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Effect of Injury Prevention Training with Global Systems Approach on Kinetics and Trunk and Lower Extremity Kinematics during Jump Landing in Active Individuals at Risk of Anterior Cruciate Ligament Injury: Quasi-experimental Study

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Review Article

Abstract

Introduction: Injury prevention training using a global systems approach has been suggested to reduce biomechanical risk factors for anterior cruciate ligament (ACL) injuries during landing. This study aimed to compare a traditional injury prevention program to injury prevention training using a global systems approach on trunk and lower extremity kinematics and kinetics during a single-leg cross drop task in athletes at risk of ACL injury.

Materials and Methods: Thirty-nine male and female athletes (control = 19 and injury prevention training using a global systems approach = 20) participated in this study. Peak knee and hip flexion, peak knee abduction, lateral trunk flexion angles, peak knee abduction moment, and peak vertical ground reaction forces (GRF) were assessed for all participants during a single-leg cross drop task at baseline and six weeks following injury prevention training. Repeated measures analysis of variance (ANOVA) was used to investigate the biomechanical data between-group differences.

Results: A significant group × time interaction effect was found for peak vertical GRF (P = 0.007), peak knee abduction moment (P < 0.001), knee abduction (P = 0.006), and lateral trunk flexion (P = 0.036), favoring the global systems approach group at six weeks. Significant main effects of time were found for the vertical GRF, knee abduction moment, hip flexion, knee flexion, knee abduction, and lateral trunk flexion (P < 0.001) after the training. No significant group × time interaction effects were found for hip flexion (P = 0.734) and knee flexion (P = 0.103).

Conclusion: Global systems approach improved the biomechanical risk factors for ACL injuries during single-leg cross drop landing compared to thigh-focused exercises.

Keywords: Anterior cruciate ligament; Injury prevention training; Landing biomechanics; Ground reaction force; Single-leg cross drop

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Introduction

Sports that involve jumping and landing movements frequently lead to skeletal-muscular injuries of the lower limb, accounting for 53% of all reported athletic injuries in the National Collegiate Sports Association, of which, 36.8% are preventable non-contact injuries (1, 2). Such injuries can result in wasted time, financial costs, reduced performance, and harm to athletes' health. Therefore, preventing non-contact injuries should be a top priority (2). These injuries have multifactorial causes, including both internal and external factors (3). To prevent such injuries, it is crucial to adjust biomechanical and neuro-muscular factors (4-6).

Dynamic alignment patterns, which can increase the risk of injury, include various movements such as trunk and hip drop, thigh adduction, and excessive foot pronation. These patterns can also lead to reduced hip

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and knee flexion, thereby increasing knee loading. Multi-segment malalignment, especially in the trunk, may occur due to a lack of unilateral leg control support (4, 5). Repetitive jumps and landings can cause damage to the anterior cruciate ligament (ACL) due to sudden ground reaction forces (GRFs) and large external moments in the knee (7, 8). Research using three-dimensional motion analysis has identified several biomechanical risk factors during jumping and landing (7), such as knee abduction, knee valgus angle, hip and knee flexion, and internal rotation, as well as high medial displacement of the knee (9-11).

To accurately predict peak landing forces and ACL damage, it is important to focus on frontal plane dynamics at the hip and knee during landing rather than sagittal measurements such as flexion (7). Knee valgus loading is a primary cause of non-contact ACL injury, while hip adduction has been found to be a significant predictor of knee abduction (7). Women tend to have more hip adduction and knee abduction range of motion (ROM) than men during landing (7, 12). Weakness in neuromuscular control and reduced muscle coordination during all landing movements can contribute to these risk factors (7, 12). Therefore, training protocols that target these issues and improve neuromuscular control can effectively reduce the incidence of ACL injuries in athletes (7).

Many knee prevention and rehabilitation approaches today focus solely on the "regional/proximal" area, ignoring the broader "global complexity" of movement patterns throughout the entire movement chain (13). Unfortunately, such programs typically comprise exercises that concentrate on the thigh region (14, 15), which only enhance local hip strength. However, it has been observed that exercises that focus only on the hips do not significantly alter lower limb kinematics during high-speed, dynamic activities like running and landing (15). To achieve better outcomes, a more comprehensive approach to knee prevention and rehabilitation is needed.

Many ACL prevention and rehabilitation programs have a vague interpretation of "proximal" control as any movement above the knee. However, recent studies show that impaired trunk control contributes to injuries to the knee and other parts of the motor chain (16). Therefore, knee rehabilitation programs should not only integrate the hip joint but also include challenges of proprioception and trunk-related perturbation (15). The trunk is a key proximal lever that directly affects the function of the lower limb and potentially the position of the hip acetabulum in the femur. Increasing trunk stability plays an essential role in controlling dynamic knee valgus and stiffness throughout the ROM (15, 19, 20). Athletes with poor neuromuscular control in the trunk are more prone to knee injuries, indicating that "proximal" control should combine both thigh and proximal trunk movements. Thus, a combined program including both thigh strengthening and proximal trunk control is necessary for effective ACL prevention and rehabilitation (15, 21).

The proposed global systems approach to exercises aims to address key principles missing from popular ACL injury prevention programs. These principles include considering the arthrokinematics of the hip joint, using the trunk as a resistance lever, and incorporating a flight phase for the return GRFs (13, 15). This approach has the potential to improve knee rehabilitation and reduce ACL injury and re-injury rates (13, 15). While previous research has shown some clinical effectiveness of focused thigh exercises, the findings are not consistent. Therefore, it is important to investigate the effect of injury prevention exercises with a global systems approach on the biomechanics of the trunk and lower limbs during landing in athletes prone to ACL injury. The present study aims to do just that, and it is hypothesized that the global systems approach will have better effects on ACL injury prevention compared to thigh-focused exercises.

Materials and Methods

This was a semi-experimental study and 42 subjects active in fields with jumps (handball, basketball, and volleyball) volunteered to participate in the research. To determine the minimum number of samples, sample size estimation software (G*Power version 3.1.9.2) was used with a test power of 0.8, effect size of 0.25, and significance level of 0.05. Subjects were selected purposefully (knee valgus greater than 10 degrees in single-leg landing test). Then, people were randomly divided (22, 23) into the group of injury prevention exercises using the global systems approach (21 people) and the control group (thigh-focused exercises) (21 people).

The study with the code of IR.KHU.REC.1400.008 received approval from specialized ethics committee of Kharazmi University, Tehran, Iran in biomedical research prior to data collection. The subjects were fully informed about the research objectives and methods, and provided voluntary participation in the study by signing an informed consent form that adhered to the latest revision of the Declaration of Helsinki.

To be eligible for the study, participants needed to meet specific criteria. These included being an active man or woman with a dynamic valgus (knee valgus angle greater than 10 degrees) during single-leg landing, having at least three years of physical activity experience in disciplines with landing jumps, having a normal body mass index (BMI) between 18 and 25 kg/m^2, and having no injuries in the trunk or lower limbs in the past year (24). Exclusion criteria included any neurological disorders, vestibular system disorders, history of surgery or spine fracture, lower limb surgery, history of knee pain, and lower limb muscle damage in the last 12 months (20, 21).

The study involved conducting 5 single-leg cross-landing tasks on the dominant limb from a 31 cm box before and after the training program. To determine the dominant limb, subjects were asked which leg they preferred to land on after jumping. The single-leg crossover landing involves balancing on one leg and landing forward and inward while landing crosswise and in front of the stationary leg. For instance, to perform a single-leg crossover landing on the right side, the subject was required to stand on the right side of the box and on their left leg. The subjects were supposed to land with their right foot in the middle of the force plane and maintain that position for 2 seconds after landing. If the subject was unable to perform the landing correctly or maintain balance after landing on the force plate, the test was repeated. Rest periods of at least 1 minute were provided between each landing to minimize fatigue. Prior to performing the single-leg crossover landing task, the subjects warmed up for 10 minutes with soft jogging, stretching, and plyometric exercises (24, 25).

To reduce the risk of ACL injury in athletes, our exercise programs included a global systems approach to injury prevention exercises and hip-focused exercises (15). These programs are designed with three stages, each with a specific goal, to promote optimal movement strategies and challenge athletes at an appropriate level (14, 26). Progression to the next stage depends on the correct execution of each task in the previous stage and is tailored to each athlete's individual abilities and skill set. We evaluated each activity separately to ensure that athletes progressed at a suitable pace and were challenged appropriately.

The control group underwent thigh-focused exercises aimed at gradually improving hip joint function through jumping-landing maneuvers. The exercises included hip strength exercises and balance exercises and were conducted over six weeks with three sessions per week, each lasting 60 minutes. The training was divided into three stages, with specific goals for each stage. The hamstrings resistance training progressed from open to a closed ROM exercises, while balance exercises started with controlling body position on an unstable surface with two legs before progressing to one leg. Plyometric exercises involved using resistance bands of weak, medium, and strong levels on the subjects' thighs while performing the jump-landing protocol.

Over the course of six weeks, participants engaged in injury prevention exercises using the global systems approach three times per week for a total of 18 sessions, each lasting approximately 60 minutes. These exercises were based on the protocol established by Dischiavi et al. (13) and included a range of activities targeting the thighs, such as single-leg squats, jumps, and balances on a Bosu ball. Additionally, participants engaged in exercises that involved triaxial resistance in the proximal trunk, such as forward lunges and side hops.

In order to gather data on a one-legged vertical jump, a motion analysis recording system with 8 cameras (Vicon, UK) sampling at 120 Hz and a force plate (Model 9260AA6, 60x50 cm, Kistler Instrumente, Switzerland) sampling at 1200 Hz were utilized. To ensure accuracy, a static calibration test was conducted before reflective markers were attached to the lower limb, pelvis, and trunk. Bilateral markers were placed on the acromioclavicular (AC) joint, anterior superior iliac spine (ASIS), greater trochanter, inner and outer femoral condyles, inner and outer malleolus, sacrum, and C7 and T10 spinous process. Additional tracking markers were added to the left side of the sacrum, mid-thigh, tibial tubercle, and distal and lateral parts of the lower leg, heel, dorsal and medial surface of the foot, fifth metatarsal, and between the second and third metatarsals. Finally, all data were filtered using a fourth-order Butterworth filter at 12 Hz.

We established specific definitions for key moments during the landing phase of a one-leg vertical jump. These included initial impact, defined as the first point at which the vertical GRF exceeded 10 N, and fingertip, defined as the moment when the vertical GRF first fell below 10 N after initial contact. The landing phase was defined as the period from initial impact to peak knee flexion. To further analyze the landing phase, we calculated the maximum abduction, flexion, adduction, and internal rotation of the thigh, as well as the maximum vertical GRF. All joint torques were reported as external torques. Additionally, we measured lateral trunk flexion, thigh flexion, knee flexion, and abduction angles as the maximum angles during the landing phase. We conducted five successful one-leg vertical jump trials and averaged the values to obtain accurate data. All data processing was performed using MATLAB software version 8.4, 2014b.

In this study, we utilized various statistical methods to analyze our data. Descriptive statistics were presented as mean ± standard deviation (SD). We tested for normal distribution using the Shapiro-

Wilk test and assessed homogeneity of variance with Levene's test. To compare demographic characteristics between subjects, we employed the independent t-test for continuous data and the chi-square test for classified data. We used repeated measures analysis of variance (ANOVA) and post-hoc Bonferroni tests to assess differences between groups in response to injury prevention exercises, specifically looking for time × group interaction effects. The effect size was calculated as the partial eta-squared (ηp^2), with values of 0.01, 0.06, and 0.14 indicating small, medium, and large effects, respectively. All statistical analyses were conducted using SPSS software (version 25, IBM Corporation, Armonk, NY, USA). Statistical significance was determined as $P < 0.05$.

Results

To ensure the accuracy of our study, we excluded three subjects – two who did not participate in the post-test and one who missed practice sessions. The normality of data was checked using the Shapiro-Wilk test and the homogeneity of variances was checked using Levene's test, both of which showed a significance level of $P < 0.050$ in the pre-test. Demographic variables did not significantly differ between the two groups, as shown in table 1. The study had a high participation rate of 92.9%.

Table 2 displays the kinematic variables analyzed, including angles of trunk lateral flexion, hip flexion, knee flexion, and abduction. Before the intervention, there were no significant differences between the experimental and control groups. However, significant time × group interaction effects were observed for trunk lateral flexion angles (F = 1.37, ηp^2 = 0.101, P = 0.490) and knee abduction (F = 1.37, ηp^2 = 0.190, P = 0.006), indicating greater improvement in the experimental group post-intervention. Specifically, post-tests revealed significantly lower angles of trunk lateral flexion (P = 0.008) and knee abduction (P = 0.029) in the experimental group compared to the control group. Although there was no significant interaction effect for hip and knee flexion, both groups showed significant increases in these angles from pre-test to post-test ($P < 0.001$). Furthermore, no significant between-group differences were observed in hip flexion (P = 0.660) or knee flexion (P = 0.134) in the post-test phase. The study analyzed maximum vertical GRF and maximum knee abduction torque in two groups. The pre-test stage showed no difference between the groups. However, a time × group interaction effect was observed for maximum vertical GRF ($F_{1.37}$ = 8.10, ηp^2 = 0.180, P = 0.007) and maximum knee abduction ($F_{1.37}$ = 24.50, ηp^2 = 0.398, $P > 0.001$) moment. Post-hoc Bonferroni analysis revealed lower scores in the experimental group for both variables over six weeks. A main effect of time was observed with an increase in both variables from pre-test to post-test in both groups.

Discussion

This study aimed to explore the effectiveness of injury prevention exercises with a global systems approach versus traditional thigh-focused exercises in reducing biomechanical risk factors for ACL injury during single-leg crossover landing in active individuals prone to ACL injury. The six-week training program demonstrated that injury prevention exercises with a global system approach were significantly more effective in reducing trunk lateral flexion angles, knee abduction, maximum vertical GRF, and maximum knee abduction torque during single-leg landing compared to thigh-focused exercises.

Studies have highlighted the importance of trunk lateral flexion, knee abduction, and knee abduction torque angles in the mechanism of ACL injury in athletes (26, 29). The knee abduction moment, which is affected by the position of the center of mass relative to the knee, is a key factor. During single-leg landing, trunk lateral flexion angles decrease and the center of mass moves inward, shortening the torque arm and resulting in a safer movement strategy. To address non-contact ACL injuries that involve multi-plane mechanisms, external resistance around the proximal trunk can create a longer lever for force transmission across multiple joints. However, creating a spiral force (vertical longitudinal axis/Z-axis) with external resistance presents a challenge for lower extremity control in athletes.

Table 1. Demographic characteristics of the participants of the two groups

Variable	Experimental group (injury prevention with global system approach, 20 people)	Control group (thigh focused approach, 19 people)	P
Age (year)	23.4 ± 2.3	24.1 ± 2.4	0.330
Height (cm)	183.1 ± 9.1	184.4 ± 6.4	0.720
Wight (kg)	74.3 ± 9.3	76.4 ± 5.9	0.330
BMI (kg/m^2)	22.1 ± 1.1	22.6 ± 0.9	0.170
Experience in jumping sports (year)	7.4 ± 2.3	7.3 ± 2.9	0.870

Data are reported as mean ± standard deviation (SD)
BMI: Body mass index

Table 2. Intra-group and inter-group changes of subjects' kinetic and kinematic variables during single-leg cross-landing

Landing variables	Group	Pre-test	Post-test	Percentage of changes	Effect size (partial eta)	Mean difference between the groups (P)	Time effect	Interaction effect of time and group
Knee flexion	Experimental	49.33 ± 5.08	58.90 ± 6.66*	↑ 19.40	0.003 (-2.94)	0.134	P < 0.001	P = 0.734
	Control	51.82 ± 4.56	61.84 ± 5.21*	↑ 19.30			F = 220.65	F = 0.12
Knee abduction	Experimental	13.51 ± 2.45	5.68 ± 2.54*	↓ 57.96	0.190 (-1.75)	0.029**	P < 0.001	P = 0.006
	Control	12.80 ± 2.02	7.43 ± 2.25*	↓ 41.95			F = 249.46	F = 8.62
Hip flexion	Experimental	53.84 ± 12.76	71.97 ± 17.99*	↑ 33.67	0.070 (2.47)	0.660	P < 0.001	P = 0.103
	Control	56.40 ± 11.42	69.49 ± 16.35*	↑ 23.21			F = 170.31	F = 2.79
Trunk lateral flexion	Experimental	8.79 ± 5.00	2.97 ± 2.88*	↑ 66.21	0.101 (-2.79)	0.008**	P < 0.001	P = 0.049
	Control	9.84 ± 4.10	5.76 ± 3.32*	↓ 41.46			F = 133.13	F = 4.14
Ground reaction force	Experimental	2240.25 ± 172.89	1942.14 ± 156.66*	↓ 13.31	0.180 (-105.61)	0.036**	P < 0.001	P = 0.007
	Control	2214.12 ± 166.10	2047.75 ± 146.51*	↓ 7.51			F = 100.75	F = 8.10
Knee abduction moment	Experimental	136.24 ± 8.52	121.83 ± 7.76*	↓ 10.58	0.398 (-6.32)	0.011**	P < 0.001	P < 0.001
	Control	135.33 ± 6.16	128.15 ± 7.02*	↓ 5.31			F = 218.88	F = 24.50

*Significant difference within the group; **Significant difference between groups
Percentage of changes compared to the pre-test (↑ increase, ↓ decrease)

Training the spiral force through the trunk was found to be effective in reducing knee abduction angles, trunk lateral flexion, vertical GRF, and knee abduction torque. This reduction in knee abduction torque can help athletes lower their risk of non-impact ACL injury, as it is a primary risk factor during landing. Although there was no significant difference in knee and hip flexion angles during single-leg cross-landing between the groups, intragroup differences were observed. Previous research has shown that a sports injury prevention exercise program can improve muscle strength, flexibility, and biomechanical properties associated with ACL injury (30).

Proximal control exercises have been shown to effectively manage lower limb musculoskeletal injuries in previous research (13, 26, 27), but there is little consensus on what constitutes proximal control. A meta-analysis by Sugimoto et al. found that exercises including proximal control were comparable to strength-based or multi-exercise interventions, but these interventions often lack specificity in the hip joint exercises used as the proximal link (16, 28). Lack et al.'s research on proximal control interventions for patellofemoral pain syndrome (PFPS) focused on directed exercises for the thigh or lumbopelvic muscles, but was limited to static movements (29). More research is needed to define and refine the use of proximal control exercises for optimal injury management (29).

To effectively prevent and rehabilitate lower extremity injuries, it is important to incorporate task-specific exercises that reduce repetitive GRFs during landing. However, exercises like single-leg squats against resistance may limit an athlete's ability to do so. Instead, exercises that apply external resistance to the shoulders can elicit a global response between the trunk, pelvis, and thighs, allowing for different angles of resistance during movement. For example, resistance bands can be used to apply rotational force during the flight phase and challenge thigh muscle units during landing. Additionally, training the flight phase in a three-plane and repetitive manner can address the endurance component of the program, as neuromuscular fatigue can increase the risk of non-impact ACL injury during landing. Practitioners should consider peripheral and central fatigue mechanisms and incorporate sport-specific landing tasks based on endurance.

The authors present a new approach to global systems that utilizes a complex intervention model. This method combines thigh-focused exercises and full-body dynamic movements designed around arthrokinematics, biomechanics, and the physical needs of the entire movement chain. By integrating the trunk as the main lever of resistance instead of the femur, this approach allows for more global and complex exercises under the name of "proximal control". The use of resistance about the Z-axis replicates the spiral effect of the lower limb when managing GRFs, resulting in unique neuromotor changes and increased strength (15). This integrated approach offers several advantages over conventional hip interventions and provides a novel way to generate strength and neuromotor changes in the hip joint. Current "proximal control" programs are limited to basic hip-focused exercises or generic warm-up routines lacking hip-specific techniques. Practitioners face the challenge of designing a pattern that incorporates "proximal control" and thigh-focused exercises while allowing for increasing complexity. This complexity includes elements necessary for sports activities, including speed, endurance, ballistic movements, motor control, and triplane movements that manage eccentric loads at varying joint angles. As exercise complexity increases, so does the number of specific movement components required (13, 15).

This framework is designed to improve athletic performance and replicate the motion of the hip joint over the ball. It takes a global approach that includes challenges to proprioception and the trunk, not just the hip joint. By emphasizing the importance of the three-plane flight phase and trunk counterrotation, practitioners can identify the specific joint movements and neuromotor patterns unique to single-leg athletic movements. This framework offers a conceptual model for the development of proximal control exercises that focus on the thigh (13, 15). Practitioners can use this model to design more complex exercises while maintaining a thigh-focused approach. The clinical advantage of this approach is that it underscores the importance of the thigh and its proximal influence on the lower limb, while also allowing for the gradual addition of elements needed to adapt to the specific needs of the exercise.

Limitations

While the present study sheds light on the potential benefits of injury prevention exercises with a global systems approach, it is important to note its limitations. Future studies should investigate the effect of such exercises on other risk factors associated with ACL injury during functional tasks, as well as gender-specific changes and differences. Additionally, further research is needed to measure changes in muscle activation, co-contraction, strength, performance, and other neuromuscular properties that may occur after exercise. It is also worth noting that the study focused solely on healthy and active participants prone to ACL injury, making it difficult to generalize the results to other populations, including patients with musculoskeletal injuries and ACL injuries specifically.

Recommendations

Athletes at risk of ACL injuries can benefit greatly from injury prevention exercises that use the global systems approach. The program is effective in reducing biomechanical risk factors and offers more beneficial changes compared to exercises that only focus on the thigh. The study's findings emphasize the importance of shifting towards global systems training for injury prevention, rather than solely focusing on the thigh. It is essential to implement this approach when intervening in athletes to reduce the risk of ACL injuries.

Conclusion

The study revealed that an ACL injury prevention program based on the global systems approach, conducted over six weeks, significantly reduced trunk lateral flexion angles, knee abduction, maximum vertical GRF, and maximum knee abduction torque. In contrast, a training program solely focused on thighs crossing one leg during landing did not demonstrate such improvements. These findings indicate that the global systems approach is viable for reducing the risk of ACL landing injuries among athletes through injury prevention training.

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Authors' Contribution

Study design and ideation: Bahram Sheikhi, Amir Letafatkar, Malihe Hadadnezhad
Getting financial resources for the study: Bahram Sheikhi, Amir Letafatkar, Malihe Hadadnezhad
Scientific and executive support of the study: Bahram Sheikhi, Amir Letafatkar, Malihe Hadadnezhad
Data collection: Bahram Sheikhi
Analysis and interpretation of the results: Bahram Sheikhi
Specialized statistics services: Bahram Sheikhi
Manuscript preparation: Bahram Sheikhi, Amir Letafatkar, Malihe Hadadnezhad
Specialized scientific evaluation of the manuscript: Bahram Sheikhi, Amir Letafatkar, Malihe Hadadnezhad
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Maintaining the integrity of the study process from the beginning to the publication, and responding to the referees' comments: Bahram Sheikhi, Amir Letafatkar, Malihe Hadadnezhad

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Conflict of Interest

The authors did not have a conflict of interest.

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