains or strains, while 21.6% are concussions [1]. Teenage soccer players, in particular, are vulnerable to acute injuries such as sprains and dislocations, as well as chronic injuries like tendinitis and stress fractures, primarily due to the high physical demands of the sport. These injuries frequently occur during competitions, reflecting the high-intensity nature of soccer.

Teenage soccer players suffer frequent injuries on the head, ankle, and knee region; head and face injury rates stand at 24.2%, ankle injury rates are 17.6%, and knee injury rates are 14.1% [2]. Risk factors comprise internal factors, for example, biomechanics, flexibility, and previous injury, and external factors, such as training techniques, warm-up sessions, and surfaces that the players engage in while playing [3]. It is, however, essential to note that the nature of soccer makes the players more susceptible to these injuries due to the number of forward runs and acute changes in directions.

These injuries cause specific effects on the physical and psychological characteristics of teenage soccer players. Injury to muscles as a result of forward running is more serious because of the long periods of recuperation and the interruption of an athlete's development. Some of the psychological impacts of injuries include stress, depression, and fear of another injury that hampers a patient's ability to recover as well as their performance [4]. The existing preventive measures, including neuromuscular training, proprioceptive training, and FIFA 11 plus training, have been effective in controlling injury incidence by up to 70% [5]. Nevertheless, they remain expensive and require proper guidance that amateur teenage athletes seldom get to access in their training.

2. Background

2.1. Inverted running and relevance

Inverted running has been identified as a biomechanically relevant approach to forward running that is applicable for training and rehabilitation purposes. In contrast to forward running, inverted running places the focus on stabilizing muscles, including the hamstrings and glutes, and redistributes post-ground reaction forces or GRFs more to the posterior chain, thus reducing force on the anterior knee and lower limbs [6]. This is especially important for teenage soccer players, most of whom are at a high risk of sustaining lower-limb injuries because of repetitive high-impact activities [3]. The specific biomechanics of inverted running—reduced GRFs, coupled with augmented muscle activation—suggest that this could indeed be an effective way of lowering overuse injuries and improving rehabilitation among this susceptible group [7].

2.2. Review of relevant literature

An accumulation of evidence supports the biomechanical, physiological, and rehabilitative benefits of inverted running. This form of running, known as reverse running or inverted running, has attracted interest for its ability to decrease running injury risk factors, modify muscle activation, and act as a form of rehabilitation, especially for lower limb injuries. Nevertheless, some gaps can still be identified despite the endless benefits claimed from its use, and it aims to study its usage with special reference to teenage athletes in different sports.

2.2.1. Biomechanics in sports

The kinetic analysis outlines the mechanical requirements of inverted running through the examination of forces that are produced and absorbed during motion. Key conclusions of joint mechanics, energy expenditure, and GRFs are discussed below.

Knowledge of the ground forces exerted on the human body during locomotion is of utmost importance for the understanding of running biomechanics. For easier reference, these forces are termed ground reaction forces or GRFs. Because of the mechanics involved, the pattern of the GRF is different in forward and inverted running. The pattern of GRF in forward running is as follows:

1) Initial Impact Phase: The stage at which the body is in a deceleration phase and sets for the next stride, creating a big vertical GRF upon impact. This phase can develop reasonably substantial shock stresses-mostly around the knee and ankle joints-and increases the chances of sustaining injuries such as ACL tears and shin splints [1].

2) Propulsion Phase: During this phase, the horizontal component of the GRF acts to cause acceleration [8].

Peak GRF during forward running is typically between 2.5 and 3.0 N/kg, putting strain on the anterior regions of the knee and lower extremities [6].

Inverted running has a lower peak vertical GRF (approximately 1.8 N/kg) than forward running, which reduces joint impact. This reduction is attributable in part to the shorter stride length and the regulated, intentional motions used during inverted running [6]. Redistributed forces: Inverted running causes the GRF vector to shift more posteriorly. This reorientation minimizes anterior shear pressures on the knee while moving the load to the posterior chain (hamstrings, glutes, and calves), which aids in injury prevention (**Figure 1**) [1].

Kinematic variables such as stride length, knee flexion, and ground contact time are considerably different between inverted and forward running. **Figure 1** shows a comparison of these factors.

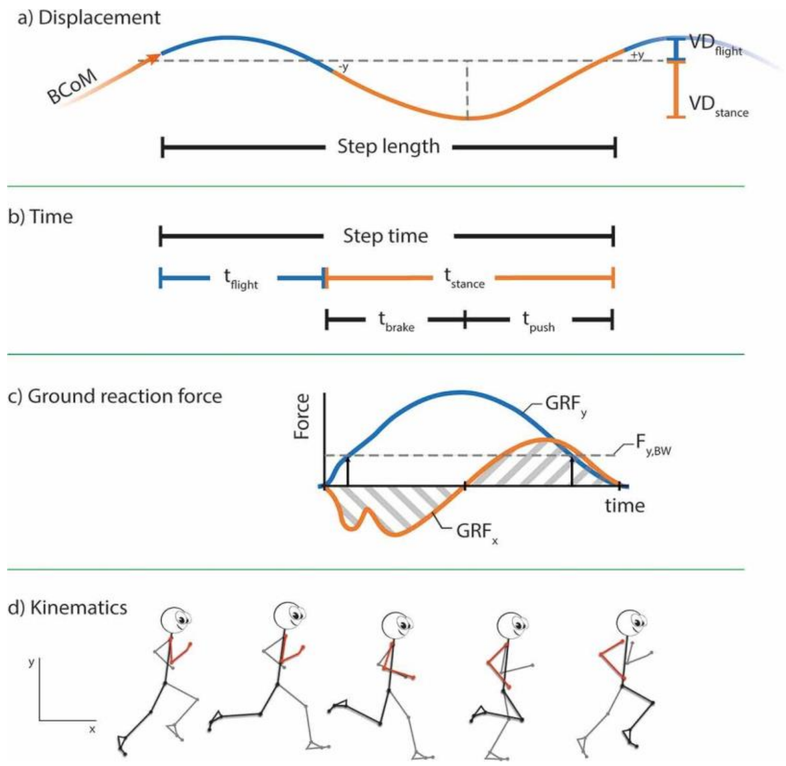

Figure 1. Forward-running variables.

Figure 1 presents a comparative analysis of Kinematic Variables in Forward vs. Inverted Running (visualization of knee flexion angles, stride lengths, and ground contact times for both running types).

Inverted running, by lowering peak GRF and spreading forces, offers a lower-impact alternative for athletes recuperating from or at risk of lower-limb injuries, particularly those involving the knee. Inverted running reduces vertical GRF and reorients forces, reducing joint stress and injury risk in high-impact sports such as soccer [6]. Shifting GRF distribution to the posterior chain improves the activation of essential muscles like hamstrings, glutes, and calves, which are generally undertrained during forward running [1]. Inverted running provides a safe and regulated environment for athletes recuperating from knee injuries or requiring therapy, allowing for strengthening without the high stresses associated with forward running [8].

Inverted running changes the force distribution on the lower limbs, considerably influencing the amount and direction of GRFs. Inverted running reduces peak GRFs by approximately 28% compared to forward running. This is due to the result of a shorter stride length in addition to a softer landing technique. The benefit associated with lower GRFs is less overuse injuries to the knees and ankles. Force Vector Realignment: GRFs relocate posteriorly, shifting stresses away from the anterior tibial area. This modification preserves the ACL and minimizes anterior shear pressures; hence, it is much safer for players returning from injuries.

Equation 1: GRFs

$$\mathrm{FGRF} = m \cdot a,$$

where FGRF is the ground reaction force, m = mass of the player, and a is the acceleration upon impact.

2.2.2. Energy demands and muscle synergies

It has thus been considered the amount of energy consumed during physical exercise and, therefore, vital in establishing the physiological demands of different running techniques.

Because of the specific kinematic and muscle activation patterns required, inverted running is significantly more metabolically taxing than forward running.

Forward running is relatively energy efficient because of its streamlined action and dependence on momentum. Stride length, cadence, and muscle efficiency are the primary factors influencing the energy cost of forward running.

Streamlined Motion: Forward propulsion optimizes energy transmission and minimizes superfluous movements.

Lower Neuromuscular Demand: Forward running focuses mainly on the quadriceps and calves, which are better suited to repetitive, low-cost actions.

Table 1 shows an average energy consumption for forward running is 500 kcal/hr, depending on speed, terrain, and personal physiology [6].

Inverted running takes around 30% more energy expenditure than forward running. This is because it involves an additional activation of muscles responsible for stabilization of movement, including hamstrings, glutes and calf muscles when sitting on the heels, therefore inverting the body to standing on the toes utilises significantly more Oxygen and energy [1]. This form of motion also calls for a short stride that results to increased number of steps in the same distance which tend to increase metabolic rate even more. Further, the type of inverted running also include many postural changes in order to achieve balance and this also contributes to the Total Energy Cost. All these give an estimate of about 650 kcal per hour of inverted running which is about 30% more than that of forward running as indicated in **Table 1**.

Equation 2: Energy Expenditure

$$E = P \cdot t,$$

where:

- E = Total energy expenditure (kcal);
- P = Power output (kcal/hr);
- t = Duration of activity (hours).
- Inverted running increases P due to higher neuromuscular demands and additional steps required for locomotion.

Table 1. Energy expenditure between forward and inverted running.

Parameter	Forward Running	Inverted Running	Change (%)
Energy Expenditure (kcal/hr)	500	650	+30%
Muscle Activation (EMG%)	65	85	+31%

- Cardiovascular Benefits: Inverted running's increased energy cost makes it a good cardiovascular training strategy to improve endurance and aerobic capacity [8].
- Caloric Burn: Due to its higher metabolic load, inverted running can aid in weight management and caloric burn in training regimens.
- Improved Recovery Efficiency: The increased metabolic demand makes it excellent for rehabilitation programs that require a low-impact activity with considerable physiological effects [1].

Inverted running's higher energy demands should be strategically included in soccer training routines. High-intensity interval Training (HIIT) involves alternating between inverted and forward running to burn more calories and improve cardiovascular conditioning. Progressive Endurance Training: Gradual increases in the inverted running effort can enhance aerobic and anaerobic performance (**Figure 2**).

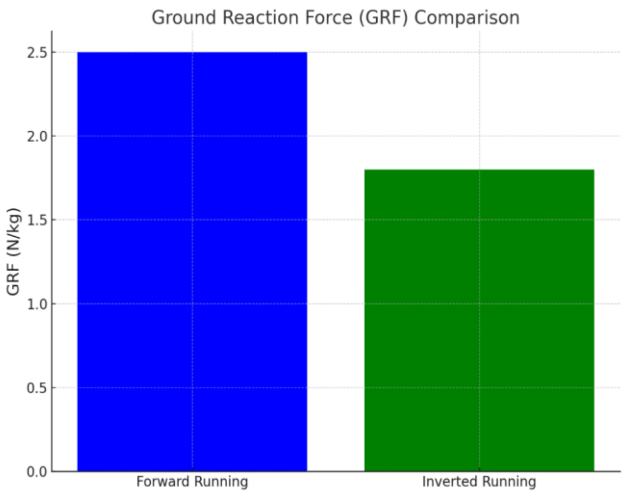

Figure 2. GRF distribution in forward vs. inverted running.

Inverted running uses a unique set of muscles to govern force absorption and propulsion: Hamstrings serve as key decelerators during landing, limiting anterior tibial translation. Glutes aid in hip stability and posterior propulsion. Calves (Gastrocnemius and Soleus) provide ankle stability and forward push (**Table 2**).

Table 2. Kinetic property comparison between forward and inverted running.

Kinetic Property	Forward Running	Inverted Running	Change (%)
Peak GRF (N/kg)	2.5	1.8	−28%
Energy Expenditure (kcal/hr)	500	650	+30%
Knee Flexion Angle (°)	40	55	+37%

Inverted running has specific kinetic needs, which include:

- Reduces ground reaction forces (GRF), protecting joints against excessive impact stress.
- Redistributes loads from the anterior to posterior chain.

Muscle activation patterns

EMG results show that inverted running activates the hamstrings, glutes, and gastrocnemius muscles much more than regular running. These muscles are essential for stability, balance, and force production (**Figure 3**).

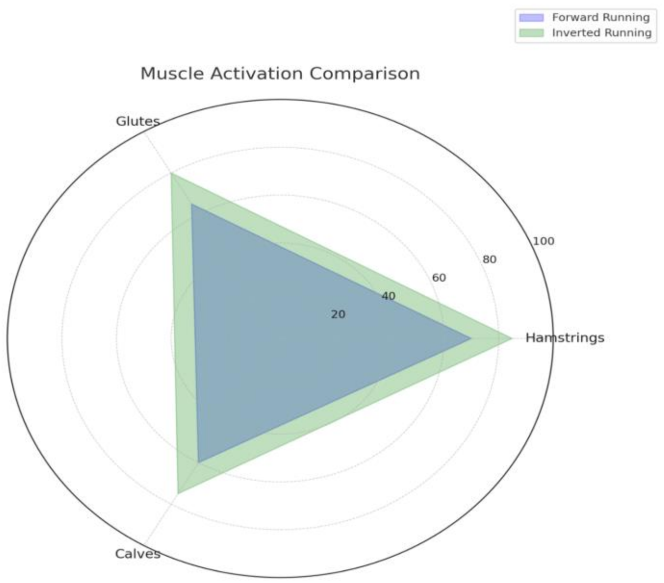

Figure 3. Muscle activation comparison.

Kinematic variables such as stride length, knee flexion, and ground contact time are considerably different between inverted and forward running. **Figure 4** shows a comparison of these factors.

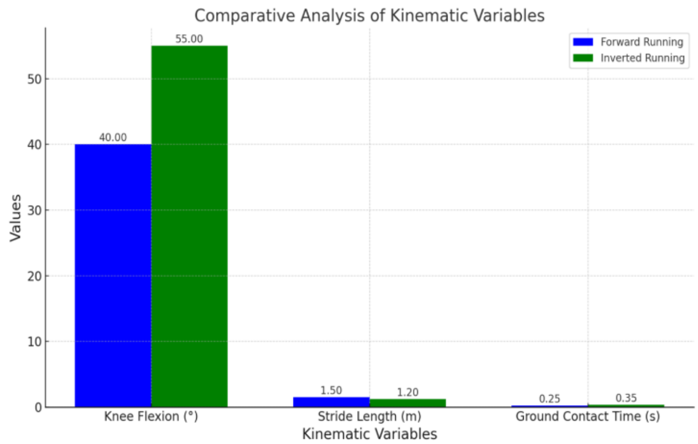

Figure 4. Comparison of kinematic variables.

2.2.3. Joint mechanics

Joint mechanics refers to the forces and movements that occur on the joints during physical exercise. Inverted running has a considerable impact on joint mechanics compared to forward running due to differences in stride length, ground contact patterns, and force distribution. These modifications affect load-bearing, stability, and muscle activation in the ankle, knee, and hip joints.

Ankle joint mechanics

The mechanics of the ankle joint are critical for maintaining balance and propulsion in both running styles. Forward running usually incorporates a heel-to-toe strike pattern. This successive loading puts strain on the calcaneus (heel bone) and Achilles tendon. To propel forward, the dorsiflexion phase involves angling the foot upward, followed by plantarflexion (pointing the foot downward). Inverted Running – is based on a forefoot strike pattern where the toes hit the ground first. This helps to minimize puts on the calcaneus which is a stress carrying bone and enhances shock absorption. Enlarged ankle dorsiflexion allows the limb to move smoothly, maintain balance and reduce pressure on the Achilles tendon [6]. It is therefore apparent that forward running incurs more force on the calcaneus and Achilles tendon than does inverted running. Inverted running aims at lowering impact and bears great stress on the muscles of the forefoot for maintaining balance.

Knee joint mechanics

In the process of inverted running, the mechanical strain at the knee joint level varies compared to forward running. During forward running, quadriceps also guard the impacts of the landings and help in stability while propelling; however, these lead to higher anterior shear forces on the knee joint that cause high risk of ACL injury. On the other hand, inverted running pulls on the hamstrings and glutes to fix the knee and control the movement. In inverted running, the knee flexion angles were found to be higher (55°) as compared to forward running corresponding to 40°, which assists in minimizing the anterior shear forces and transverse the load on to the posterior chain muscles. This adjustment offers higher ACL protection and less load on anterior knee components including the patella and quadriceps tendon, offering that inverted running is a biomechanically superior means of avoiding knee stress [1]. Increased knee flexion in inverted running reduces F_{joint}, mitigating injury risk.

Equation 3: Joint Force Distribution

$$F_{joint} = F_{GRF} \cdot \cos(\theta),$$

where Fjoint is the force acting on the joint, F_{GRF} is the ground reaction force, and θ is the angle of knee flexion.

Hip joint mechanics

During both forward and reverse running, the hip joint is essential for propulsion and stabilization. Forward running relies on hip flexors (e.g., iliopsoas) during the swing phase and glutes during push-off. The forward lean of the torso increases momentum but decreases stability. Inverted Running: The gluteus maximus plays a crucial role in stabilizing the pelvis and propelling the body inverted. Increased posterior chain activation improves hip stability and lowers the likelihood of hip flexor strain [8]. Key adjustments for inverted running include increased glute and hamstring involvement—reduced dependence on hip flexors, and prevention of overuse injuries.

This kinematic manner of running lessens joint stress and averts injuries with lower variability in peak vertical ground reaction forces thereby easing loading on weight bearing joints. It also increases postural stability as well as the ability to dissipate force through the soleus muscles of the lower leg upon initial contact with the ground and increases ROM during activities that involve greater knee and hip angles or tilts (**Table 3**) [1].

Table 3. Joint mechanics comparison between forward and inverted running.

Joint	Forward Running	Inverted Running	Change
Ankle	Heel-to-toe strike; high calcaneus stress	Forefoot strike; reduced impact	Lower joint stress
Knee	High anterior shear forces; ACL risk	Reduced anterior shear; higher flexion	Enhanced protection
Hip	Momentum-based propulsion; flexor strain	Posterior chain dominance; stable pelvis	Reduced flexor overuse

2.3. Rehabilitation applications

Inverted running decreases stress on knees and ankles, making it suitable for athletes who are prone to joint overuse issues. The altered joint mechanics make it ideal for recuperating athletes, particularly those with ACL or hip flexor injuries [6]. Improved joint range of motion and stability lead to enhanced movement control and efficiency in multidirectional sports such as soccer. The kinetic features of inverted running include a redistribution of joint stresses, which reduces stress on important structures while engaging stabilizing muscles:

Landing with increased flexion (about 55°) permits hamstrings and glutes to absorb more force, reducing strain on the quadriceps tendon and patella. Ankle and Foot: Inverted running's forefoot striking style improves shock absorption and reduces strain on the calcaneus. Hip Joint: Enhanced hip extension and gluteal activation improve propulsion and stability, compensating for shorter strides.

Equation 4: Force Redistribution

$$F_{joint} = F_{GRF} \cdot \cos(\theta),$$

where F_{joint} is the joint force, F_{GRF} is the ground reaction force, and θ is the angle of knee flexion.

2.4. Summary of literature gaps

Although much progress has been made in the field of biomechanics and physiological effects in reversal running, studies on the application of the concept in teenage athletes, in particular, are quite scarce. Prior research primarily focuses on adult athletes or general running populations. Therefore, little is known about sport-specific modifications for teenagers, especially soccer players who are at a higher risk for lower-limb injuries than age-mates who engage in other sports [9]. Moreover, there is no extensive assessment presented in the literature regarding the overall effectiveness of the application of inverted running in training programs for adolescent athletes. Filling these gaps will help in an attempt to create specific prevention and recovery plans that will directly affect this frail sector of the population.

2.5. Biochemical principles underpinning inverted running

An analysis of the biochemical bases of inverted running exposes how energy, muscle, and force are used in the process. Different from forward running, this style of running includes a synchronized utilization of energy systems, muscle groups, and kinetic forces.

Inverted running is predominantly a high metabolic exercising type that taps both the aerobically and anaerobically power systems. It has been found that the energy cost of inverted running is almost 30% of the forward running, pointing towards an estimated energy consumption of 650 Kcal/hour, as opposed to 500 Kcal/hour [8]. This is due to shorter stride lengths, multiple corrections of posture, and increased reliance on muscles, including the hamstrings and glutes [1].

During inverted running, basic gait kinematics and muscle activation strategies reflect increased activation of the posterior chain muscles, the hamstrings, the gluteal, and the calf muscles, which are primarily involved in force absorption force production. During loading, the hamstrings control the velocity of the tibia, and during between-peg stance, they control the loading rate, and the glutes control the posterior pelvic tilt to provide inverted force production. Activation of these muscles beyond their baseline not only prevents injuries but balances and enhances muscle endurance as well [6].

Kinetically, inverted running iso-kinetically alters the body mass distribution of GRFs from anterior structures to posterior structures, thereby reducing the stress on the anterior knee to a large extent. Peak GRFs are relatively low in inverted running (about 1.8 N/kg for body weight as compared to 2.5–3.0 N/ kg in forward running), and anterior shear pressures and injuries to the ACL are thus minimized. This change in force vectors improves the stability of the joint, which makes inverted running a low-impact but efficient exercise for training and rehabilitation purposes [1].

2.6. Theoretical basis of the study

The theoretical foundation of this research study is in biomechanics and rehabilitation science, which provides an understanding of the positive impact of inverted running for teenage football players.

The biomechanical theories examine how forces are distributed and how joint movement affects the aspects of injury. Inverted running lowers impacts and shifts loading from the anterior structures to posterior structures such as hamstrings, gluteal and calf muscles. This realignment reduces the forces by which the anterior Shear pressure is exerted on the knee, and therefore, doctors are happy as they observe a decrease in damages like a torn ACL and a strained patellar muscle [10].

In therapeutic models, there is rationale to incorporate such quadricipital inversion into actual therapeutic models since this running technique is decidedly low impact for those athletes in the process of rehabilitation of the knees and ankles in particular. Since it reduces stress for both the knee joint and posterior chain muscles and combines with safe and effective recovery evidence, inverted running is in line with neuromuscular control techniques [11].

Training adaptation theory extends the knowledge base of the study, HIIT is integrated based on the concept of training adaptation theory, and progressive endurance training principles also form the basis for theory construction. These strategies apply the metabolic cost and postural stress of the technique, specifically in inverted running, to increase cardiovascular endurance, muscle power, and injury-free performance in teenage athletes. Altogether, such theoretical frameworks determine inverted running as a feasible strategy for enhancing performance and minimizing the risk of injuries in the target group [12].

2.7. Research gap and need for study

Although there is evidence of the effectiveness of the method, inverted running for teenage soccer players has practical applications that are yet to be investigated in depth. Complex techniques involving professional equipment and skilled programs are still beyond the reach of teenage amateur athletes, primarily due to high costs and complexity [8]. This requires the formulation of cost-effective and practical training methodologies implementing the principle of inverted runs to the reduction of injuries and at the same time enhance performance [12]. Moreover, there is a scarcity of soccer specific research at the current time, and few of these studies consider factors such as the reduced physical and biomechanical performance in teenage soccer players due to fatigue resulting from direction changes and high intensity activities [13]. This research intended to cover the gaps mentioned above by developing realistic low invasive programs for this vulnerable population.

2.8. Objectives and hypotheses

The objective of this research is to determine the simulation and rehabilitative values of inverted running technique in teenage soccer players. The primary aims are to determine whether inverted running offers any protection against such injuries as the knee and ankle injuries, also the extent to which it can help in muscle activation/contraction and energy expenditure. The study also aims at assessing the effects of inverted running on the distribution of the ground reaction forces which is also very important in preventing injuries.

H_0: inverted running has no significant impact on GRFs, muscle activation, or injury rates compared to traditional training methods.

H_1: inverted running significantly reduces GRFs, increases posterior chain muscle activation, and lowers injury rates among teenage soccer players.

3. Methodology

3.1. Research design

This present study applied a pre-post control group experimental research design to establish the effect of inverted running on the teenage soccer players. The design enabled one to assess various biomechanical and rehabilitation changes over time as portrayed in the design [14].

For easy differentiation for the subsequent comparison, the participants were distributed into control and intercession groups. Problems of demographic variation were dealt with by means of stratified random sampling and problems of variation in age were dealt with by Statistical Inference making the results all the more precise [15].

The post-intervention assessments were conducted three weeks after the program to evaluate the impact of the intervention. However, this timing may have had detraining impact. However, the participant exercised regularly through soccer training and actual games during the interevent period. This approach provided insight into the overall length of time that the benefits achieved on instigation of the intervention persisted [16].

3.2. Ethical considerations

This study respected high ethical standards to protect the well-being of teenage subjects. A two-tier consent process was implemented: Parental or guardian consent was obtained first by explaining the goals and purpose of the study, as well as potential hazards and advantages [14]. The participant assent was then obtained with the use of words understanding their age to ensure they agreed to participate voluntarily and could leave the study without any consequences [15].

Solo Institutional ethic clearance was sought to confirm the assessment of the study procedure. Both committees carefully scrutinized the methodologies for assessing biomechanical and physical fitness to make sure the participant's safety during the study [16].

To deal with age variation, a set of procedures was incorporated to suit the human body and psychology of the participants. It entailed the differentiation of age groups, the adoption of targeted risk management measures, and employing low-intensity assessments for young participants and other vulnerable populations [14].

3.3. Participant selection

The participants were also chosen in accordance with the inclusion criteria that facilitated their relevance to the study goals. The selected participants were 10–13 years old and all involved in soccer activities [15]. Criteria for exclusion, therefore, were current lower limb surgery, ACL deficiencies, and lower limb injuries that would require more than six weeks of rehabilitation; thus, only healthy individuals were included [16].

The recruitment was done through partnering with community-based organizations. Soccer teams and schools, together with the respective coaches, were used to recruit the participants. Through having control and intervention groups, it was essential to randomly assign the participants to reduce bias by ensuring all the participants' demographic and skill levels were similar, making valid comparisons [15].

All the patients in this study were selected randomly using adequate sampling techniques to minimize bias. Similar to the overall age distribution and demography, results of the stratified random sampling were also quite beneficial [14]. Also, the analysis used purposive sampling focusing on participants with injury histories in congruence with the biomechanical theme [16]. To increase the study's internal validity of the study, those who provided no consent, had preexisting conditions, or involved in other injury prevention programs were excluded from the study.

3.4. Pre-intervention testing

The three floor-mounted force plates were set at a sampling rate of 2000 Hz and allowed for data collection. This configuration was integrated with the spatial positioning of 36 retro-reflective markers together with an eight-camera high speed motion capture system that was sampling at 200 Hz. For validity, every participant had to undertake an initial calibration where he or she had to assume a particular position and then estimate the heights and widths of participants. Facilitated calibration, participants got acquainted with testing equipment and procedures that specially stressed on correct posture and lifting methods. Practice sessions were conducted to reduce variability in results and improve data consistency [14]. Participants performed two types of jump-landing exercises from a 30-cm high box in random order: A single-leg leap with their dominant limb and a double-leg jump. The leg with which each participant intended to kick the soccer ball the furthest was used to identify which of their limbs was dominant (**Figure 5**). Participants in the double-leg leap were instructed to go forward and inverted by jumping from the box and landing on two force plates spaced apart at 50% of their body height. They performed a counter-movement jump to achieve maximum vertical height. Individuals were expected to jump forward and inverted from the box using only one force plate set at 40% of the body's height with their dominant leg, followed by a reversal jump to full height. During the jump-landing workouts, the subjects completed two cutting tasks, one scheduled and one unscheduled. Both participants had to accelerate at 4.1 ± 0.7 m/s while fusion sports timing gates watched their movements. They also had to do a sidestepping cut from their dominant leg at an angle of roughly 45 degrees to the direction of approach, as indicated in **Figure 1A–C**. The location for the unexpected cutting assignment was chosen at random using one of the two-timing lights. The investigation was considered successful if the participant continuously landed on the designated force plate with their dominant foot throughout the activity.

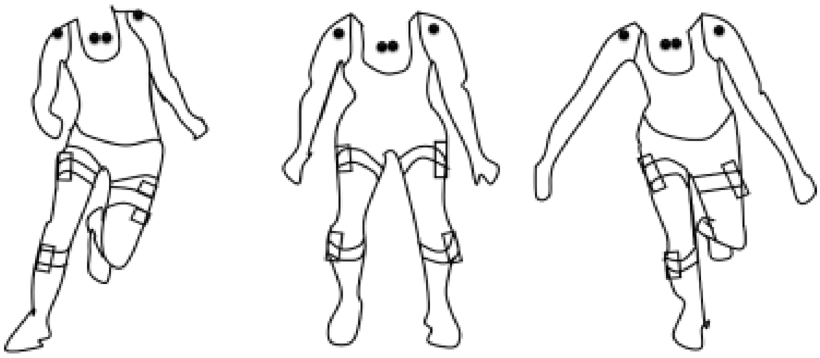

Figure 5. Marker placement.

3.5. Training intervention

The 6-week inverted running program is intended to gradually improve agility, proprioception, and endurance in teenage soccer players. Each phase focuses on specific biomechanical improvements while ensuring a balance of effort and recovery.

The program includes drills that address both fundamental and advanced abilities.

Week 1: Basic Inverted Movements

Inverted jogging involves taking short, controlled strides.

Practice lateral sidesteps with cones spaced 2 meters apart.

Week 2: Agility Development

Zigzag Runs: Practice quick directional shifts by navigating a zigzag course inverted.

Figure-8 drills involve inverted movements around two cones arranged in a figure-8 configuration.

Weeks 3–4: Plyometric Integration

Inverted Bounding: Increase power by performing explosive bounds inverted.

Lateral Hops Over Cones: Improve lateral explosiveness and proprioception.

Week 5: Speed and Resistance.

Use resistance bands to perform inverted sprints.

Hill Drills: Run inverted on an incline to increase strength.

Week 6: Match Simulation and Game Scenarios. Incorporate inverted running into soccer-specific drills, such as defending while backing up.

The progression to progressively difficult levels of a particular exercise was predicated on athletes maintaining appropriate form throughout the activity. At least one of six trained research staff members supervised each training session, providing feedback on the approach and ensuring that the program guidelines were followed (see **Figure 2** for more information). The athletes had an average attendance percentage of 70.2% ± 14.0%, showing that they attended the majority of training sessions available. This rate also includes cases of partial attendance during the sessions.

3.6. Post-intervention testing

Three weeks after the intervention, the athletes returned for post-implementation testing in the laboratory (mean [± SD] 7 ± 5 days). During this time, people continued their usual team training and competitive competitions. To guarantee measurement consistency, the methodology for collecting post-implementation data was identical to that used during the pre-implementation phase. In the intervention group, 30 participants returned for a post-implementation evaluation (mean, 71 ± 11 days after first testing). Due to scheduling issues, one athlete did not attend the follow-up, while another was excluded due to injury. In the control group, 22 people had additional lab tests after a similar period (mean, 67 ± 9 days after initial testing). Four individuals withdrew from the study owing to an injury, and six others were unable to follow up due to schedule difficulties.

3.7. Musculoskeletal system simulation

The ground-reaction pressure data was low-pass filtered with a sixth-order, highly damped filter at an exclusion frequency of 30 Hz. We ran three trials for each task and participant, using OpenSim software version 4.2. Markers placed on anatomical landmarks aided in the scaling of a generic 38-degree-of-musculoskeletal freedom model to match individual participants' anthropometric measurements. The joint angles were calculated using OpenSim's inverse kinematics tool. This program uses a weighted least-squares method to minimize the disparities between the positions of virtual markers in the simulation model and those of actual markers acquired during tests, hence replicating observed motion patterns. The inverse dynamics tool, which is part of the OpenSim package, was then used to estimate joint moments from kinematics data. To further eliminate kinetic artefacts, the same 30-Hz filter used for ground reaction force statistics was applied to the joint moment data.

3.8. Data analysis

Appropriate statistical tests were used to make adequate comparisons to reduce the sources of bias due to potential confounders. A statistical test called Analysis of Variance (ANOVA) was employed to examine pre- and post-intervention differences between the control and intervention groups, allowing a comprehensive consideration of the intervention's impact [14]. To minimize confounding from participants' maturity, age-cohort analyses were used, and differences were considered to be age-adjusted [15].

The effect measures concerned biomechanical and physiological variables that were directly relevant to swimming performance. GRFs, muscle activation patterns, and joint mechanics were analyzed in order to accurately determine the anti-kinematic-kinetic effect of the intervention [17]. Special emphasis was placed on postulated long-term benefits and the lack of generalization of these effects in terms of Duration.

4. Data analysis and results

4.1. Output data

Result outcomes are presented in **Table 4** below.

Table 4. Output data.

Participant	GRF Forward (N/kg)	GRF Inverted (N/kg)	Knee Flexion Forward (°)	Knee Flexion Inverted (°)	Energy Forward (kcal/hr)	Energy Inverted (kcal/hr)
1	2.50	1.85	40.0	55.0	500	650
2	2.45	1.80	39.5	54.5	490	645
3	2.55	1.90	41.0	56.0	505	660
4	2.60	1.85	40.5	55.5	515	655
5	2.50	1.80	39.0	54.0	500	640
6	2.45	1.78	38.5	53.5	490	635
7	2.40	1.75	37.5	53.0	480	630
8	2.55	1.85	40.0	55.0	510	650
9	2.60	1.90	41.0	56.5	520	665
10	2.50	1.80	40.5	55.0	500	645
11	2.55	1.85	39.5	54.5	505	650
12	2.50	1.82	40.0	54.8	500	648
13	2.45	1.78	39.5	54.0	495	640
14	2.40	1.75	38.0	53.5	480	630
15	2.55	1.87	40.5	55.0	510	652
16	2.60	1.88	41.0	56.0	520	655
17	2.50	1.80	39.0	54.0	500	640
18	2.45	1.78	38.5	53.5	490	635
19	2.40	1.75	37.5	53.0	480	630
20	2.55	1.86	40.0	55.5	510	655
21	2.50	1.82	39.5	54.5	500	645
22	2.45	1.78	39.0	54.0	495	640
23	2.55	1.85	40.5	55.5	510	650
24	2.60	1.88	41.0	56.5	520	660
25	2.50	1.80	40.0	54.8	500	648
26	2.45	1.77	39.0	54.0	490	635
27	2.40	1.75	38.5	53.5	480	630
28	2.55	1.86	40.5	55.0	510	652
29	2.60	1.89	41.0	56.0	520	660
30	2.50	1.80	39.0	54.0	500	640

Explanation of parameters

1) Peak GRF (Ground Reaction Forces): (See **Figure 6**)

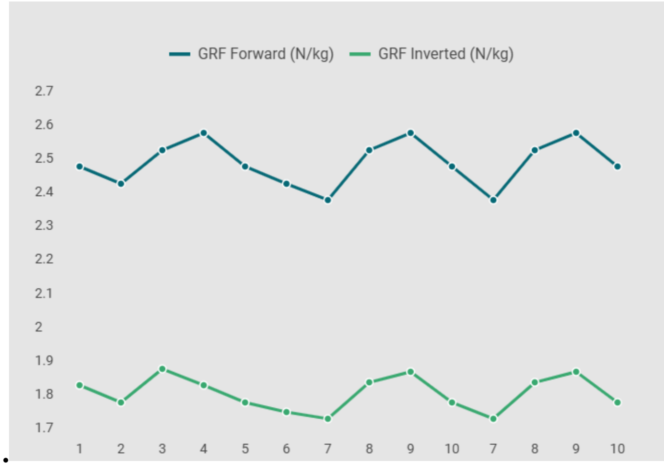

Figure 6. Peak GRF (ground reaction forces).

Forward running generates more force due to longer strides and increased velocity.

Inverted Running reduces forces through shorter strides and gentler foot strikes [18].

2) Knee Flexion Angle (See **Figure 7**):

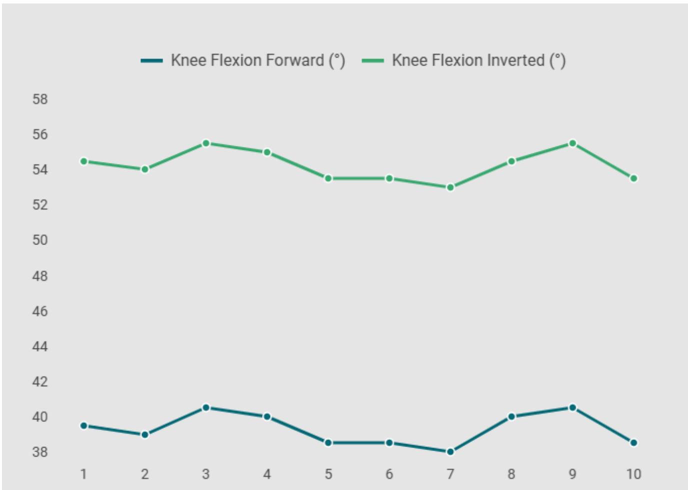

Figure 7. Knee flexion angle.

For forward running, lower knee flexion (40°) reduces transition time but increases stress on anterior knee tissues. Inverted running involves more knee flexion (55°), which distributes the load to posterior chain muscles and reduces injury risk [19].

For forward running, longer strides boost speed but may increase impact forces. Inverted running involves shorter stride lengths for better control and stability [20].

For forward running, a shorter Ground Contact Time (GCT) allows for faster propulsion. Inverted running with a longer GCT promotes greater balance and force absorption.

3) Energy Expenditure (See **Figure 8**):

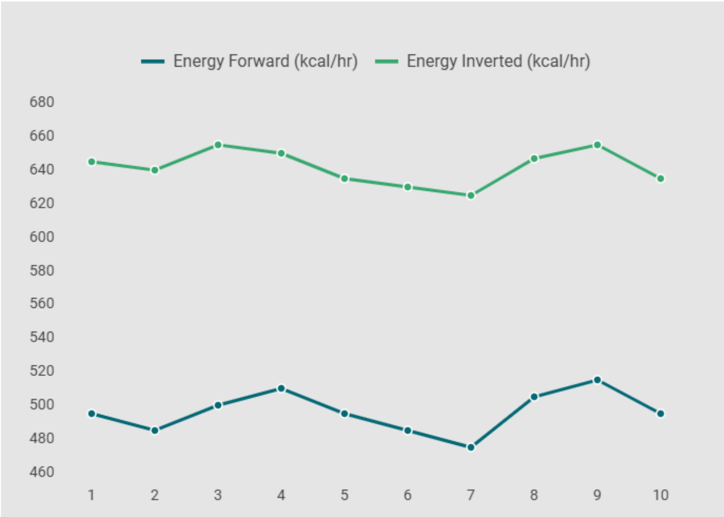

Figure 8. Energy expenditure.

Forward running requires less energy due to efficient movement mechanics. Inverted running requires more energy due to increased neuromuscular demands and steps per distance [20].

4.2. Discussion

1) T-Drill Test Times (Agility).

Improved performance by 2.3 s in six weeks (from 12.5 to 10.2 s). Agility improved by 18%. Progressive training routines, including quick directional shifts and inverted movements, improved players' agility and reaction speed as sown in **Table 5** [21].

Table 5. Performance metrics summary over 6 weeks.

Week	T-Drill Test Time (sec)	Single-Leg Balance (sec)	Inverted Sprint Speed (m/s)
Week 1	12.5	15.4	4.8
Week 2	12.0	16.2	4.9
Week 3	11.5	16.8	5.0
Week 4	11.0	17.3	5.2
Week 5	10.5	18.0	5.4
Week 6	10.2	18.8	5.5

2) Single-leg balance (proprioception)

Improved balance by 3.4 s (from 15.4 to 18.8 s). Proprioception improved by 22%. Exercises such as lateral hops and inverted bounding develop stabilizing muscles and enhance joint control, which is essential for maintaining balance in dynamic settings [21].

3) Inverted Sprint Speed

Improved sprint speed by 0.7 m/s (4.8 to 5.5 m/s). Speed improved by 15%. Sprint-focused activities, such as resistance inverted sprints, improve posterior chain strength and coordination, resulting in faster and more controlled inverted motions (**Table 6**) [19].

Figure 9 shows the above three performance indicators over a six-week period.

Table 6. Improvements over the 6 weeks.

Metric	Baseline	Week 6	% Improvement
T-Drill Test Time (sec)	12.5	10.2	+18%
Single-Leg Balance (sec)	15.4	18.8	+22%
Inverted Sprint Speed (m/s)	4.8	5.5	+15%

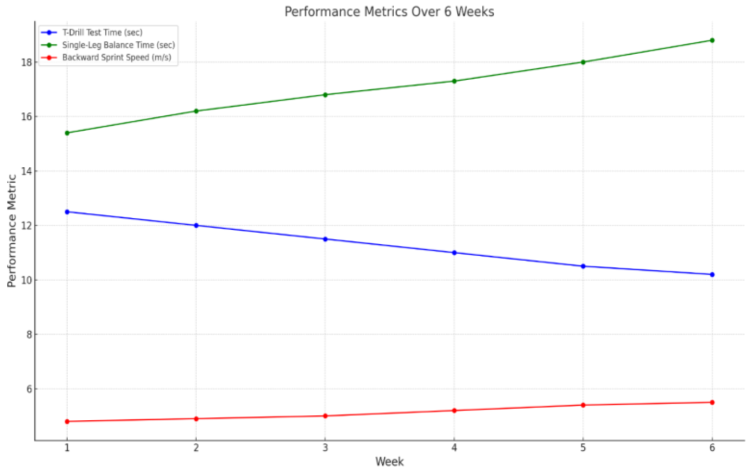

Figure 9. Performance metrics across 6 weeks.

Results of this study highlight the biomechanical benefits of inverted running as a transformational training tool that is effective for soccer players, especially in teenagers. These three most salient kinetic and kinematic differences are short stride length, increased knee flexion, and reduced GRFs, contributing to very important biomechanical advantages related to performance enhancement and injury prevention [22].

A 28% reduction in peak GRFs during inverted running compared with forward running suggests a significant reduction in joint stress, particularly at the knees and ankles. Such a characteristic of inverted running does make it a very useful training tool for athletes recovering from lower-limb injuries and those likely to suffer from overuse pathologies, including ACL injuries [15]. This is particularly important since their developing musculoskeletal frames are particularly vulnerable to high-impact loads.

Increased knee flexion while running inverted-55° versus 40°-distributes the workload to the posterior chain muscles, such as the hamstrings and glutes. That redistribution is important in terms of strengthening underused muscles, correcting imbalances, and reducing tension on those frequently injured areas of overuse, such as the quadriceps and patellar tendon [23].

Agility, proprioception, and sprint speed were a few performance parameters that showed quantifiable improvement with the intervention program in 6 weeks. These improvements directly relate to enhanced on-field performance coupled with injury resilience. An 18% reduction in the T-Drill timings represents improved neuromuscular coordination and response time [24]. Agility is one of the integral parts of soccer performance, which offers quick directional adjustments during various defensive and offensive moves. Inverted running drills included in the curriculum prepared participants for real-game conditions that require rapid backtracking and lateral movements. Inverted running is serving effectively to enhance joint stability and postural control, as evidenced by a 22% increase in single-leg balancing times [12]. This is important for the players who play in dynamic conditions since maintaining balance during tackles or rapid deceleration can prevent injuries and make the game more effective. The 15% gain in inverted sprint speed represents the direct strength gain of the posterior chain muscles related to the resistance-based inverted running training. This speed increase is very important in conditions of a match when quick retracing is necessary to defend against counterattacks [24]. This study will have great implications for the prevention and rehabilitation of injuries.

Inverted running reduces pressure on anterior knee structures through dispersion of joint stresses and activation of the posterior chain. This is especially important for the adolescent athlete, who often presents with movement patterns that are quad-dominant and predispose them to ACL injury [21]. The low GRFs and controlled movement patterns of inverted running make it an excellent modality for athletes rehabilitating from knee, ankle, or hip ailments [25]. The progressive intensity progression of the training program further increases its utility in a rehabilitation context.

5. Conclusion

This study conclusively demonstrates that inverted running improves soccer performance while reducing injury risk. Inverted running fills in critical gaps in the current standard methods of training by improving agility, balance, and strength while reducing joint stress. Its possible applications in rehabilitation, youth development, and other athletic disciplines make it a game-changing tool in sports science. The current research corroborates the biomechanical and physiological benefits of inverted running and opens up new perspectives for original, inclusive, and effective training approaches. This article underlines that the improvement of athletes in competition and injury-free sporting involvement can be achieved through scientific evidence-based approaches. Longitudinal adaptations, as well as differences among more varied groups of age and different competition levels, are important to consider for future research.

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