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Evaluating Kinematic and Plyometric characteristics of Drop Jump in Young Basketball Players: a cross-sectional study

Andrea Bonini

andrea.bonini@phd.units.it

University of Trieste

Miloš Ajčević

University of Trieste

Valentina Tommasini

University of Trieste

Beatrice Blasio

Saint Camillus International University of Rome and Medical Sciences (UniCamillus)

Marco Prenassi

AREA Science Park

Francesca Policastro

Institute for maternal and child health IRCCS BURLO GAROFOLO

Francesco Frontani

Alma Mater Europaea

Research Article

Keywords: Basketball, Drop Jump, Plyometric Performance, Biomechanics, Youth Athletes, Machine Learning

Posted Date: September 15th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10625420/v1

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Additional Declarations: No competing interests reported.

Abstract

Background

Functional assessments, such as the Drop Jump (DJ) test, are essential for evaluating neuromuscular status, training effectiveness, and injury prevention in basketball players. Jumping features vary with age and training level, highlighting the need for tailored programs. However, limited data exists on drop jump patterns progress in young basketball players during growth.

Aim

This study aimed to examine age-related changes in drop jump and identify key parameters extracted from video analysis and the OptoJump system in young athletes.

Methods

Participants included male basketball players aged 13 to 16 years, divided into four age groups (13, 14, 15, and 16 years). Kinematic and performance parameters were evaluated. Differences between adjacent age groups were assessed. Linear regression was applied to identify significant factors contributing to jump height within each age group. Machine learning (ML) models were designed to distinguish between ‘good’ and ‘bad’ jump, with respect to the plyometric execution.

Results

Results showed that, between 13 and 15 years of age, athletes exhibited progressive changes in jumping kinematics, characterized by greater knee flexion and reduced ankle contribution. Comparisons between 15- and 16-year-old players highlighted reduced knee flexion, enhanced ankle involvement, and shorter ground contact times in the older group, indicating improved plyometric capabilities. Linear regression identified ankle and knee flexion as the key contributors to jump height. ML confirmed ankle flexion (positive), knee flexion and knee valgus (negative) as main contributors to plyometric performance.

Conclusions

Our study highlights age-related adaptations in drop jump patterns among young basketball players, emphasizing the importance of tailored evaluations.

Introduction

Basketball is an intermittent team sport characterized by repeated high-intensity actions, including sprinting, changes of direction, and jumping, interspersed with periods of lower-intensity activity [1]. Vertical jumping is a key component of basketball performance, occurring on average once per minute during competitive games [2]. These movements rely on the stretch-shortening cycle (SSC), requiring efficient muscle–tendon function to optimize elastic energy storage and release [3]. Consequently, basketball demands high levels of strength, power, agility, and sport-specific skills [4].

The high physical demands also expose athletes to an increased risk of injury, particularly anterior cruciate ligament (ACL) tears and ankle sprains, often associated with landing tasks or player contact [5]. Therefore, training programs should optimize performance while reducing injury risk through appropriate periodization, load management, and age-specific interventions [6].

Functional assessments are widely used to evaluate neuromuscular status, monitor training adaptations, and guide injury prevention. Among jump-based tests, the drop jump (DJ) is one of the most common assessments of fast SSC function and reactive strength [3, 7]. In basketball, unilateral DJ is particularly useful because it reflects sport-specific demands and provides information on lower-limb strength, power, dynamic stability, and inter-limb asymmetries [8, 9]. A key performance indicator derived from the DJ is the Reactive Strength Index (RSI), calculated as the ratio between jump height and ground contact time, which reflects the ability to rapidly generate force during SSC tasks [10]. Objective evaluation of DJ performance is especially important in young athletes, as adolescence represents a critical period for motor development and the acquisition of efficient movement patterns [11]. Since jumping mechanics evolve with growth and training experience [12], age-specific assessment may help optimize training, injury prevention, and rehabilitation strategies.

Previous studies have mainly focused on adult elite athletes or on the effects of plyometric training interventions [13]. Consequently, the kinematic characteristics and performance progression of the unilateral drop jump during adolescence remain insufficiently described [14].

This study aimed to explore age-related changes in the kinematic and performance characteristics of the drop jump, using parameters acquired through a motion capture system and subsequently processed via video analysis, along with performance metrics measured by the OptoJump system in basketball players aged 13 to 16 years. As a secondary objective, we sought to determine which kinematic parameters were most strongly associated with jump height, analysing each age group separately. Finally, we aimed to develop an interpretable machine learning model for the classification of plyometric jumping performance based on kinematic parameters, which could be applied by trainers and physiotherapists to objectively assess jumping in real-world settings.

Methods

Participants

The study population consisted of male athletes from the *Azzurra Basketball* club (Trieste) competing in the elite youth championship. Participants were divided into four age groups according to their year of birth: Under 13 (Group 1), Under 14 (Group 2), Under 15 (Group 3), and Under 16 (Group 4). Athletes with a history of severe injury or lower-limb pain affecting jump execution, as assessed by experienced physiotherapists, were excluded. Anthropometric characteristics (height and weight), basketball experience, dominant side, and DJ performance and kinematic parameters obtained through the OptoJump system and video analysis were collected. Fifty athletes were initially enrolled; three were

excluded because of lower-limb pain before testing. The final sample comprised 47 players (Group 1, *n* = 11; Group 2, *n* = 11; Group 3, *n* = 13; Group 4, *n* = 12), including three left-dominant athletes. The sample size of each age group is comparable to those used in several studies on kinematic and kinetic jump evaluations, as reported in a recent review [15].

The research was conducted according to the principles of the Declaration of Helsinki. All participants' parents provided their written informed consent. The study was approved by the Ethical Committee of Saint Camillus International University of Rome and Medical Sciences with the protocol number E00711-2022. This study adheres to the guidelines developed by Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) [16].

Design and procedure

The drop jump is a plyometric exercise in which the athlete drops from a predetermined height and, upon landing, immediately performs a maximal-effort vertical jump, aiming both to minimize ground contact time (CT) and to achieve maximum jump height. The starting height of 30 cm was chosen based on evidence from the literature in this field [13]. Before performing the jump, participants were instructed to achieve the greatest vertical height possible while observing two restrictions: keeping hands on the hips at all times, thus avoiding upper-body interference, and jumping and landing on the same spot, to ensure that the jump was vertical [17].

Experimental procedure and acquisition devices

The testing protocol was carried out in ecological conditions. The experimental procedure was carried out as reported in the previous work [18]. After the warm-up, seven reflective markers were placed on each athlete, one for each lateral malleoli, one immediately below the knee lateral epicondyle of both knees, one on each great trochanter of the femur and the last one on the xiphoid process of the sternum. The testing area consisted of an Optojump system, and three GoPro cameras (MoCap system). Participants stood between the Optojump bars. One camera was positioned anteriorly, with two additional cameras placed laterally, all at a distance of 2 m from the subject [19].

Trunk flexion, knee flexion, ankle flexion and knee valgus were measured with the reflective markers strategically placed to enable precise kinematic evaluation. Considering the athlete's standing starting position on the platform as the reference point, all angles were calculated as the maximum reached in the landing phase of the jump. All parameters were extracted using Kinovea software, whose reliability and validity have been reported in several previous studies [19].

Statistical analysis

The normality of the variables was assessed using Lilliefors test. The normal variables are presented as mean and Standard Deviation (SD) and the non-normal variables as median and range. Differences

between adjacent age groups were assessed using Student's t-test for normally distributed and the Wilcoxon rank-sum test for non-normally distributed variables, respectively. Considering the Bonferroni correction, a $p < 0.017$ was considered statistically significant.

A univariate linear regression was used to identify, for each age group, the parameters associated with the jump height. In this analysis, the level of significance was set at 0.05

Machine learning models

Machine learning (ML) models were created to distinguish between 'good' and 'bad' jumps, with respect to the plyometric execution. A jump was classified as "good" if the RSI of the subject was above the average value of the corresponding group. Feature selection process was based on RelieF, with the threshold fixed at 0.05 [20].

Naive Bayes and logistic regression methods were employed to produce interpretable models [21].

All models were evaluated using a 5-fold cross-validation method. All analyses were carried out in Python Orange Data Mining library and toolbox [22].

Results

The overall procedure is described in figure 1.

Age-related difference in landing phase kinematics and performance parameters

Comparisons between adjacent age groups were performed to evaluate age-related differences in kinematic and performance parameters, highlighting progressive evolution of jumping characteristics. In the comparison between under 13 and under 14 groups (Table 1), statistically significant differences were identified for right and left trunk flexion ($p=0.004$, $p=0.003$), left knee flexion ($p =0.008$), right ankle flexion ($p= 0.007$), right knee valgus ($p= 0.003$) and right and left ground contact time ($p=0.003$, $p= 0.015$). In addition, left ankle flexion showed a difference at the limit of significance ($p=0.02$).

In the comparison between under 14 and under 15 groups (Table 1), right knee flexion ($p= 0.003$), left ankle flexion ($p=0.016$), time of flight of left side jump ($p = 0.015$) and left jump height ($p=0.016$) showed statistically significant difference.

Between group under 15 and under 16 groups (Table 1), bilateral knee flexion ($p=0.006$, $p=0.006$), bilateral ankle flexion ($p<0.001$, $p<0.001$), left knee valgus ($p=0.007$), right and left time of flight ($p<0.001$, $p<0.001$), right and left jump height ($p<0.001$, $p<0.001$) and right and left RSI ($p=0.016$,$p=0.005$) showed statistically significant differences. A statistically significant difference was also shown by BMI ($p=0.005$).

Jump height correlation for age groups

Right side

For under 13 group, knee valgus showed a significant correlation with jump height (p=0.036). For under 14 group, knee and ankle flexion showed a significant correlation with jump height (p=0.045, p=0.023). For under 15 group, knee and ankle flexion (p=0.012, p=0.037), as well as contact time (p=0.049), showed a significant correlation with jump height. For under 16 group, ankle flexion and contact time showed a significant correlation with the outcome (p<0.001, p=0.027).

Left side

For under 13 group, trunk flexion and contact time showed a significant correlation with jump height (p=0.038, p=0.046). For under 14 group, knee, ankle flexion and knee valgus showed a significant correlation with jump height (p<0.001, p<0.001, p=0.030). For under 15 group, knee and ankle flexion showed a significant correlation with jump height (p<0.001, p<0.001). For under 16 group, trunk and ankle flexion showed a significant correlation with the outcome (p=0.002, p=0.009).

Predictive model for group 4

For under 16 group, a ML model based on kinematics features was developed to differentiate between “good” and “bad” plyometric jumping pattern. The application of Relief algorithm with a threshold value of 0.05 highlighted the following features as valuable for the subsequent model development. For right side: ankle flexion, knee valgus, knee flexion; for left side: ankle flexion, knee flexion, knee valgus, trunk flexion. The logistic regression model demonstrated superior performance compared to others, achieving AUC of 86%, 92% (R,L); CA of 83%, 83% (R,L), F1 of 83%,80% (R,L), Precision of 83%, 80% (R,L), Sensitivity of 83%, 80% (R,L) and Specificity of 83%, 86% (R,L). All the considered evaluation metrics were obtained using 5-fold cross-validation criterion. Lastly, the nomograms of the logistic regression model for the right and left sides are presented below, ranking the predictors according to their relative contribution to good performance. For the right side, the most influential predictor was ankle flexion, positively associated with good plyometric performance, followed by knee flexion and knee valgus, both showing negative associations. For the left side, the order of importance was knee flexion, ankle flexion, knee valgus, and trunk flexion; knee flexion, knee valgus, and trunk flexion were negatively associated with a good plyometric performance, whereas ankle flexion was positively associated.

Discussion

Our findings provide new insights into age-related changes in unilateral drop jump mechanics in basketball players aged 13–16 years. Between 13 and 15 years of age, athletes progressively adopted a jumping strategy characterized by greater knee contribution and reduced ankle involvement, suggesting that force production predominates over efficient SSC utilization during early adolescence. This pattern is likely related to the imbalance between muscle strength and tendon stiffness that occurs during

growth [24] and is further supported by greater trunk involvement and increased knee valgus, reflecting compensatory strategies and reduced neuromuscular control [25]. Conversely, 16-year-old athletes demonstrated greater ankle contribution, shorter contact times, reduced knee flexion, and improved knee alignment, indicating a more mature and efficient plyometric strategy. These findings are consistent with previous evidence showing that maturation-related increases in muscle-tendon stiffness enhance SSC efficiency and drop jump performance [13, 26, 27]. The progression of knee and ankle flexion across age groups is summarized in Fig. 3.

Linear regression identified ankle and knee flexion as the primary determinants of jump height across all age groups, confirming the central role of lower-limb power generation in vertical jumping performance [28]. In the youngest athletes, greater knee valgus was associated with higher jump height, suggesting that immature players may rely on compensatory movement strategies to generate force. Although such adaptations may temporarily improve performance, excessive knee valgus is a well-established risk factor for anterior cruciate ligament injury [29], emphasizing the importance of early identification and targeted neuromuscular training. Reduced contact time was positively associated with jump performance in all groups except the youngest, further supporting the progressive maturation of SSC function. Trunk flexion positively influenced jump height on the left side in the youngest and oldest groups, possibly reflecting sport-specific adaptations related to repeated unilateral lay-up movements and the functional asymmetries commonly observed in basketball players [30, 31].

In addition to conventional analyses. we developed an interpretable machine learning model to identify the kinematic variables associated with plyometric performance. Logistic regression provided a practical framework for quantifying both the strength and direction of the association between movement parameters and the Reactive Strength Index (RSI). On the right side, the model included ankle flexion, knee flexion, and knee valgus, whereas on the left side trunk flexion was also retained. Greater ankle flexion and reduced knee flexion were associated with better plyometric performance, supporting previous evidence that efficient drop jump execution relies on greater ankle contribution and reduced knee dominance [33]. On the left side, excessive trunk flexion negatively affected RSI, suggesting that although it may reflect sport-specific adaptations [31], greater core stability is associated with more efficient plyometric execution [34]. Finally, lower knee valgus was associated with higher RSI on both sides, emphasizing the importance of knee valgus assessment, given its association with both reactive jump performance and anterior cruciate ligament injury risk reported in previous studies [29].

This study presents some limitations, such as the recruitment of participants from a single basketball club. However, the sample characteristics are representative of athletes in the specified age group. Future studies might aim to implement multi-camera setups, include broader kinetic profiling, and consider biological maturation metrics.

Conclusions

Our study demonstrated how the kinematic and performance characteristics of the drop jump progressively evolve in athletes aged 13 to 16 years. As athletes mature from 13 to 15 years of age, their jumping pattern changes, showing increased knee flexion and reduced ankle flexion, likely due to an unstable plyometric profile and imbalances in muscle and tendon capacities. As players mature, improvements in muscle and tendon stiffness promote a transition toward a more efficient jumping strategy, involving greater ankle joint engagement, less knee flexion, shorter ground contact time and better joint alignment. We also developed an interpretable machine learning model to assess plyometric jumping performance based on kinematic variables, achieving strong predictive metrics. This model represents a practical tool for coaches and physiotherapists to objectively evaluate jumping performance.

Declarations

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics approval

This study was performed in line with the principles of the Declaration of Helsinki. The study was approved by the Ethical Committee of Saint Camillus International University of Rome and Medical Sciences with the protocol number E00711-2022

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent to Publish

Not applicable.

Funding

The authors did not receive support from any organization for the submitted work.

Author Contribution

F.F. F.P. and B.B. conceptualization, F.F. F.P. M.P and A.B methodology, B.B. F.F. M.P. and V.T collect the data and perform the tests, A.B. M.P. and M.A. provides the statistical analysis, F.P. B.B. V.T. and A.B. wrote the main manuscript, A.B. and M.P. prepared tables and figures, F.F. and M.A. revised the draft and suggest modification.all authors reviewed and approved the final version

Data availability

The datasets of the current study are not publicly available due to ethical and privacy restrictions and cannot be shared

Code availability

The code used for analysis in this study is not publicly available due to intellectual property and institutional policy restrictions.

Tables

Tables 1-5 are available in the Supplementary Files section.

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Figures

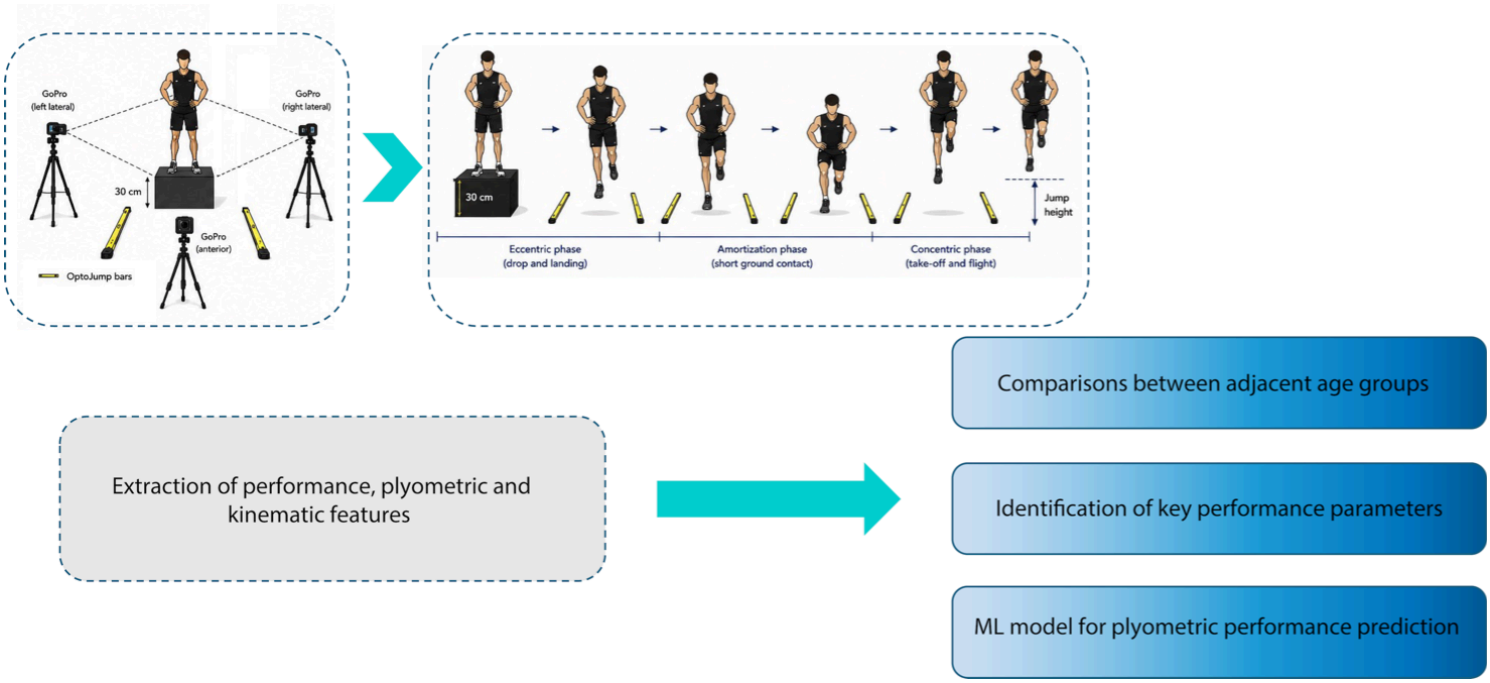


Figure 1

Overview of the experimental protocol, including the testing setup, single-leg drop jump execution, parameters acquisition and proposed analyses.

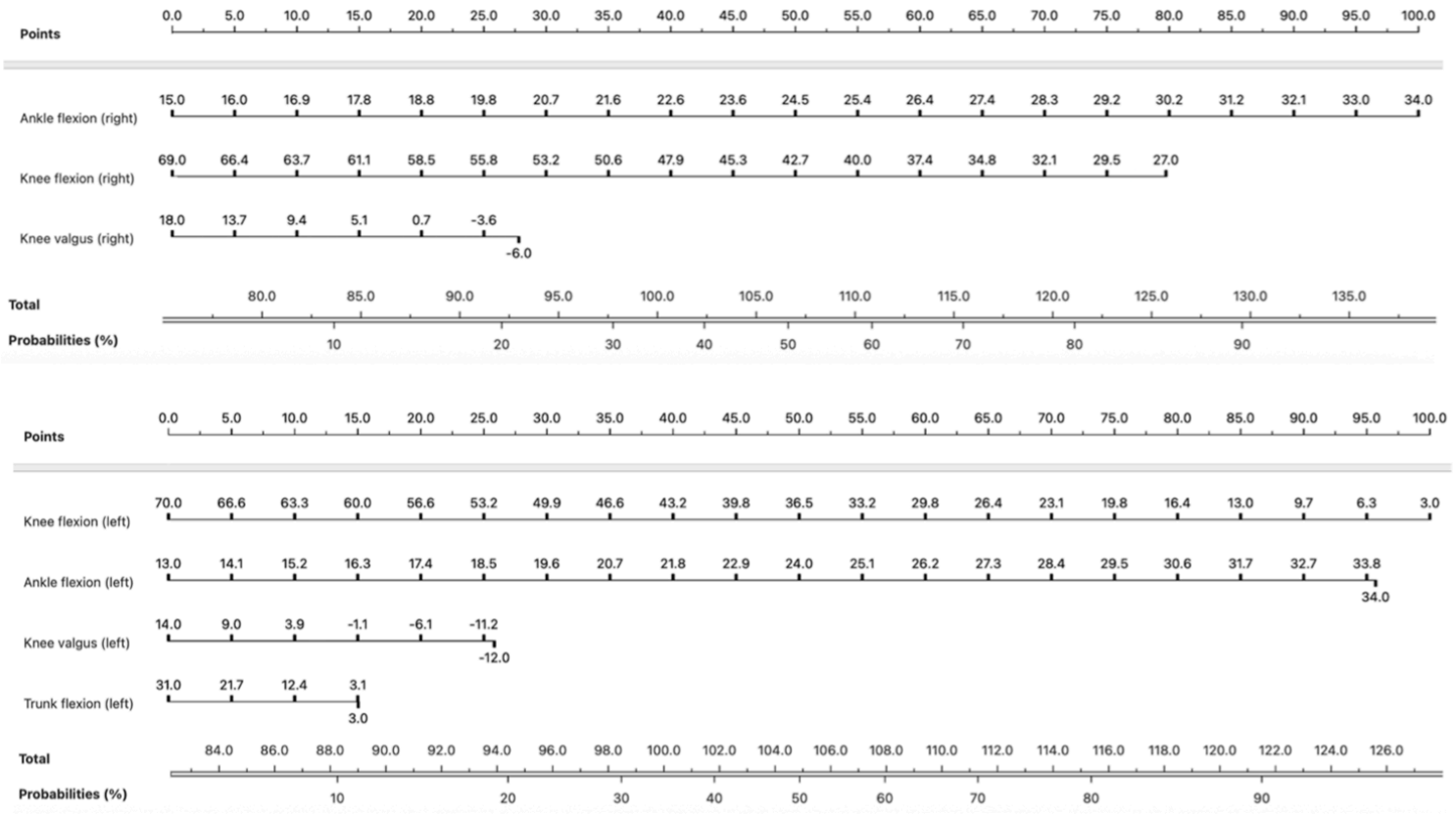


Figure 2

Logistic regression nomogram for under 16 group, right side (upper panel); left side (lower panel). This nomogram represents the predictive model obtained using logistic regression method for under 16 group.

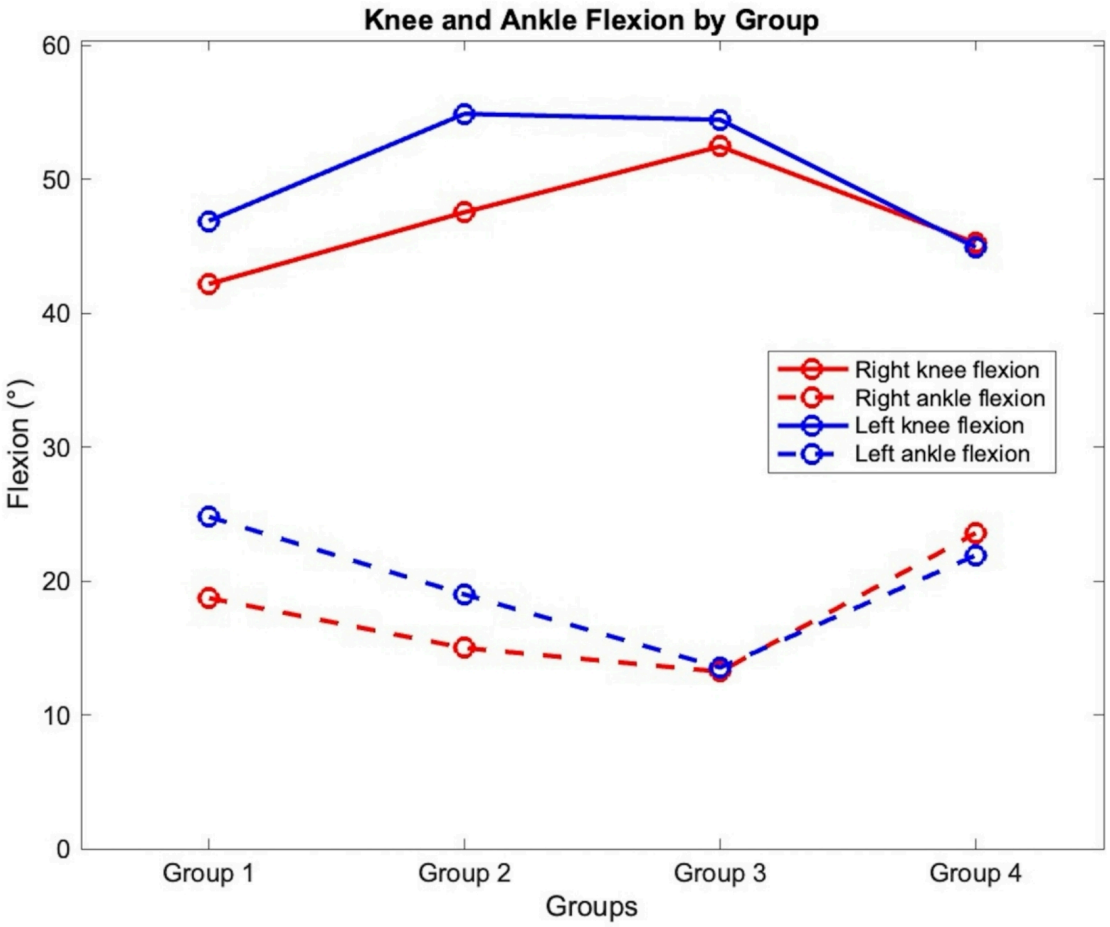


Figure 3

Progression of knee and ankle flexion parameters across groups.

Supplementary Files

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