The effects of injury prevention programs to offset the biomechanical markers of ACL injury risk during fatigue among soccer players

Los efectos de los programas de prevención de lesiones para mitigar los marcadores biomecánicos del riesgo de lesión del LCA durante la fatiga en jugadores de fútbol

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Abstract

Introduction and Objective. It is widely recognized that multicomponent intervention programs significantly improve lower extremity biomechanics, contributing to injury risk reduction. However, the effectiveness of multicomponent Injury Prevention Exercise Programs (IPEPs) in reducing the risk of non-traumatic anterior cruciate ligament (ACL) injuries under fatigue conditions remains unclear. The objective of this study was to analyze the impact of a multicomponent IPEP on biomechanical markers of ACL injury risk in soccer players during a match simulation. Methodology. Nineteen male soccer players (n=19) were randomly assigned to an intervention group (n=10) or a control group (n=9). The intervention group incorporated a specific PEP into their usual training for 15 weekly sessions, while the control group maintained their conventional training routine. Landing biomechanics was assessed using vertical jump with drop (bipodal) and unipodal hop tests at times 0, 15, 30, 45, 60, 75, 90, and 105 minutes of a ball-based match simulation (Ball-Sport Simulation, BOSS).
Results. The intervention group showed significant improvements in kinematic patterns, with positive differences in knee and hip angles compared to the control group, both before fatigue and during the simulated match. These improvements were evident in the pre- and post-intervention assessments. However, no changes in knee kinetics during bipodal landing were observed as a result of the PEP.
Conclusions. The implementation of a multicomponent Preventive Exercise Program can induce positive effects on knee and hip kinematics, contributing to a reduction in biomechanical markers associated with the risk of ACL injury, even under simulated fatigue conditions. However, its influence on joint kinetics requires further investigation. These findings support the systematic inclusion of PEP programs in the regular training of soccer players.

Keywords

Anterior cruciate ligament (ACL); biomechanics; injury; prevention; soccer.

Resumen

Introducción y Objetivo. Se reconoce ampliamente que los programas de intervención multicomponente mejoran significativamente la biomecánica de las extremidades inferiores, contribuyendo a la reducción del riesgo de lesiones. Sin embargo, la eficacia de los Programas de Ejercicios de Prevención de Lesiones (PEP) multicomponente para disminuir el riesgo de lesiones no traumáticas del ligamento cruzado anterior (LCA) bajo condiciones de fatiga aún no está clara. El objetivo de este estudio fue analizar el impacto de un PEP multicomponente sobre los marcadores biomecánicos del riesgo de lesión del LCA en jugadores de fútbol durante una simulación de partido. Metodología. Diecinueve jugadores de fútbol masculinos (n=19) fueron asignados aleatoriamente a un grupo de intervención (n=10) o a un grupo control (n=9). El grupo de intervención incorporó un PEP específico a su entrenamiento habitual durante 15 sesiones semanales, mientras que el grupo control mantuvo su rutina de entrenamiento convencional. La biomecánica del aterrizaje fue evaluada mediante pruebas de salto vertical con caída (bipodal) y salto unipodal, en los momentos 0, 15, 30, 45, 60, 75, 90 y 105 minutos de una simulación de partido con balón (Ball-Sport Simulation, BOSS).
Resultados. El grupo de intervención mostró mejoras significativas en los patrones cinemáticos, con diferencias positivas en los ángulos de rodilla y cadera en comparación con el grupo control, tanto antes de la fatiga como durante el desarrollo del partido simulado. Estas mejoras fueron evidentes en las evaluaciones pre y post intervención. Sin embargo, no se observaron cambios en la cinética de la rodilla durante el aterrizaje bipodal como resultado del PEP.
Conclusiones. La implementación de un Programa de Ejercicios de Prevención multicomponente puede inducir efectos positivos sobre la cinemática de la rodilla y la cadera, contribuyendo a reducir los marcadores biomecánicos asociados al riesgo de lesión del LCA, incluso bajo condiciones de fatiga simuladas. No obstante, su influencia sobre la cinética articular requiere mayor investigación. Estos hallazgos apoyan la inclusión sistemática de programas PEP en el entrenamiento regular de futbolistas.

Palabras clave

Biomecánica; fútbol; lesión; ligamento cruzado anterior (LCA); prevención.

Introduction

The impact of an ACL injury extends beyond the immediate recovery period, increasing the risk of developing negative health conditions later in life, such as early onset osteoarthritis, meniscal and chondral damage around the knees, and hypokinetic diseases resulting from reduced physical activity (Yu & Garrett, 2007). Recent studies confirm that injury patterns vary significantly by player position and competition level (Gamonales et al., 2024a), with fatigue exacerbating high-risk motion profiles during match play (Di Paolo et al., 2023). As reported by Lyman et al. (2009), the alarming increase in ACL injury rates has prompted further studies to implement injury prevention interventions aimed at reducing ACL injury risks during matches (Padua et al., 2018). These interventions have shown effectiveness in reducing ACL injury rates by improving neuromuscular control and lower extremity biomechanics. Several studies have assessed the efficacy of multi-component intervention programs in mitigating injury incidences during match-play (Gilchrist et al., 2008; LaBella et al., 2011; Waldén et al., 2012).

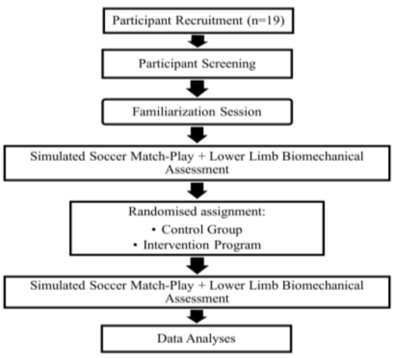
However, a critical question remains unanswered. While it is understood that these multi-component intervention programs enhance lower extremity biomechanics, thus reducing injury risk, the accumulation of fatigue still significantly influences the risk of injury (Borotikar et al., 2008; McLean & Samorezov, 2009). To our knowledge, the efficacy of current multi-component injury prevention exercise programs (IPEPs) in mitigating non-traumatic ACL injury risk during bouts of fatigue remains unknown. A deeper exploration of lower extremity biomechanics under fatigue is necessary. This knowledge will provide valuable insights into the effectiveness of multi-component IPEPs throughout the duration of a simulated soccer match, offering a more nuanced understanding of their ability to reduce ACL injury risk during an entire game.

Exploring lower extremity biomechanics in a fatigued state will enhance our understanding of how efficient multi-component IPEPs are in mitigating non-traumatic ACL injury risk in a sports match from a temporal perspective. Therefore, this study aims to investigate the effects of multi-component intervention programs designed to reduce ACL injury risk among soccer players throughout a simulated soccer match.

Method

This study was conducted with the approval of the Universiti Teknologi MARA Research Ethics Committee (600-IRMI(5/1/6)). This study used a randomized two-group pretest-posttest design (Ato et al., 2013) to evaluate the efficacy of an Injury Prevention Exercise Program (IPEP) in mitigating ACL injury risk during soccer-specific fatigue. Following an initial biomechanical assessment, Participants were randomly assigned to either the control or intervention group using computer-generated block randomization (block size = 4) to ensure balanced allocation. The randomization sequence was concealed from researchers until group assignment (Montero & León, 2007). Participants in the intervention group underwent an injury prevention exercise program (IPEP), while those in the control group continued with their usual training regimen. Both groups were assessed a second time following the completion of the program (Figure 1).

Figure 1. Research Flowchart of the Study.



Participants

Nineteen male participants volunteered for this study. Their mean age, height, and body mass were 25.6 ± 4.3 years, 1.68 ± 0.05 meters, and 65.1 ± 9.9 kilograms, respectively. G*Power a-priori sample size calculation indicated that 8 samples were required per group for all analyses, totalling 16 samples. Since the participants in this study were assessed in paired conditions (pre-test and post-test, control, and intervention), the total number of participants required was 8. To account for a 10% dropout rate, at least 9 participants per group were recruited.

Procedure

Instrument

Ball-Oriented Soccer Simulation

The Ball-Oriented Soccer Simulation (BOSS) used in this study was an intermittent, multidirectional overground running protocol that integrated soccer activities with a ball (i.e., passing, heading, dribbling, and shooting) developed by Hamdan et al. (2020). The BOSS protocol was designed to mimic the frequency and velocity of activities during an actual soccer match-play, as described elsewhere. A 15-minute audio cue was used to guide the participants through the BOSS course, repeated throughout 45 minutes of the first half and another 45 minutes of the second half of the match-play simulation. This protocol aligns with emerging field-based approaches for prospectively assessing ACL injury risk (Bossuyt et al., 2015), capturing fatigue progression through sport-specific tasks rather than lab-isolated movements.

Intervention Program

An exercise program was introduced to the participants to counteract the disruptions caused by fatigue during soccer match-play. The exercises included in the program consisted of specific activities highlighted to reduce the risk of injury (Padua et al., 2018). This prospective longitudinal intervention (Montero & León, 2007) spanned 15 sessions over 5–8 weeks (varying by team training frequency) and then once per week for the sessions that followed (Olsen et al., 2005; Steffen et al., 2008). Further details of the exercise program can be found in the Appendix. The post-test was scheduled upon the participants' completion of the 15th session. If the scheduled post-test was not immediately after the 15th session, the participants were instructed to continue performing the intervention once a week until the date of their post-test.

Control Group

The control group maintained their usual warm-up regimen, which included dynamic warm-ups but excluded structured injury prevention exercises. This ensured the control condition represented typical practice without IPEP contamination.

Biomechanical Assessment

The lower limb biomechanical assessments required participants to perform drop vertical jumps (bipedal landing) and single-leg hop tasks (unipedal landing) following a simulated soccer match play protocol. The drop vertical jumps were performed from a 30 cm elevated platform onto a landing zone at a distance of 50% of each participant's height (Padua et al., 2009), whereas the single-leg hops were performed from a level surface at a distance of 75% of each participant's height (Bossuyt et al., 2015). A successful trial for each landing was determined as a landing with one foot fully on one force plate. Three successful trials were recorded for each time point and each drop vertical jump task. For the single-leg hops, the mean was acquired from three successful trials on the left foot and three successful trials on the right foot.

24 infrared cameras collected kinematic data for the lower limb biomechanical markers of ACL injury risk at 240 Hz (Qualisys, Gothenburg, Sweden). Forty-four reflective markers were placed on all participants by the same investigator to reduce inter-tester bias in accordance with the Liverpool John Moores University Lower Limb and Trunk (LJMU LLT) model. Functional hip and knee joint centers were calculated for maximum error reduction of anatomical landmark placement over these joints (Robinson & Vanrenterghem, 2012) using Visual3D (C-Motion, Germantown, MD, USA). An inverse kinematic model

was utilized to reduce errors arising from surface movement and soft tissue artifacts. Knee joint moments were calculated using inverse dynamics. More explicit descriptions of the LJMU LLT model can be found elsewhere (Malfait et al., 2014; Vanrenterghem et al., 2010).

Three-dimensional marker trajectories were low-pass filtered using a 4th order Butterworth filter at 18 Hz prior to inverse dynamics calculations (Kristianslund et al., 2012). The initial contact was defined as the time instant when the foot meets the ground.

Kinetic data for the lower limb biomechanical markers of ACL injury risk were collected by two 0.9 × 0.6 m embedded force platforms (Kistler, Winterthur, Switzerland), sampling at 240 Hz. Dempster's regression equation was applied to all segmental data using geometrical volumes to represent each segment. Force data were low-pass filtered using a critically damped filter at 18 Hz prior to inverse dynamics calculations (Kristianslund et al., 2012). Peak knee abduction moments were derived from the frontal plane knee moments during weight acceptance phases in both unipedal and bipedal landings, as Dempsey et al. (2007) defined. Initial contact was defined by a vertical ground reaction force surpassing 20 N over a width of 40 samples (Zeni et al., 2008). During this instance, sagittal plane knee and hip joint angles were calculated.

Data analysis

The statistical analysis in this study was divided into three parts. Each part of the analyses was designed to test specific hypotheses independently. The themes of the hypotheses assigned to each part were as follows:

- Part 1: Comparison of biomechanical responses to the BOSS between the control and intervention groups.
- Part 2: Comparison of biomechanical responses to the BOSS between the Pre-intervention test (Pre-test) and the Post-intervention test (Post-test).

A 2 × 8 repeated measures ANOVA was employed. Independent variables were defined by grouping designation (intervention (n = 10) versus control (n = 9)) for Part 1, and by testing phase (pre-test versus post-test) for Part 2. For all analyses, mean sagittal plane hip angles, knee angles, and frontal plane knee moments at each time point of repeated measurements (time: 0 min, 15 min, 30 min, 45 min, 60 min, 75 min, 90 min, 105 min) were treated as the dependent variables. Any violations of the sphericity assumption detected in Mauchly's test of sphericity were corrected using the Greenhouse-Geisser epsilon. If the epsilon was < 0.75, the Greenhouse-Geisser correction was applied, whereas if the epsilon was > 0.75, the Huynh-Feldt correction was used (Girden, 1992). Post-hoc analyses were conducted using Bonferroni correction procedures to minimize Type I errors. All analyses were conducted using the statistical software package SPSS (IBM SPSS v.28, New York, USA) with alpha set at 0.05.

Results

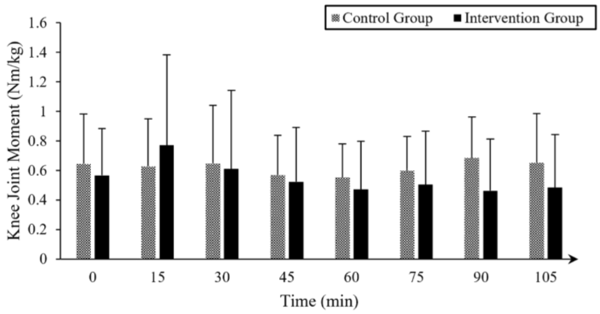
Two participants from the control group were unable to complete the study; the reported results represent the analyses for the remaining 17 participants (intervention: n = 10; control: n = 7). As the statistical analysis for this study was divided into two parts, reporting the analysis results follows the two parts outlined in the statistical analysis section.

Comparison of biomechanical responses to the BOSS between the control and the intervention group

This analysis aimed to identify any differences between the control and intervention groups in landing task kinematics and kinetics during the BOSS. To achieve this, the baseline assessment (pre-test) measurements were separated from the post-test measurements, and the left and right limb measurements were both included without discrimination. The 2 × 8 repeated measures ANOVA was conducted on the post-test measurements, revealing the following findings.

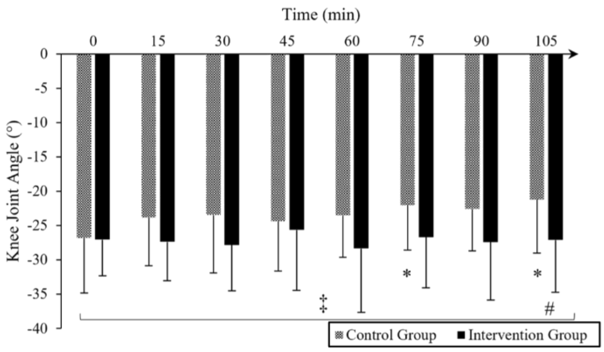
The knee joint moments showed a trend towards a significant main effect of time ($F_{2.557, 81.828}$ = 2.625, p = 0.063, partial η^2 = 0.077). No interaction between the participants' grouping designation and the changes in knee moments was observed ($F_{2.557, 81.828}$ = 2.269, p = 0.096, partial η^2 = 0.066, Figure 2).

Figure 2. Changes in Knee Joint Moments between Control and Intervention Group Observations during Drop Vertical Jump Tasks.



There was a significant main effect of time on knee angles throughout the BOSS during drop vertical jump tasks ($F_{4.304, 137.742}$ = 2.625, p = 0.034, partial η^2 = 0.076), and a significant interaction was observed in knee angles during the drop vertical jump tasks ($F_{4.304, 137.742}$ = 3.116, p = 0.015, partial η^2 = 0.089, Figure 3). Post-hoc analyses revealed that the knee angles in the control group were significantly more extended at the end of the BOSS (105 min) compared to their measurements at 0 min (p < 0.001; FIGURE 3). The control group's knee angles were also more extended than the intervention group's measurements at 105 min (p = 0.032; Figure 3).

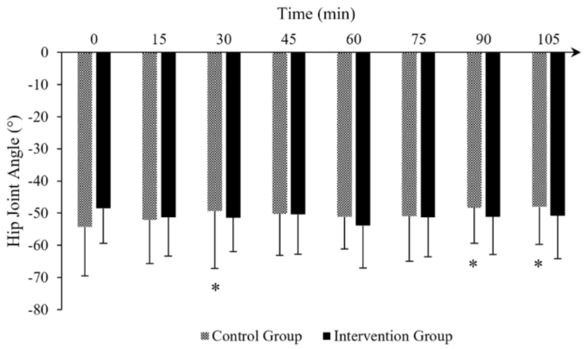
Figure 3. Changes in Knee Joint Angles between Control and Intervention Group Observations during Drop Vertical Jump Tasks.



Note: Knee joint angles during drop vertical jump task landings. ‡ Indicates significant main effect of time. * Indicates significant differences compared to baseline (0min). # Indicates significant differences between control and intervention groups.

There was no significant main effect of time on hip angles ($F_{4.173, 133.535}$ = 1.763, p = 0.137, partial η^2 = 0.052). However, significant interactions were observed in hip angles during the drop vertical jump tasks ($F_{4.173, 133.535}$ = 3.453, p = 0.009, partial η^2 = 0.097, Figure 4). Post-hoc analyses revealed that the hip angles in the control group were significantly more extended at the end of the BOSS (105 min) compared to their measurements at 0 min (p = 0.007, Figure 4).

Figure 4. Changes in Hip Joint Angles between Control and Intervention Group Observations during Drop Vertical Jump Tasks.



Note: Hip joint angles during drop vertical jump landing tasks. * Indicates significant differences compared to baseline (0min).

However, single leg hop tasks did not reveal any significant differences throughout the BOSS ($p > 0.05$; Figure 5, Figure 6 and Figure 7).

Figure 5. Changes in Knee Joint Moments between Control and Intervention Group Observations during Single Leg Hop Tasks.

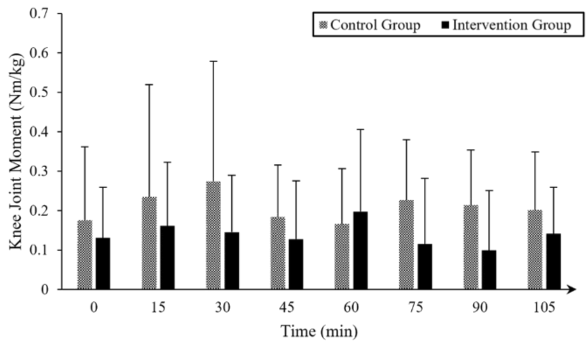


Figure 6. Changes in Knee Joint Angles between Control and Intervention Group Observations during Single Leg Hop Tasks.

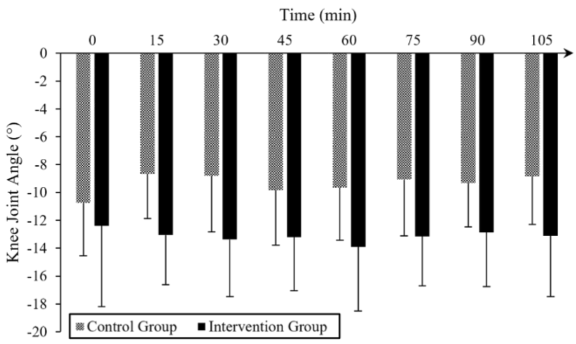
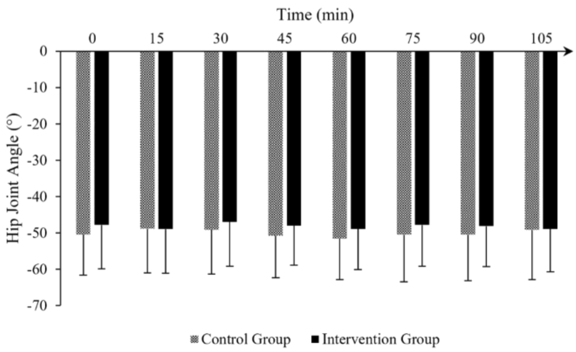


Figure 7. Changes in Hip Joint Angles between Control and Intervention Group Observations during Single Leg Hop Tasks.

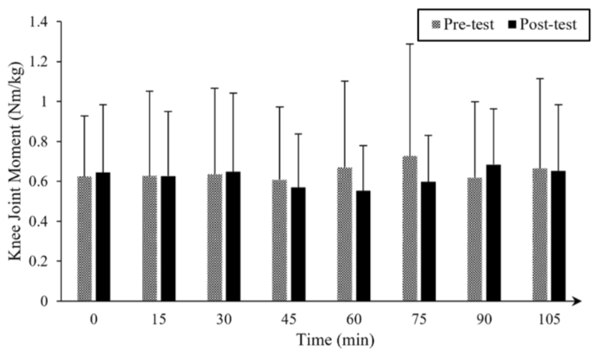


Comparison of biomechanical responses to the BOSS between the pre-test phase and the post-test phase

This analysis aimed to explicitly identify any differences between the pre-test and post-test measurements in landing task kinematics and kinetics during the BOSS. To achieve this objective, the control group measurements were separated from the intervention group measurements, while the left and right limb measurements were included without discrimination. The 2 × 8 repeated measures ANOVA was conducted on both control and intervention group measurements, revealing the following findings. No significant differences were detected in all measurements during the single leg hop trials ($p > 0.05$). however, the drop vertical jump tasks reveal the following findings:

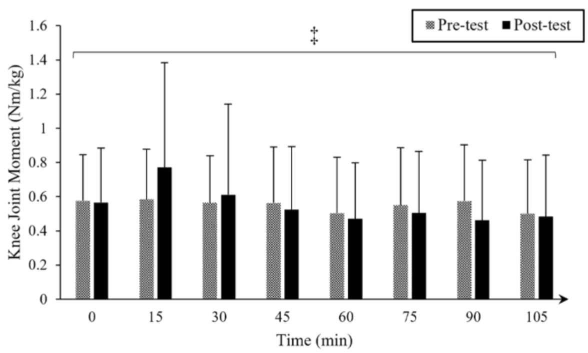
The control group exhibited no significant main effect of time on the knee joint moments ($F_{2.741, 82.237} = 0.53$, $p = 0.647$, partial $\eta^2 = 0.017$, Figure 8).

Figure 8. Changes in Knee Joint Moments between Pre- and Post-test Observations during Drop Vertical Jump Tasks Among Control Group



The intervention group exhibited a significant main effect of time on peak knee joint moments ($F_{2.411, 81.981} = 3.466$, $p = 0.028$, partial $\eta^2 = 0.093$, Figure 9).

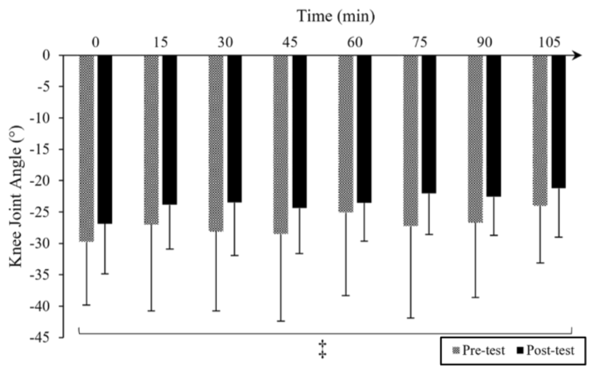
Figure 9. Changes in Knee Joint Moments between Pre- and Post-test Observations during Drop Vertical Jump Tasks Among Intervention Group



Note: Knee joint moments during drop vertical jump task landings in the intervention group. ‡ Indicates significant main effect of time.

There were significant main effects of time on knee angles during drop vertical jump tasks throughout the BOSS in the control group ($F_{4.077, 122.303} = 5.425$, $p < 0.001$, partial $\eta^2 = 0.153$, Figure 10). No interaction was detected between pre-test and post-test measurements ($p > 0.05$).

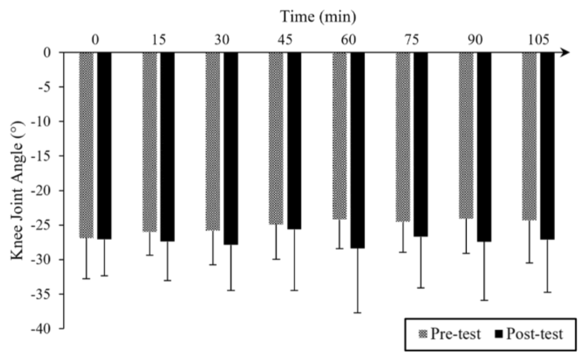
Figure 10. Changes in Knee Joint Angles between Pre- and Post-test Observations during Drop Vertical Jump Tasks Among Control Group



Note: Knee joint angles during drop vertical jump task landings in the control group. ‡ Indicates significant main effect of time.

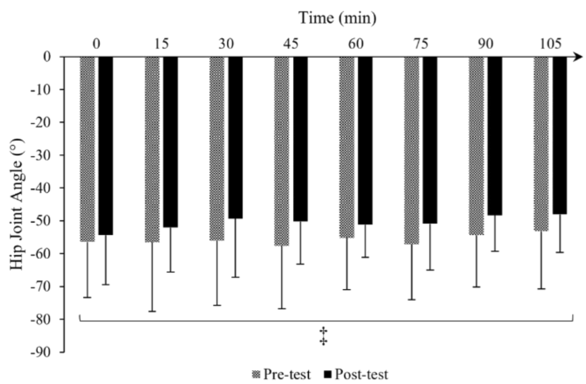
However, there was no significant main effect of time on knee angles for the intervention group ($F_{3.568, 121.304} = 1.107$, $p = 0.396$, partial $\eta^2 = 0.029$, Figure 11). No interaction was detected between pre-test and post-test measurements ($p > 0.05$).

Figure 11. Changes in Knee Joint Angles between Pre- and Post-test Observations during Drop Vertical Jump Tasks Among Intervention Group



There were significant main effects of time on hip angles during drop vertical jump tasks throughout the BOSS in the control group ($F_{3.885, 116.536} = 2.843$, $p = 0.028$, partial $\eta^2 = 0.087$; Figure 12). Similarly to the knees, no interaction was detected between pre-test and post-test measurements ($p > 0.05$).

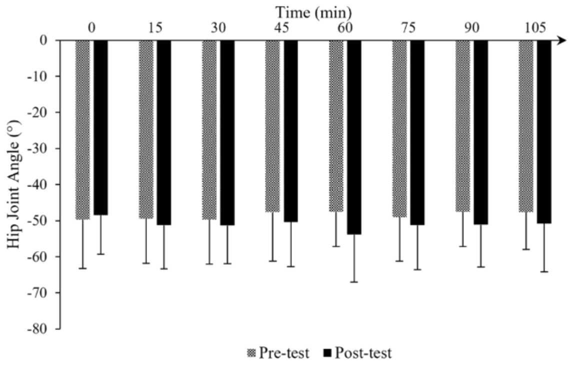
Figure 12. Changes in Hip Joint Angles between Pre- and Post-test Observations during Drop Vertical Jump Tasks Among Control Group



Note: Hip joint angles during drop vertical jump task landings in the control. ‡ Indicates significant main effect of time.

However, there was no significant main effects of time on hip angles ($F_{4.212, 143.2} = 0.84$, $p = 0.507$, partial $\eta^2 = 0.024$, Figure 13). No interaction was detected between pre-test and post-test measurements ($p > 0.05$).

Figure 13. Changes in Hip Joint Angles between Pre- and Post-test Observations during Drop Vertical Jump Tasks Among Intervention Group



Discussion

Several takeaway points are highlighted based on the findings of this study. To consider these findings, the discussion section was organised to match the presentation in the results section:

The effects of an intervention program in offsetting the risk of ACL injury risk among soccer players

No differences were observed in knee joint moments. However, in the post-test phase, some noticeable differences were observed in the control group, specifically that the knees were more extended towards the end of the BOSS regardless of group designation. This suggests that biomechanical changes may occur following continuous exertion in simulated soccer match-play. Pairwise comparisons revealed that the knees and hips were more extended for the control group compared to pre-simulation. Furthermore, at the end of the BOSS, the knees were more extended among the control group landings than the intervention group landings.

The findings suggest that implementing specific, targeted exercises may positively offset biomechanical impairments during landings following soccer-specific exertions. The control group's knee angles were found to be between 24% and 39% more extended than the intervention group in both drop vertical jump and single leg hop landing trials. These findings support and promote the benefits of specific, targeted IPEPs as championed by Padua et al. (2018).

One way this study exhibits supporting evidence for the implementation of specific, targeted IPEPs is through the temporal sustainability of biomechanics during landings, demonstrated by the magnitude of deterioration in knee angles over time. As represented in Figure 3 and Figure 4, knee extension in the control group increased by 17% to 21%, whereas the intervention group's knee extension deteriorations ranged between 0% and 6% following a similar set of soccer-specific exertions over a similar duration. This observation highlights the efficacy of these IPEPs in offsetting ACL injury risk, particularly in the fatigued state during the later stages of soccer match-play.

The effects of an intervention program on landing biomechanics among soccer players

Another demonstration of how specific, targeted IPEPs may benefit players comes from the second part of the analysis. The main findings indicate notable changes in landing biomechanics parameters over time, especially in drop vertical jump landing tasks. Similar to observations in the first part of the analysis, this suggests temporal changes in landing biomechanics following soccer-specific exertions. However, this analysis brings another perspective into consideration and interpretation of the results.

As illustrated in Figure 10 and Figure 12, the sagittal plane knees and hips were slightly more extended throughout the BOSS during the post-test phase among the control group by 3-21% compared to their pre-test assessments. On the other hand, the intervention group exhibited 1-16% less extended knees and hips in the post-test compared to pre-test observations as demonstrated in Figure 11 and Figure 13. Our finding of sustained knee flexion aligns with academy-level observations where positional demands modulate injury susceptibility (Gamonales et al., 2024a), suggesting IPEPs should be tailored to player roles. This observation supports another aspect of IPEP implementation benefits highlighted by Padua et al. (2018): improved biomechanics, neuromuscular control, and functional performance. Numerous researchers (Chappell & Limpisvasti, 2008; Hewett et al., 1996; Irmischer et al., 2004; Lephart et al., 2005; Lim et al., 2009; Myer et al., 2006; Myer et al., 2005; Prapavessis et al., 2003; Vescovi et al., 2008) have demonstrated achievements in minimizing ground contact kinetics and improving landing kinematics through multicomponent IPEPs.

An added value of this study is the temporal observations over time while completing the BOSS. While previous studies (e.g., Myer et al., 2006; Myer et al., 2005) reported pre-test and post-test observations, this study may be the first to report observations of the investigated parameters following an IPEP with respect to fatigue from soccer-specific exertions. Based on the findings of this study, it may be speculated that the addition of injury prevention exercises alongside players' usual training not only facilitates biomechanical adaptations towards safer landing kinematics but, as Bonato et al. (2003) reported significant correlations between muscle fatigue and changes in the biomechanics of motion, this may suggest that the intervention played a role in improving the sustainability of the landing kinematics with better muscular tolerance to fatigue. This speculation, however, should be considered with caution, as muscle activation or muscle activity was not assessed in this study and warrants further investigation.

Limitations

Several limitations of this study should be taken into consideration. Firstly, according to the guidelines mentioned by Padua et al. (2018), the injury prevention exercises were required to be performed as a dynamic warm-up or as part of a comprehensive strength and conditioning program. This suggests that the IPEP may be less effective than a standalone intervention. To address this issue, the control and intervention groups were instructed to continue their regular training routines. The control group was allowed to perform their regular warm-up routines while the intervention group performed the injury prevention exercises as their warm-up routines.

Furthermore, the implementation of the exercise program was in accordance with practices from previous studies where participants performed injury prevention exercises for 15 consecutive sessions (Olsen et al., 2005; Steffen et al., 2008). This meant that participants could complete their 15 sessions at varying durations depending on the frequency of their training programs. For example, a participant training twice a week would complete the intervention in eight weeks, whereas a participant training three times a week could complete the intervention in five weeks. To accommodate the waiting time due to post-test scheduling, participants were instructed to continue performing the intervention at a frequency of once a week until their post-test session.

Additionally, participants performed the IPEP without any bias of their playing position in soccer or other relevant components such as psychology or nutritional supplementations. Future IPEP designs should integrate position-specific demands (Gamonales et al., 2024b) and psychological resilience training (Ramos-Pastrana et al., 2024) to address the multifactorial nature of ACL injury risk during fatigue.

Practical applications

The practical applications of this study emphasize the importance of selecting appropriate warm-up routines in soccer. According to the recommendations by Padua et al. (2018), IPEPs should be multicomponent in nature, incorporating at least three of the five exercise categories (i.e., strength, plyometrics, balance, flexibility, and agility) as demonstrated in the IPEP in this study (refer to the appendix). Psychological aspects of ACL recovery (Ramos-Pastrana et al., 2024) further underscore the need for multicomponent IPEPs addressing both biomechanical and cognitive fatigue factors. Additionally, Padua et al. (2018) indicate the recommended training frequency at least 2-3 times a week. Therefore, the implementation of such IPEPs could easily be introduced into recreational or professional training programs without hindering the training progressions of players and team members.

Conclusions

This study found biomechanical differences in knee and hip parameters following an injury prevention intervention compared to a control group. Pre- and post-test observations also showed kinematic improvements under pre-fatigue conditions and throughout temporal assessments during the BOSS. However, injury prevention exercise programs did not seem to induce any improvements in bipedal knee joint kinetics.

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References

Ato, M., López-García, J. J., & Benavente, A. (2013). A classification system for research designs in psychology. *Annals of Psychology*, 29(3), 1038–1059.

Bonato, P., Ebenbichler, G. R., Roy, S. H., Lehr, S., Posch, M., Kollmitzer, J., & Della Croce, U. (2003). Muscle Fatigue and Fatigue-Related Biomechanical Changes During a Cyclic Lifting Task. *Spine*, *28*(16), 1810-1820. https://doi.org/10.1097/01.Brs.0000087500.70575.45

Borotikar, B. S., Newcomer, R., Koppes, R., & McLean, S. G. (2008). Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. *Journal of Clinical Biomechanics*, *23*(1), 81-92. https://www.clinbiomech.com/article/S0268-0033(07)00168-4/fulltext

Bossuyt, F. M., García-Pinillos, F., Raja Azidin, R., Vanrenterghem, J., & Robinson, M. A. (2015). The Utility of a High-intensity Exercise Protocol to Prospectively Assess ACL Injury Risk. *International Journal of Sports Medicine*, *95*(02), 125-133.

Chappell, J. D., & Limpisvasti, O. (2008). Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *American Journal of Sports Medicine*, *36*(6), 1081-1086.

Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., Munro, B. J., & Russo, K. A. (2007). The Effect of Technique Change on Knee Loads during Sidestep Cutting. *Journal of Medicine and Science in Sports and Exercise*, *39*(10), 1765.

Di Paolo, S., Nijmeijer, E. M., Bragonzoni, L., Gokeler, A., & Benjamines, A. (2023). Definition of High-Risk Motion Patterns for Female ACL Injury Based on Football-Specific Field Data: A Wearable Sensors Plus Data Mining Approach. *Sensors*, 23(4), 2176.

Gamonales, J. M., Hernández-Beltrán, V., Perdomo-Alonso, A., Barqueras-Martínez, J., Gómez-Carrero, S., Ferreira, C. C., Paulo, R., & Espada, M. C. (2024a). Analysis of sports injuries in academy integrated u-16 and u-18 football players. *Retos, 56,* 17–23. https://doi.org/10.47197/retos.v56.104386

Gamonales, J. M., Hernández-Beltrán, V., Perdomo-Alonso, A., Barqueras-Martínez, J., Gómez-Carrero, S., Ferreira, C. C., Santos, F. J., & Espada, M. C. (2024b). Does the category and position of play influence sports injuries in football? *Retos, 54,* 817–824. https://doi.org/10.47197/retos.v54.103513

Gilchrist, J., Mandelbaum, B. R., Melancon, H., Ryan, G. W., Silvers, H. J., Griffin, L. Y., Watanabe, D. S., Dick, R. W., & Dvorak, J. (2008). A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *American Journal of Sports Medicine*, *36*(8), 1476-1483. https://journals.sagepub.com/doi/10.1177/0363546508318188?url_ver=Z39.88-2003&rfr_id=ori:rid:crossref.org&rfr_dat=cr_pub%3dpubmed

Girden, E. R. (1992). *ANOVA: Repeated measures*. SAGE.

Hamdan, M., Ang, G. Y., Sharir, R., Yeo, W. K., & Azidin, R. M. F. R. (2020). Changes in Hamstring Eccentric Peak Torques and Angles of Peak Torque Following 90 Minutes of Soccer Specific Exertions. *Malaysian Journal of Movement, Health & Exercise*, *9*(2).

Hewett, T. E., Stroupe, A. L., Nance, T. A., & Noyes, F. R. (1996). Plyometric training in female athletes: decreased impact forces and increased hamstring torques. *American Journal of Sports Medicine*, *24*(6), 765-773.

Irmischer, B. S., Harris, C., Pfeiffer, R. P., DeBeliso, M. A., Adams, K. J., & Shea, K. G. (2004). Effects of a knee ligament injury prevention exercise program on impact forces in women. *The Journal of Strength & Conditioning Research*, *18*(4), 703-707.

Kester, B. S., Behery, O. A., Minhas, S. V., & Hsu, W. K. (2017). Athletic performance and career longevity following anterior cruciate ligament reconstruction in the National Basketball Association. *Journal of Knee Surgery, Sports Traumatology, Arthroscopy*, *25*(10), 3031-3037.

Kristianslund, E., Krosshaug, T., & Van Den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. *The Journal of Biomechanics*, *45*(4), 666.

LaBella, C. R., Huxford, M. R., Grissom, J., Kim, K.-Y., Peng, J., & Christoffel, K. K. (2011). Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools: cluster randomized controlled trial. *Archives of pediatrics & adolescent medicine*, *165*(11), 1033-1040.

Lephart, S. M., Abt, J., Ferris, C., Sell, T., Nagai, T., Myers, J., & Irrgang, J. (2005). Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *The British Journal of Sports Medicine*, *39*(12), 932-938. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1725089/pdf/v039p00932.pdf

Lim, B.-O., Lee, Y. S., Kim, J. G., An, K. O., Yoo, J., & Kwon, Y. H. (2009). Effects of sports injury prevention training on the biomechanical risk factors of anterior cruciate ligament injury in high school female basketball players. *American Journal of Sports Medicine*, *37*(9), 1728-1734.

Lyman, S., Koulouvaris, P., Sherman, S., Do, H., Mandl, L. A., & Marx, R. G. (2009). Epidemiology of anterior cruciate ligament reconstruction: trends, readmissions, and subsequent knee surgery. *Journal of Bone & Joint Surgery*, *91*(10), 2321-2328.

Malfait, B., Sankey, S., Azidin, R. R., Deschamps, K., Vanrenterghem, J., Robinson, M. A., Staes, F., & Verschueren, S. (2014). How reliable are lower-limb kinematics and kinetics during a drop vertical jump. *Journal of Medicine and Science in Sports and Exercise*, *46*(4), 678-685.

McLean, S. G., & Samorezov, J. E. (2009). Fatigue-induced ACL injury risk stems from a degradation in central control. *Journal of Medicine and Science in Sports and Exercise*, *41*(8), 1661-1672.

Montero, I., & León, O. G. (2007). A guide for naming research studies in psychology. *International Journal of Clinical and Health Psychology*, 7(3), 847–862.

Myer, G. D., Ford, K. R., Brent, J. L., & Hewett, T. E. (2006). The effects of plyometric vs. dynamic stabilization and balance training on power, balance, and landing force in female athletes. *The Journal of Strength & Conditioning Research*, *20*(2), 345.

Myer, G. D., Ford, K. R., PALUMBO, O. P., & Hewett, T. E. (2005). Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *The Journal of Strength & Conditioning Research*, *19*(1), 51-60.

Olsen, O.-E., Myklebust, G., Engebretsen, L., Holme, I., & Bahr, R. (2005). Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. *Bmj*, *330*(7489), 449. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC549653/pdf/bmj33000449.pdf

Padua, D. A., DiStefano, L. J., Hewett, T. E., Garrett, W. E., Marshall, S. W., Golden, G. M., Shultz, S. J., & Sigward, S. M. (2018). National Athletic Trainers' Association Position Statement: Prevention of Anterior Cruciate Ligament Injury. *Journal of Athletic Training*, *53*(1), 5-19. https://doi.org/10.4085/1062-6050-99-16

Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., Garrett, W. E., & Beutler, A. I. (2009). The Landing Error Scoring System (LESS) Is a Valid and Reliable Clinical Assessment Tool of Jump-Landing Biomechanics: The JUMP-ACL Study. *American Journal of Sports Medicine*, *37*(10), 1996-2002. Prapavessis, H., McNair, P. J., Anderson, K., & Hohepa, M. (2003). Decreasing landing forces in children: the effect of instructions. *Journal of Orthopaedic & Sports Physical Therapy*, *33*(4), 204-207.

Ramos Pastrana, L. M., Giménez Egido, J. M., & Olmedilla Zafra, A. (2024). Aspectos psicológicos asociados a la rehabilitación del LCA y las recidivas en futbolistas: una revisión sistemática (Psychological aspects associated with ACL rehabilitation and recurrence in football players: a systematic review). *Retos*, *55*, 397–410. https://doi.org/10.47197/retos.v55.105115

Robinson, M. A., & Vanrenterghem, J. (2012). An evaluation of anatomical and functional knee axis definition in the context of side-cutting. *The Journal of Biomechanics*, *45*(11), 1941-1946.

Steffen, K., Myklebust, G., Olsen, O. E., Holme, I., & Bahr, R. (2008). Preventing injuries in female youth football–a cluster-randomized controlled trial. *The Scandinavian Journal of Medicine & Science in Sports*, *18*(5), 605-614.

Vanrenterghem, J., Gormley, D., Robinson, M., & Lees, A. (2010). Solutions for representing the whole-body centre of mass in side cutting manoeuvres based on data that is typically available for lower limb kinematics. *Gait & Posture*, *31*(4), 517-521.

Vescovi, J. D., Canavan, P. K., & Hasson, S. (2008). Effects of a plyometric program on vertical landing force and jumping performance in college women. *Physical Therapy in Sport*, *9*(4), 185-192. https://doi.org/https://doi.org/10.1016/j.ptsp.2008.08.001

Waldén, M., Atroshi, I., Magnusson, H., Wagner, P., & Hägglund, M. (2012). Prevention of acute knee injuries in adolescent female football players: cluster randomised controlled trial. *BMJ Open Sport Exercise Medicine*, *344*, e3042. https://www.bmj.com/content/bmj/344/bmj.e3042.full.pdf

Yu, B., & Garrett, W. E. (2007). Mechanisms of non-contact ACL injuries. *The British Journal of Sports Medicine*, *41*(suppl 1), i47-i51.

Zeni, J., Richards, J., & Higginson, J. (2008). Two simple methods for determining gait events during treadmill and overground walking using kinematic data. *Gait & Posture*, *27*(4), 710-714.

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Appendix

Injury Prevention Exercises for the Intervention Group

This warm-up program aims to mitigate the disruptions caused by fatigue during soccer match-play. The exercises implemented in the program consist of specific exercises designed to reduce the risk of injury. The program is to be incorporated into the existing training regimen practiced by participants for 15 consecutive sessions, followed by once-weekly sessions thereafter.

Component	Exercise	Distance	Repetitions/Duration
Flexibility	Calf Stretch		30s each side
	Quadriceps Stretch		30s each side
	Hamstrings Stretch		30s each side
	Hip Adductor Stretch		30s each side
	Hip Flexor Stretch		30s each side
	Iliotibial Band Stretch		30s each side
Balance	Single-Legged Balance		2 × 15s each side
	Single-Legged Balance with Upper Body Movement		2 × 15s each side
	Single-Legged Balance with Partner Perturbation		2 × 15s each side
Strength	Double-Legged Squats		3 × 8-15reps
	Single-Legged Squats		5reps each side
	Nordic Hamstrings Lowers		5reps
	Plank		15s × 4reps
	Side Plank		15s × 2reps each side
Plyometrics	Squat Jump		30s each side
	Multidirectional Single- Legged Hop		30s each side
	Bounding	40-45m	
Agility	Forward/Backward Jogging		
	Diagonal Run and Cut	45m	
	High Knee Skipping	35m	30s
	High Knee Carioca		30s