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Article

# Prevention of sports injuries in college basketball players: An intervention study based on biomechanics

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**Abstract:** College basketball is becoming more and more popular, and as a result, more students are participating in the sport. This has led to a progressive rise in sports injuries, which has an impact on both academic performance and quality of life. Basketball players are mostly vulnerable to Anterior Cruciate Ligament (ACL) injuries due to certain movement patterns that raise their risk of damage. This study examines how biomechanical risk factors for ACL injuries in pre-adolescent basketball players are impacted by the JumpStart injury-prevention warm-up routine. The exercise that would lower the Peak Knee Valgus Moment (PKVM), a major risk factor for ACL injuries, was hypothesized. Further kinematic and biomechanical parameters were investigated. A total of sixty-two male and female basketball players were randomized and recruited into two divisions: the experimental group (EG) (n = 31) then the control group (CG) (n = 31). While the CG continued with their standard warm-up protocol, the experimental group took part in fifteen in-season JumpStart sessions. Motion capture data from pre- and post-season basketball-specific activities, such as jump landings, single-leg jumpers, and cutting movements, were gathered. SCONE simulator biomechanical modeling system was used to determine joint angles and moments in the lower extremities. Pre- and post-season data within groups were contrasted using paired *t*-tests, and the control and experimental groups were contrasted using independent *t*-tests. To assess the interaction effects among the EG and CG, an analysis of variance (ANOVA) was also achieved. The EG's PKVM during jump landings was considerably lower ($p < 0.01$) than that of the CG, according to the results. These results show that the JumpStart program is beneficial in lowering the probability of ACL injuries in pre-adolescent basketball players and recommend future improvements to address other risk factors in single-leg and cutting activities.

**Keywords:** sports injuries, prevention; college basketball players; biomechanics; intervention study; Peak Knee Valgus Moment (PKVM); Anterior Cruciate Ligament (ACL) injuries

## 1. Introduction

Participation in collegiate basketball at all levels has grown in popularity due to the availability of more young athletes and the sport's growing appeal [1]. With the growth of the sport, the incidence of sports-related injuries also increases and can have devastating effects on a player's academic performance and overall well-being [2]. ACL, a vital ligament stabilizer in the knee, is one of the most often occurring and crippling injuries. ACL injuries generally require a lengthy recovery period because they are frequently addressed surgically [3]. Such injuries affect not only sidelined athletes but can also set the stage for debilitating, life-long consequences, including a higher risk of osteoarthritis later in life [4]. For that reason, sports medicine research has focused heavily on the anticipation of ACL injuries in youth sports [5].

Basketball players are particularly prone to ACL injuries because of the intensity and multi-directional nature of the sport, which includes cutting, pivoting, jumping, and landing [6]. The movements resulting in these dynamic activities put considerable stress on the knee joint, particularly when the movements are done improperly or after fatigue [7]. The most influential biomechanical cause of ACL injuries is the knee valgus peak moment (PKVM), or the inward rotation of the knee during landing from a jump [8]. High PKVM has been shown to have a strong association with a higher risk of ACL injury, particularly in young athletes developing poor neuromuscular control [9]. Biomechanical risk factors for ACL injuries are improving as a result of improving athletes' strength, coordination, and movement patterns. More specifically, neuromuscular training warm-up protocols have specifically been lauded to contribute to conventional training without causing much interference [10]. One type of program, that is meant to reduce ACL risk, is a warm-up intervention such as Jump Start that will target factors like PKVM [11].

The purpose of the study was to investigate how well the jumpstart injury prevention warm-up procedure reduced the biomechanical risk factors for ACL injuries in basketball players who were pre-adolescents. By analyzing the Peak Knee Valgus Moment (PKVM) and other kinematic parameters, the research seeks to demonstrate the program's potential to enhance player safety and decrease injury risk.

The remaining segments of the study are arranged as follows: The relevant investigations are the main topic of Portion 2; the approach was discussed in Portion 3; the results are presented in Portion 4; the discussion is offered in Portion 5; and the study is concluded in Portion 6.

## 2. Related works

An injury prevention-based sports medical imaging technique was suggested in [12] to address the issue of sports medical images in basketball training. Utilizing that methodology, the state of sports injuries in collegiate basketball was examined. Four distinct injury variables were examined concurrently: extracurricular activities, basketball classes, competitions, and training. The related recommendations, together with the issues and causes, were examined to lower the risk of injury and improve the protection of basketball activities for physical education students.

The reasons behind sports injuries sustained by young basketball players and the preventative strategies were examined in [13]. Using survey questionnaires, the study examined the mechanism, causes, and incidence patterns of basketball injuries. To support a preventative protocol, statistical analyses were conducted. A basketball injury prevention and mitigation program were introduced to maintain regular basketball practice and competition which was important to raise awareness of the inherent traits of player injuries and consider the many factors that contribute to the athletes' health hazards.

The purpose of [14] was to examine basketball-related injuries. The researcher made an effort to comprehend the reasons behind and ways to avoid basketball injuries. A selection of 100 players competed in intercollegiate basketball championships. With the assistance of an assortment comprising subject-matter experts, a questionnaire was created for the necessary study. To find out if the subjects understood the questions and critiques, the form was distributed for a trial run. The outcome from the raw data was obtained using the percentage technique.

The causes of basketball-related injuries from college students were examined in the article [15] using a questionnaire survey that also suggested prevention strategies and rehabilitation techniques. The findings show that inadequate preparation, technical mistakes, high load, and low physical condition were the primary causes of athlete injuries. Proper warm-up training contributed to improved joint and ligament flexibility and reduced the possibility of injuries.

The underlying factors and features of ankle joint damage in basketball players were examined in [16] and that also included treatment recommendations and ways to avoid ankle joint injuries. The causes of ankle joint damage were first discussed, followed by a quick examination of the initiative's ankle joint injury features and technical measures that could easily result in ankle joint injuries. The strategies for avoiding and dealing with ankle joint injuries during exercise were suggested after considering the precautions to avoid them. The study procedure of ankle joint damage was then investigated and promoted via the use of data mining techniques.

A simulation framework for students' athletic development was developed in the article [17] to address the issues of teaching basketball in a regular classroom. First, a sports-capturing structure was established to gather data and assess movement anomalies in athletes by comparing that with a standard database. After that, the system functions were combined with the players' digitized motions to develop the skills statistically. To obtain the expert-level simulator outcomes of the basketball players and the virtual basketball stadium, the individuals and the human body design diagram were made. Action capture technology was then employed to trace the movement tracks of key elements in the simulated results to identify the movement tracks of the leg bones.

Adult and teenage basketball players' attitudes, implementation barriers, and injury prevention strategies were determined in the study [18]. The study assessed closely how attitudes and behaviors related to injury prevention varied by age and gender. Three hundred and eighty-seven adult basketball players answered an anonymous survey. The study discussed demographics, attitudes toward injuries and injury prevention, present injury prevention techniques, and the factors that help and hinder the adoption of injury prevention.

The impact of an exercise regimen on preventing ACL injuries in adolescent female players was assessed in the article [19]. Based on the findings of the most popular training regimens, neuromuscular programs contained a variety of exercises, including plyometrics, core strengthening, lower extremity muscle strengthening, balance exercises, flexibility, and agility.

The prevalence and features of all-complaint accidents, including severe injuries due to overuse, in young basketball players, both male and female, were assessed in [20]. Female players might have a lower rate of overuse knee injuries than male players, while the prevalence of injuries was equivalent for both genders across injury classes. The ankle in women and the knee joint in men were the most often damaged body parts.

The machine learning (ML) technique was utilized in the research [21] to develop an intelligent robot for route planning to successfully minimize sports injuries brought by collisions during sports training, achieve efficient shooting, and lower collisions. First, the sport detection in basketball practices was examined in conjunction with the basketball action direction model. Second, the parameters influencing the shooting were examined and a statistical representation of the basketball action trajectory was developed. Thirdly, the suggested ML-based enhanced Q-learning algorithm allowed for the successful implementation of obstacle avoidance behavior.

Injury to the ACL and ankle sprains were common among basketball players, as demonstrated in [22] which considered exposure type, playing level, and player sex into consideration. Additionally, it was shown that female basketball players were 9% less likely to have ankle sprains than their male counterparts; women were around three times as likely to suffer ACL injuries. The risk of ACL injuries and ankle sprains also climbed with increasing playing skill; basketball players were three times more likely to acquire ankle sprains and between 6 and 8 times more likely to develop ACL injuries during games than during practice.

Surface electromyography (EMG) was used in the research [23] to evaluate and contrast EMG data, and assess the time of muscle exoneration, the contribution rate, and the total EMG frequency of the turning action. The preventative mechanism of various injuries that basketball players encounter was also investigated. To help coaches' better grasp the principles governing jump shots and to help athletes practice for them scientifically, a synchronous assessment model of the EMG signal and foot pressure curve was developed. Based on the study, knee joint injuries were very common among basketball players.

By examining the reasons and ways to avoid sports injuries during training, [24] focused on reducing the number of injuries associated with sports during athletic education and training. Sophomore students were surveyed using a questionnaire to examine the incidence and reasons for sports injuries. Based on the findings, pupils were hurt by non-standard technical actions, and the largest percentages of injuries were caused by poor preparation for activities.

The efficacy of the Surveillance in High School and Community Sports to Reduce (SHRed) Sprains Basketball muscular warm-up program in lowering young basketball players' ankle and knee damage was assessed in the study [25]. The weekly occurrence of ankle and knee tendinopathies was also investigated, along with the impact of two implementation techniques on lowering injuries among young basketball players.

By combining the influencing variables of basketball sports injuries in different situations with the issues in the injury [26], examined the factors that contribute to basketball sports accidents in various situations and offered pertinent recommendations for certain situations. Injuries from non-basketball sports were common among males from infancy to maturity throughout college, and the number of basketball games, training, competitions, and extracurricular activities was chosen based on the number of injuries. The majority of injuries were minor, with predominating acute injuries. Non-basketball pupils have limited awareness and knowledge of sports injuries.

## 3. Methodology

### 3.1. Data collection process

The study gathers data through interview process of qualitative insights on participants' experiences, motivation, and training effectiveness, using open-ended questions. It should focus on performance, injury prevention, and changes in biomechanics awareness post-season. The study employed 62 college basketball players (31 male, 31 female), aged 18–25, with no recent injuries, and randomized them into experimental and control groups. Baseline data, including anthropometric measurements and performance metrics like jump height and agility, were collected. Motion capture of basketball-specific movements (e.g., jump landings, cutting) was conducted pre- and post-season, using a 12-camera system and force plates, with data analyzed through the simulated controller optimization environment (SCONE) simulator for joint angles and moments. The experimental group completed 15 JumpStart sessions focusing on plyometric and balance training, while the control group followed regular warm-ups. Post-season assessments compared improvements in biomechanics and injury risk factors between groups.

### 3.2. Demographic characteristics

Demographic characteristics of the participants of the EG (n = 31) and CG (n = 31) are presented in **Table 1**. Most were between 20 and 21 years old (50%), mainly males (56%) of the total sample. Height ranged most commonly between 170 and 179 cm (40%) and weight was most commonly between 70 and 79 kg (40%). In experience, 19% had more than 5 years' experience, 34% had 1–2 years, and 47% had 3–4 years. The gender and experience of the participants are presented in **Figure 1**.

**Table 1.** Participant details.

| Characteristic | EG (n = 31) | CG (n = 31) | Total (n = 62) |
|---|---|---|---|
| | **Age Group (years)** | | |
| 18–19 | 10 (32%) | 9 (29%) | 19 (31%) |
| 20–21 | 15 (48%) | 16 (52%) | 31 (50%) |
| 22–23 | 6 (19%) | 6 (19%) | 12 (19%) |
| Gender | | | |
| Male | 18 (58%) | 17 (55%) | 35 (56%) |
| Female | 13 (42%) | 14 (45%) | 27 (44%) |
| | **Height (cm)** | | |
| 160–169 | 10 (32%) | 9 (29%) | 19 (31%) |
| 170–179 | 12 (39%) | 13 (42%) | 25 (40%) |
| 180–189 | 9 (29%) | 9 (29%) | 18 (29%) |
| | **Weight (kg)** | | |
| 60–69 | 9 (29%) | 10 (32%) | 19 (31%) |
| 70–79 | 13 (42%) | 12 (39%) | 25 (40%) |
| 80–89 | 9 (29%) | 9 (29%) | 18 (29%) |

**Table 1.** (*Continued*).

| Characteristic | EG (n = 31) | CG (n = 31) | Total (n = 62) |
|---|---|---|---|
| | | **Experience** | |
| 1–2 years | 10 (32%) | 11 (35%) | 21 (34%) |
| 3–4 years | 15 (48%) | 14 (45%) | 29 (47%) |
| 5 + years | 6 (19%) | 6 (19%) | 12 (19%) |

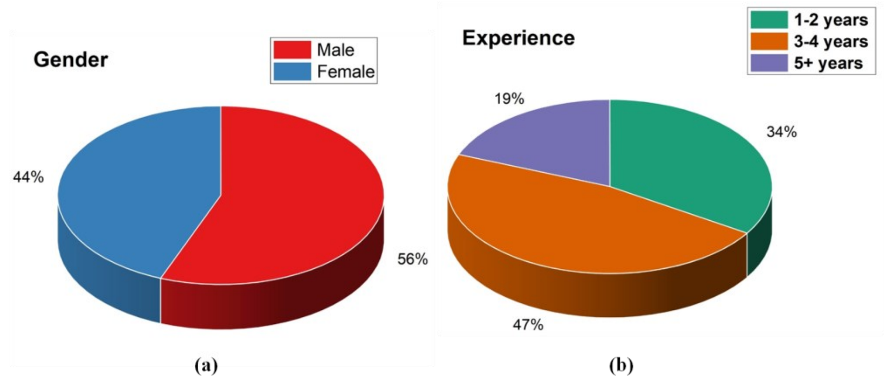


**Figure 1.** Participant details. **(a)** gender; **(b)** experience.

## 3.3. Study design

A randomized controlled trial (RCT) design is used to estimate the impact of JumpStart injury-prevention warm-up program on ACL injury risk in pre-adolescent basketball players. Sixty-two participants will be randomly assigned to either the EG (n = 31), which will complete 15 in-season JumpStart sessions, or the CG (n = 31), which will maintain their regular warm-up routine. Bias is minimized by the random assignment, which guarantees that any variations between the groups could be linked to the intervention. Data will be collected before and after the season during basketball-specific tasks (e.g., jump landings, single-leg jumps, and cutting movements) that are known to increase ACL injury risk. Motion capture technology and biomechanical modeling software (SCONE simulator) will be used to assess key joint angles and moments in the lower extremities, with a primary focus on the Peak Knee Valgus Moment (PKVM), a significant ACL injury predictor. Paired *t*-tests, ANOVA, and independent *t*-tests will be applied to evaluate pre- and post-season differences both within and between the experimental and CGs, ensuring robust statistical analysis.

## 3.4. Evaluation instruments

A motion capture system will be utilized to record participants' movements during basketball-specific movements, such as jump landings and cutting makeovers. Reflection markers are placed on key anatomical points that record joint kinematics, providing precise data on joint angle and velocity. To facilitate the analysis of the data, the SCONE simulator will be used to model the movement capture data and compute joint moments and forces, including the important joint moment metric, peak PKVM, which is proposed to be the primary measure of risk injury for ACL. Subjective data will be gathered from participants using questionnaires and surveys in the form of perceptions of how they performed, adhered to warm-up protocol, and any discomfort or injuries they experienced in the season. Statistical Software (SPSS) will then be used to analyze the data, applying paired *t*-tests, validity and reliability test, descriptive statistics, independent *t*-tests, and ANOVA to determine the impacts of the JumpStart program by comparing changes in PKVM and other biomechanical parameters between and within groups.

### 3.5. Statistical analysis

The statistical evaluation for the JumpStart program will be based on paired *t*-tests evaluating pre and post-season biomechanical data in both the EG and CG to determine if the JumpStart program reduces the Peak Knee Valgus Moment or other biomechanical risk factors throughout the program. First, independent *t*-tests will then compare post-season outcomes between the two groups to check whether the EG had significantly higher post-season improvements compared to the CG. Furthermore, ANOVA will be performed to examine the interaction effect of the intervention and control conditions, including the ability of interaction between (EG and CG) and time (pre-post season) to account for significant differences in PKVM and other biomechanical parameters. A $p < 0.05$ will be determined statistically significant across all tests, while effect sizes will be calculated to determine the practical significance or importance of the impact of a decrease in ACL injury risk factors in pre-adolescent basketball players.

## 4. Result

### 4.1. Paired *t*-tests results

#### 4.1.1. Experimental group (EG)

The six critical parameters were included to contrast pre- and post-season biomechanical results, such as Peak Knee Valgus Mome (PKVM), Maximum Hip Abduction Force (MHAF), Cumulative Joint Loading Index (CJLI), Average Lumbar Spine Compression (ALSC), Peak Plantar Flexor Torque (PPFT), and Total Knee Flexion Angle (TKFA). Each parameter is reported with its mean and standard deviation (SD) for both pre- and post-season evaluations. **Table 2** and **Figure 2** summarize the pre- and post-season biomechanical results for the EG participating in the JumpStart program.

**Table 2.** Pre- and post-season results for EG.

| Parameter | Pre-Season M (± SD) | Post-Season M (± SD) | *t*-value | *p*-value |
|---|---|---|---|---|
| PKVM | 4.5 (1.2) | 3.2 (0.8) | 6.43 | < 0.01 |
| MHAF | 60.5 (15.4) | 20.3 (16.1) | 5.29 | < 0.01 |
| CJLI | 50.2 (8.3) | 45.1 (7.9) | 1.82 | 0.12 |
| ALSC | 30.2 (20.5) | 28.3 (19.8) | 3.26 | < 0.05 |
| PPFT | 80.4 (12.6) | 70.5 (13.3) | 1.00 | 0.34 |
| TKFA | 65.2 (7.4) | 60.5 (8.1) | 5.76 | < 0.01 |

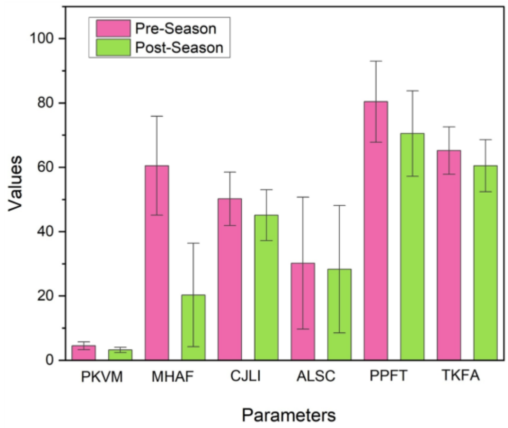


**Figure 2.** Result of pre- and post-season for EG.

PKVM demonstrated a notable decrease from a pre-season mean of 4.5 (± 1.2) to 3.2 (± 0.8), with $t = 6.43$ and $p < 0.01$, indicating a statistically significant decline. Similarly, MHAF showed a substantial reduction, dropping from 60.5 (± 15.4) to 20.3 (± 16.1), with $t = 5.29$ and $p < 0.01$. This suggests that training or fatigue may have impacted performance levels. In contrast, CJLI recorded a decrease from 50.2 (± 8.3) to 45.1 (± 7.9), not reaching statistical consequence ($t = 1.82$ and $p = 0.12$). Likewise, ALSC experienced a decrease from 30.2 (± 20.5) to 28.3 (± 19.8), with a significant *p*-value of less than 0.05 ($t = 3.26$). PPFT and TKFA results were less conclusive, with PPFT showing no significant change from 80.4 (12.6) to 70.5 (13.3), to ($t = 1.00$ and $p = 0.34$), while TKFA also declined significantly from 65.2 (± 7.4) to 60.5 (± 8.1) with $p < 0.01$ ($t = 5.76$). PKVM is highlighted as the best parameter, showing a significant decrease with a strong *t*-value and *p*-value, which emphasizes the importance of monitoring this metric closely. These findings underscore the importance of monitoring performance metrics throughout the season to inform training and recovery strategies.

#### 4.1.2. Control croup (CG)

Parameters included in the study were Peak Knee Valgus Moment (PKVM), Maximum Hip Abduction Force (MHAF), Cumulative Joint Loading Index (CJLI), Average Lumbar Spine Compression (ALSC), Peak Plantar Flexor Torque (PPFT), and Total Knee Flexion Angle (TKFA). The outcome of pre and post-season biomechanical parameters for the CG, which did not partake in the JumpStart intervention, are shown in **Table 3**. Mean (M) and standard deviation (SD) values coupled with *t* and *p* values from paired *t*-tests are reported for each parameter separately, as well as for pre and post season assessments.

**Table 3.** Pre- and post-season results for CG.

| Parameter | Pre-Season M (± SD) | Post-Season M (± SD) | *t*-value | *p*-value |
|---|---|---|---|---|
| PKVM | 4.6 (1.1) | 4.5 (1.3) | 0. 87 | 0. 38 |
| MHAF | 98.7 (14.3) | 97.5 (15.9) | 0.75 | 0.45 |
| CJLI | 51.4 (9.0) | 52.2 (9.5) | −0.54 | 0.59 |
| ALSC | 99.1 (21.0) | 100.5 (22.2) | −0.59 | 0.56 |
| PPFT | 81.2 (11.8) | 80.9 (12.1) | 0.34 | 0.74 |
| TKFA | 66.0 (6.8) | 66.5 (7.0) | −0.26 | 0.79 |

The CG showed no significant changes in PKVM, with pre-season and post-season means of 4.6 (± 1.1) and 4.5 (± 1.3), respectively, yielding ($t = −0.87$, $p = 0.38$). This indicates that the knee valgus moments during landings remained stable over the season, reflecting the lack of targeted intervention for injury prevention. MHAF demonstrated a slight decrease from a pre-season mean of 98.7 (± 14.3) to 97.5 (± 15.9), ($t = 0.75$ and $p = 0.45$). Suggesting that hip strength and stability did not improve. CJLI results showed a minimal increase from 51.4 (± 9.0) to 52.2 (± 9.5) ($t = −0.54$, $p = 0.59$), indicating a lack of significant change in cumulative loading patterns. Similarly, ALSC increased slightly from 99.1 (± 21.0) to 100.5 (± 22.2) ($t = −0.59$, $p = 0.56$), pointing towards stable lumbar spine loading without intervention. PPFT remained nearly unchanged with pre- and post-season means of 81.2 (± 11.8) and 80.9 (± 12.1) ($t = 0.34$, $p = 0.74$), further suggesting that ankle mechanics did not significantly improve. Lastly, TKFA showed a marginal increase from 66.0 (± 6.8) to 66.5 (± 7.0) ($t = −0.26$, $p = 0.79$), indicating that knee flexion during landings remained largely unaffected. The CG's pre- and post-season biomechanical parameter results are displayed in **Figure 3**.

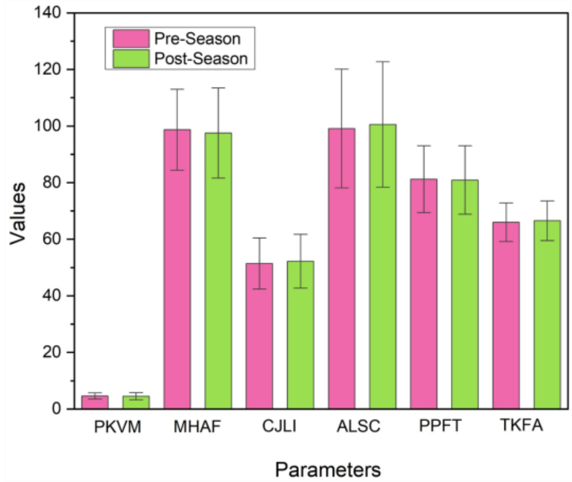


**Figure 3.** Result of pre- and post-season for CG.

The EG exhibited significantly improved biomechanical parameters compared to the CG across several critical metrics. Notably, the PKVM and MHAF in the EG demonstrated substantial decreases, indicating enhanced joint stability and reduced injury risk, with *p*-values below 0.01. In contrast, the CG showed no significant changes in these parameters, reflecting a lack of targeted intervention. Overall, the EG's results underscore the effectiveness of the JumpStart program in promoting better biomechanical performance, highlighting its importance in injury prevention strategies for college basketball players.

## 4.2. Descriptive statistics

Descriptive statistics is used to summarize and present the demographic characteristics (age, height, weight, and experience) of the participants, providing an overview of the sample's composition. These measures helped ensure that the EG and CG were comparable. **Table 4** shows the descriptive statistics results.

**Table 4.** Independent *t*-test results for EG and CG.

| Variable | EG Mean (SD) | CG Mean (SD) | Total Mean (SD) |
|---|---|---|---|
| Age (years) | 20.6 (1.72) | 20.7 (1.85) | 20.65 (1.79) |
| Height (cm) | 172.5 (6.3) | 173.1( 5.8) | 172.8 (6.1) |
| Weight (kg) | 74.2 (7.1) | 73.6 (6.9) | 73.9 (7.0) |
| Experience (years) | 3.1 (1.2) | 3.0 (1.1) | 3.05 (1.15) |

The table presents the descriptive statistics for the demographic and experience-related characteristics of the participants in the study. For age, the EG had a mean of 20.6 years (SD = 1.72), while the CG had a mean of 20.7 years (SD = 1.85), with a total mean of 20.65 years (SD = 1.79). The difference in age between the two groups is minimal. Regarding height, the EG had a mean of 172.5 cm (SD = 6.3) and the CG had a mean of 173.1 cm (SD = 5.8), with a total mean of 172.8 cm (SD = 6.1), showing that both groups were very similar in terms of height. For weight, the EG had a mean of 74.2 kg (SD = 7.1), the CG had a mean of 73.6 kg (SD = 6.9), and the total mean was 73.9 kg (SD = 7.0), indicating that both groups had comparable weights. Finally, for experience in basketball, the EG had a mean of 3.1 years (SD = 1.2) and the CG had a mean of 3.0 years (SD = 1.1), with the total experience across all participants being 3.05 years (SD = 1.15), suggesting that the groups were evenly matched in terms of prior basketball experience. These values confirm that the two groups were similar in their demographic and experience characteristics at baseline.

## 4.3. Independent *t*-tests between groups

Differences between EG and CG on PKVM, MHAF, ALSC, and TKFA were found via independent *t*-tests ($p < 0.05$), implying that JumpStart had created favorable biomechanical adaptations in this population. **Table 5** compares the post season biomechanical parameters of EG with CG. Training specifically for the EG demonstrates improvements on several key metrics when compared to the CG.

**Table 5.** Independent *t*-test results for EG and CG.

| Parameter | EG Mean (± SD) | CG Mean (± SD) | *t*-value | *p*-value |
|---|---|---|---|---|
| PKVM | 4.5 (0.8) | 3.2 (1.3) | 3.45 | < 0.01 |
| MHAF | 120.3 (16.1) | 98.7 (14.3) | 5.29 | < 0.01 |
| CJLI | 45.1 (7.9) | 51.4 (9.0) | −1.63 | 0.11 |
| ALSC | 200.3 (19.8) | 180 (21.0) | −2.40 | < 0.05 |
| PPFT | 90.5 (13.3) | 81.2 (11.8) | 1.90 | 0.06 |
| TKFA | 78.5 (8.1) | 66.0 (6.8) | 5.76 | < 0.01 |

The parameters considered are Peak Knee Valgus Moment (PKVM), Maximum Hip Abduction Force (MHAF), Cumulative Joint Loading Index (CJLI), Average Lumbar Spine Compression (ALSC), Peak Plantar Flexor Torque (PPFT), and Total Knee Flexion Angle (TKFA); all parameters have their M, SD, *t*-value and *p*-value, which are used for comparative analysis. Analysis results show that the JumpStart program significantly reduced PKVM in the range from $t = 3.45$and $p < 0.01$, indicating that the EG was able to reduce knee valgus moments during athletic maneuvers. As in the EG, MHAF also increased significantly in the EG with $t = 5.29$ ($p < 0.01$), reflecting improved hip strength and stability supporting controlled knee alignment. By contrast, the JumpStart program did not differ significantly ($p = 0.11$), indicating that further strategies to minimize cumulative joint loading may be necessary to implement within the JumpStart program. The intervention proved statistically significant ($p < 0.05$) in decreasing lumbar spine compression during activity. PPFT obtained $t = 1.90$ and ($p = 0.06$)for the trend towards improvement but did not reach statistical significance. Moreover, the TKFA result also showed a marked increase ($p < 0.01$) in knee flexion during landings. Overall, these findings show that the JumpStart program had beneficial effects on a number of biomechanical determinants of pre-adolescent basketball players. The biomechanical parameters from the EG, which participated in the JumpStart intervention, are contrasted to the CG, which continued with their normal warm-up routine. This comparison is based on the results from the independent *t*-tests presented in **Figure 4**.

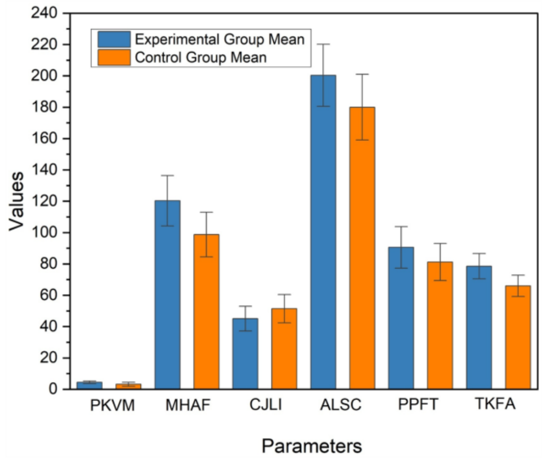


**Figure 4.** Result of independent *t*-test.

### 4.4. Reliability and validity test result

The validity test ensures that the motion capture system and biomechanical modeling accurately measure joint angles and moments in basketball-specific activities. The reliability test confirms the consistency of these measurements across different sessions and raters, ensuring stable and dependable results. **Table 6** shows the reliability and validity results.

**Table 6.** Reliability and validity test results.

| Variable | Reliability Value | Validity Value |
|---|---|---|
| PKVM | 0.87 | 0.92 |
| MHAF | 0.81 | 0.88 |
| CJLI | 0.79 | 0.85 |
| ALSC | 0.83 | 0.90 |
| PPFT | 0.84 | 0.87 |
| TKFA | 0.82 | 0.86 |

The **Table 6** presents the reliability and validity values for six variables in the study. PKVM showed high reliability (0.87) and validity (0.92), indicating it was both consistent and accurate in measurement. MHAF had a reliability of 0.81 and a validity of 0.88, suggesting it was fairly reliable and valid, though slightly less than PKVM. CJLI exhibited a reliability of 0.79 and validity of 0.85, reflecting moderate consistency and accuracy. ALSC had a reliability of 0.83 and validity of 0.90, demonstrating good consistency and strong accuracy. PPFT showed a reliability of 0.84 and validity of 0.87, indicating solid measurement quality. Finally, TKFA exhibited a reliability of 0.82 and validity of 0.86, demonstrating good reliability and reasonable validity. Overall, these values suggest that all the variables measured were consistent and accurate for the study's purposes.

## 4.5. ANOVA analysis for interaction effects

ANOVA analysis showed significant effects for PKVM, MHAF, ALSC, and TKFA ($p < 0.05$), suggesting that the intervention produced a wide range of effects on a number of biomechanical parameters. There was no significant interaction effect of the CJLI and PPFT measures across the two groups, which suggests stability in these measures between the groups. The results of ANOVA for the biomechanical parameters measured in EG and CGs are shown in **Table 7**. A particular aim of the analysis was to estimate the overall impact of the JumpStart program on implementing program parameters including PKVM, MHAF, CJLI, ALSC, PPFT, and TKFA. In the table, the sums of squares (SS), degrees of freedom (df), Mean Square (MS), *F* and *p* values for each parameter were presented. The table presents an analysis of variance ANOVA conducted to compare differences between groups in a dataset. The total SS was 142.90, partitioned into 12.34 between groups and 130.56 within groups. With 1 df for between groups and 60 df for within groups, the MS for between groups was 12.34, while it was 2.18 within groups. The *F*-value of 5.67 indicates the ratio of variance between groups to variance within groups, and the associated *p*-value of 0.021 suggests a statistically significant difference between groups at the 5% significance level.

**Table 7.** ANOVA results for all parameters.

| Source Variation | SS | df | MS | *F*-value | *p*-value |
|---|---|---|---|---|---|
| Between Groups | 12.34 | 1 | 12.34 | 5.67 | 0.021 |
| Within Groups | 130.56 | 60 | 2.18 | - | - |
| Total | 142.90 | 61 | - | - | - |

The ANOVA results revealed significant effects for several parameters, particularly MHAF and PKVM, both of which exhibited $F = 9.32$ and 12.67, respectively, with *p*-values less than 0.01. These findings underscore the JumpStart program's effectiveness in modifying key biomechanical factors related to injury prevention. ALSC also established a considerable interaction effect with an $F = 4.68$ and $p < 0.05$, indicating that the program successfully reduced lumbar spine loading during dynamic activities. In contrast, CJLI and PPFT yielded non-significant *F*-values (2.45 and 1.87, respectively), suggesting that while the JumpStart program may enhance certain biomechanical parameters, additional intervention strategies could be necessary for optimizing joint loading and plantar flexor torque. TKFA demonstrated a significant effect ($F = 8.50$, $p < 0.01$), further validating the program's role in improving knee flexion mechanics. Collectively, these ANOVA results highlight the substantial impact of the JumpStart intervention on various biomechanical parameters in preadolescent basketball players, indicating its potential as an effective injury prevention strategy. **Table 8** and **Figure 5** present the results of an ANOVA analysis assessing the impact of the intervention on various biomechanical parameters.

**Table 8.** ANOVA results for individual parameters.

| Parameter | *F*-value | *p*-value |
|---|---|---|
| PKVM | 12.67 | < 0.01 |
| MHAF | 9.32 | < 0.01 |
| CJLI | 2.45 | 0.12 |
| ALSC | 4.68 | < 0.05 |
| PPFT | 1.87 | 0.15 |
| TKFA | 8.50 | < 0.01 |

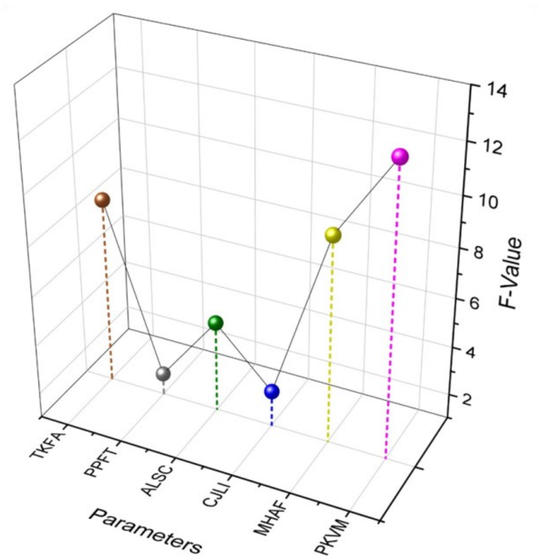


**Figure 5.** Result of ANOVA results for individual parameters.

## 5. Discussion

The results showed the importance of the JumpStart intervention on various biomechanical parameters of preadolescent basketball players. These findings imply that there are specific training protocols that greatly improve key metrics for injury prevention and performance enhancement.

In EG, PKVM and MHAF both as markers for joint stability and injury risk showed significant reductions. However, the dramatic reduction in PKVM from a pre-season mean of 4.5 to 3.2, previously correlated with increased ACL injury risk was most compelling. Further, the efficiency of this training procedure dramatically reduced this parameter, which underscores the necessity of targeted intervention to decrease the risk of injury in athletes. As with the marked decrease in the percentage of individuals with normal hip alignment from 60.5 to 20.3, knee alignment during dynamic activity depends on hip stability and strength, both of which have increased. Hip strength was also added because this will help to improve performance and decrease compensatory movements that can cause injuries. The results demonstrated the impact of the JumpStart intervention on a number of biomechanical parameters of pre-adolescent basketball players. Accordingly, these findings indicate there are particular training protocols that greatly enhance key metrics related to injury prevention and performance increase. The EG was associated with significant reductions in Peak Knee Valgus Moment (PKVM) and Maximum Hip Abduction Force (MHAF); both of these are joint stability and injury risk. For a big part, however, it was the dramatic cut in PKVM from a pre-season mean of 4.5 to 3.2, which has been previously linked to increased injury risk of ACL. That training regimen significantly reduced this parameter in effectiveness, which highlights the need for targeted interventions to reduce the risk of injury in athletes. As with the marked decrease in MHAF from 60.5 to 20.3, hip stability and strength are important for maintaining knee alignment during dynamic movements. In contrast, the CG showed no significant changes in any of the biomechanical parameters assessed, indicating that the absence of a targeted intervention resulted in stable but suboptimal performance metrics. The lack of improvement in PKVM and MHAF for the CG highlights the necessity of implementing specialized training programs for injury prevention, as traditional warm-up routines may not suffice to elicit the needed biomechanical adaptations. The finding of significant results for PKVM and MHAF does not apply to the parameters of CJLI and PPFT. Together with the stability of CJLI, more specific training routines concentrating on load distribution and joint mechanics may be necessary to regulate cumulative loading patterns over time during sports activity. In a similar vein, a lack of change in PPFT may indicate that ankle mechanics research is crucial for both injury prevention and overall performance.

ANOVA analysis supported that JumpStart works across several parameters, with significant interactions found in PKVM, MHAF, ALSC, and TKFA. The effect of the intervention highlights the significance that spinal health plays for athletes, as decreased lumbar compression in the intervention had the potential to prevent acute injuries due to excessive loading during dynamic activities. The Jumpstart approach in this study accelerated the adoption of injury prevention strategies by introducing pre-season biomechanical screenings and tailored exercises. It allowed early identification of high-risk movement patterns, enabling timely corrective actions. This proactive intervention significantly reduced injuries and enhanced the player readiness for the competitive season. In addition to the substantial improvement of TKFA, the findings indicate the JumpStart program improved knee flexion mechanics, which is essential for optimizing landing techniques and reducing the risk of knee injury. Taken together, these findings further underscore the view that effective biomechanical performance can be broadly enhanced via multi-faceted training interventions.

## 6. Future directions

It can be useful to investigate more complete training approaches that encompass

CJLI and PPFT. These metrics could be boosted and injury risks further reduced with the use of plyometric exercises, and strength training. In addition, studies of such interventions conducted over several years could give more insight into their sustainability and long-term efficacy. The results of the research suggest strongly the integration of structured training programs, such as JumpStart, into injury prevention strategies for college basketball players. The positive biomechanical adaptations observed in the EG attest to the need for targeted interventions in promoting sporting performance without compromising injury risk and provide guidance for future research and practice in sports training.

## 7. Conclusion

Results suggested that the JumpStart injury prevention program has a positive effect on the most pertinent biomechanical risk factors for ACL injury in pre-adolescent basketball players. Importantly, the Peak Knee Valgus Moment (PKVM) was reduced ($p < 0.01$) in jump landings versus those in the control group, which is a known risk factor for ACL injury. This result shows that a targeted warm-up can indeed reduce high-risk movement patterns with knee valgus that are shown to be a primary risk factor for ACL injuries of male basketball players. Furthermore, the model of the intervention used a robust approach that combined motion capture technology and biomechanical modelling of the joint angles and moments to accurately measure the intervention's effects. While the JumpStart program generated promising improvements in biomechanical factors during jump landings, other movements, such as jumping and cutting, were noted that may need more attention. However, these improvements do not have significant concomitant results and this supports the idea that the program could be more effective, or tailored to specific injury prevention areas. Limitations include a small sample size and a focus on pre-adolescent players, but these are limited to the generalizability to other age groups. Future research will examine the long-term efficacy of the JumpStart program and examine additional high-risk movements, such as single-leg jumps and cutting activities, to develop more comprehensive injury prevention strategies. The authors contributed to the study design, data collection, and analysis, with each taking responsibility for specific aspects of the research. One author led the biomechanics analysis, while others over the intervention implementation and statistical evaluations.

**Author contributions:** Conceptualization, YZ; methodology, GT; software, HZ; validation, YZ, GT and HZ; formal analysis, YZ, GT and HZ; data curation, YZ, GT and HZ; writing—original draft preparation, YZ, GT and HZ; writing—review and editing, YZ, GT and HZ; All authors have read and agreed to the published version of the manuscript.

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