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Correlation of knee joint laxity with bioimpedance parameters and bone frame size

Correlación de la laxitud de la articulación de la rodilla con parámetros de bioimpedancia y complexión ósea

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ABSTRACT. Introduction: femorotibial laxity plays a crucial role in knee stability, as increased laxity can raise the risk of injuries not only to the anterior cruciate ligament (ACL) but also to other key structures such as the posterior cruciate ligament (PCL) and the posteromedial and posterolateral corners. This study analyzed the factors associated with laxity in young individuals, as identifying the elements that influence this condition is essential for its prevention. The objective was to evaluate knee joint laxity in young people, considering factors such as sex, bone structure, body composition, and physical activity. **Material and methods:** a total of 114 patients over 18 years old without any history of knee ligament injuries were included. Body composition was evaluated with the OMRON HBF-514c body composition monitor and scale. The ACL laxity was measured using the KNEELAX 3® arthrometer, while internal and external rotation was measured with PhidgetSpatial Precision inertial sensors. Physical activity was classified with Tegner scale while

RESUMEN. Introducción: la laxitud de la articulación femorotibial desempeña un papel crucial en la estabilidad de la rodilla, ya que un aumento en la laxitud puede elevar el riesgo de lesiones no sólo en el ligamento cruzado anterior (LCA), sino también en otras estructuras clave como el ligamento cruzado posterior (LCP) y las esquinas posteromedial y posterolateral. En este estudio, se analizaron los factores asociados con la laxitud en jóvenes, ya que identificar los elementos que influyen en esta condición es fundamental para su prevención. El objetivo fue evaluar la laxitud de la articulación de la rodilla en jóvenes, considerando variables como el sexo, la complexión ósea, la composición corporal y la actividad física. **Material y métodos:** un total de 114 pacientes mayores de 18 años sin antecedentes de lesiones ligamentarias de rodilla fueron incluidos en este estudio. La composición corporal fue evaluada con la báscula OMRON HBF-514C. La laxitud del LCA fue medida con artrometría (KNEELAX 3®), y la rotación interna y

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Lachman and Pivot Shift tests were performed as well as indicators of the ACL stability. **Results:** the mean age was 21.04 ± 2.2 years. Greater knee laxity (6.9 mm at 88N and 8.9 mm at 132N with p values of 0.047 and 0.001 respectively) and increased internal (28.7º) and external rotation (27.76º) were observed in women. ACL laxity was higher in individuals with smaller bone frame size (8.67 mm at 132N) and higher body fat percentage. In addition, participants with higher physical activity levels showed lower ACL laxity. **Conclusion:** knee joint laxity was found to be greater in women, individuals with smaller bone frame size, and those with higher body fat percentage, which may increase the risk of injuries. Simultaneously, knee joint laxity was found to be lower in individuals with higher activity levels. It was concluded then that strengthening the musculature and making physical activity are essential for ligamentary injury prevention.

Keywords: injuries prevention, Joint hyperlaxity, rotational stability.

externa con sensores inerciales *(PhidgetSpatial Precision)*. Las pruebas de Lachman y *Pivot Shift* fueron realizadas como indicadores de la estabilidad del LCA. La actividad física se clasificó con la escala de Tegner. **Resultados:** la media de edad fue 21.04 ± 2.2 años. Una mayor laxitud femorotibial (de 6.9 mm a 88N y de 8.9 mm a 132N con valores de p de 0.047 y 0.001 respectivamente) y mayor rotación interna (28.7º) y externa (27.76º) fue observada en mujeres. La laxitud del LCA fue mayor en personas con menor complexión ósea (8.67 mm a 132N) y mayor grasa corporal. Individuos con mayor actividad física presentaron menor laxitud del LCA. **Conclusión:** la laxitud femorotibial es mayor en mujeres, personas con menor complexión ósea y mayor grasa corporal, lo que puede incrementar el riesgo de lesiones. Se encontró que la laxitud femorotibial es menor en personas con un alto nivel de actividad física. Así, fortalecer la musculatura y realizar actividad física son clave para prevenir lesiones ligamentarias de la rodilla.

Palabras clave: prevención de lesiones, hiperlaxitud articular, estabilidad rotacional.

Abbreviations:
ACL = anterior cruciate ligament
ICC = intraclass correlation coefficient
MCL = medial collateral ligament
MRI = magnetic resonance imaging
PCL = posterior cruciate ligament
PLC = posterolateral corner
PMC = posteromedial corner

Introduction

The stability of the knee joint relies on various anatomical structures, including ligaments, muscles, the joint capsule, menisci, etcetera.[1,2] The anterior cruciate ligament (ACL) plays a crucial role in preventing anterior displacement of the tibial plateau relative to the femoral condyle and in maintaining stability during rotational movements, this can be attributed to its tensile resistance, measured at 17,256 ± 269 N.[3] However, kinetic forces acting on the knee, particularly during valgus flexion between 60º and 90º, can exceed the ACL's load-bearing capacity, increasing the risk of injuries such as tears or ruptures.[4]

The diagnosis of ACL injuries involves clinical tests, including the Lachman and Pivot-Shift tests, which demonstrate high sensitivity and specificity.[5] Additionally, magnetic resonance imaging (MRI) further enhances diagnostic accuracy.[6,7] In terms of quantitative laxity assessment, arthrometry is considered the gold standard, as it measures ACL laxity by evaluating anterior tibial displacement under varying applied forces.[8] While not routinely used in individuals without knee conditions, this tool is particularly valuable for diagnosing injuries in athletes.[9]

The posterior cruciate ligament (PCL) plays a crucial role in preventing posterior tibial translation and provides secondary stabilization against varus, valgus, and external rotational forces.[10] PCL rupture can lead to increased internal and external tibial rotation, negatively impacting joint stability.[11,12,13] Additionally, rotational stability of the knee depends on the structures of the posterolateral and posteromedial corners.[14,15,16] The posterolateral corner (PLC) consists of the lateral collateral ligament, the popliteus tendon, and the popliteofibular ligament, which contribute to resisting external tibial rotation and varus stress.[14,15] The posteromedial corner (PMC) includes the posterior oblique ligament, the semimembranosus expansions, and the medial collateral ligament (MCL), which help control internal tibial rotation and valgus stress.[17] Injury of these structures, in combination with PCL deficiency, can result in significant rotational instability, further compromising knee function.[14,16,17]

ACL injuries have increased significantly over the last two decades, despite the efforts of researchers and clinicians to mitigate risk.[18] Approximately 200,000 to 250,000 ACL injuries occur annually in the United States, making them the most common cause of knee injuries among young athletes.[19] Furthermore, the incidence of these injuries is three times higher in female athletes participating in contact or high-impact sports involving rotational landings.[19] Additional risk factors include higher body weight which is associated with an increased risk of ACL injury,[20] as well as certain anatomical characteristics such as a narrow femoral notch, a steep lateral tibial slope, and reduced medial tibial plateau depth, all of which have been shown to significantly influence the risk of ACL injury, particularly in young women due to differences in skeletal development.[21] Ligamentous laxity and hormonal fluctuations have also been associated with an increased risk of ACL injury.[22]

Although epidemiological data on anterior cruciate ligament (ACL) injuries in Mexico remain limited, a study conducted in Brazil reported a higher frequency of ACL injuries in women, consistent with global trends.[23]

Available national studies have primarily focused on populations already affected by injury or those who have undergone surgical intervention. For instance, one study in adults who underwent ACL reconstruction analyzed risk factors and the frequency of re-ruptures, highlighting the influence of clinical history and physical characteristics on recurrence. However, few investigations have evaluated predisposing factors in healthy populations.[24]

Evaluating knee laxity while accounting for factors such as gender, age, physical activity level, body composition, medical history, clinical tests, anthropometric and demographic data, and bone frame size is essential for understanding their impact on joint stability. A comprehensive analysis of these factors may help identify predispositions to injury and contribute to the development of preventive strategies based on biomechanics and sports medicine.[7,18,19,20]

The objective of this study was to assess knee joint laxity in relation to age, gender, bioimpedance, physical activity level, and bone frame size in young individuals, aiming to improve understanding of its impact on musculoskeletal health, injury prevention, and physical performance. Our hypothesis was that knee joint laxity varies according to age, sex, bioimpedance, and bone frame size, with greater laxity observed in females, younger individuals, and those with lower muscle mass and higher body fat percentage, being the latter attributed to both hormonal and biomechanical factors. These differences in laxity may influence the predisposition to ACL injuries and other stabilizing structures of the knee.

Material and methods

An observational, cross-sectional, analytic and prospective study was conducted among students from the faculty of medicine at Universidad Autónoma de Nuevo León (UANL). Data collection took place within the school facilities between the months of August and December 2024. Participants were recruited through a social media outreach strategy *(Figure 1)*.

Inclusion criteria included all students enrolled in the Faculty of Medicine at UANL who were of legal age and provided informed consent for participation and data collection. Exclusion criteria included individuals who declined participation, as well as those with a medical history of anterior or posterior cruciate ligament injury, regardless of prior surgical treatment. Additionally, individuals diagnosed with a collagenopathy or presenting with collateral ligament injuries, posterior femorotibial instability, or meniscal lesions at the time of evaluation were excluded from the study.

Prior to data collection, the research team underwent training on the use of the arthrometer KNEELAX 3® (Mr. Systems, Haarlem, The Netherlands), PhidgetSpatial Precision inertial sensors, and physical assessment tests. This training was conducted by the principal investigator, R Morales-Ávalos, to ensure accurate data acquisition. The equipment was calibrated prior to each use through the respective software, ensuring accurate measurements in both the inertial sensors and the KNEELAX 3® system.

KNEELAX 3® was selected due to its ability to provide objective and controlled measurements of anterior tibial translation, with reduced variability in applied force compared to the KT-1000; although absolute values differ, both devices yield comparable side-to-side difference outcomes.[24]

After obtaining written informed consent from all participants to use their data in the study, their initials were recorded to ensure privacy, and each was assigned a unique study registration number. Additionally, data on age, gender, comorbidities, relevant surgical history, and prior lower limb injuries were collected. Body composition was assessed using the Omron HBF-514C digital scale, which provides seven indicators: BMI, basal metabolic rate, body fat percentage, visceral fat level, skeletal muscle percentage, and body age. Bilateral measurements of waist, thigh, and wrist circumferences were also taken. Physical activity level was assessed using the Tegner Activity Scale,[25] a validated tool that ranks functional activity from 0 (sick leave or disability due to knee problems) to 10 (competitive sports at elite level). In this study, a score of > 6 was categorized as high physical activity, as it corresponds to individuals engaged in regular participation in recreational or competitive sports such as running, tennis, soccer, or skiing. This cutoff is supported by previous literature, which has used similar thresholds to distinguish between moderate and high levels of activity in healthy and athletic populations. Moreover, a Tegner score > 6 has been associated with higher functional demands and greater mechanical load on

Figure 1: Recruitment flyer.

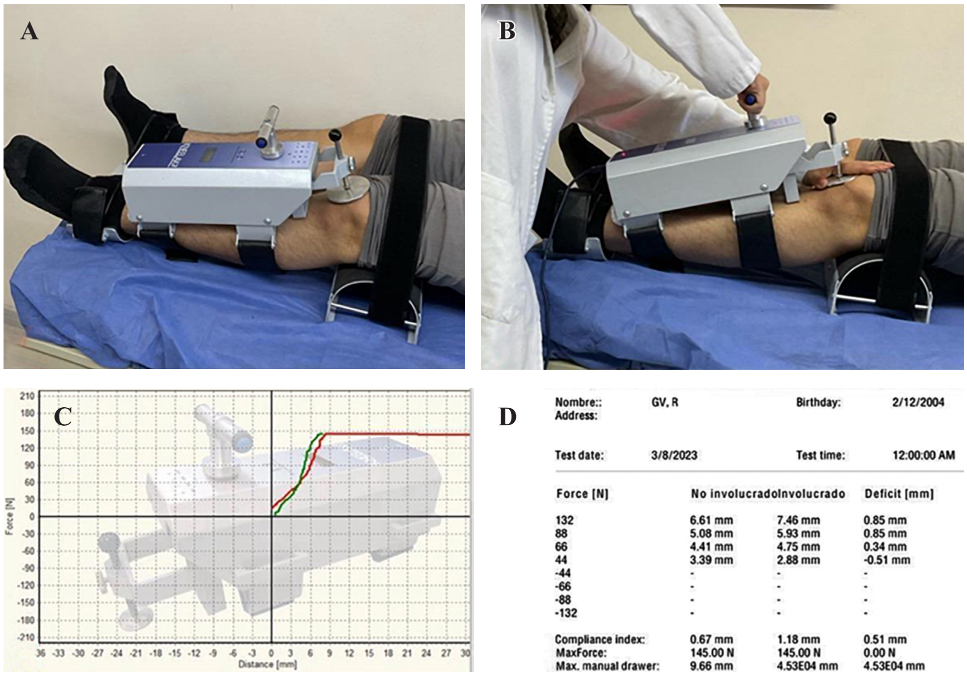

Figure 2:

A) The process includes participant positioning using KT-1000 arthrometer. **B)** Test execution. **C)** Result visualization as a graph in the software. **D)** Representation of anterior translation values in millimeters.

Figure 3: A) The process begins with the collocation of the inertial sensor on the participant's right leg. **B)** Positioned 5 cm below the patella, followed by internal and external rotation performed by the evaluator. Subsequently, the rotation angles are recorded using a gyroscope and displayed in the Phidget Spatial Precision software.

the knee joint, making it a relevant indicator for exploring the correlation between activity level and joint laxity.[25]

Bone frame size was defined using the Grant index, calculated as height (in centimeters) divided by wrist circumference (centimeters), allowing classification of body build as small, medium, or large.

To assess generalized joint laxity, the Beighton score was used,[26] evaluating specific criteria, including hyperextension of the fifth metacarpophalangeal joint, elbow and knee hyperextension, thumb-to-forearm contact, and placing both palms flat on the floor with fully extended knees. A score of five or higher indicates hyperlaxity, suggesting excessive bilateral laxity in at least three joints.[26] Additionally, the Sit and Reach Test was used to assess flexibility, particularly in the lower back and hamstring muscles, providing further insight into overall joint mobility.[27]

Measurement techniques

Anterior tibial translation assessment: anterior tibial translation relative to the femur was measured using the KNEELAX 3® arthrometer. Participants were positioned in a supine decubitus position with the knee in 30º of flexion and secured with a velcro brace for stability.[27] An anterior tibial traction force was applied to assess anterior displacement in both lower limbs at forces of 40, 60, 88, and 132N *(Figure 2)*. The recorded values were documented for analysis.[28]

Lachman test: the Lachman test was performed with the knee flexed to 20-30º, stabilizing the femur with one hand while applying anterior traction to the tibia with the other. A positive test was defined as significant anterior tibial translation.[7]

Pivot-shift test: the Pivot-Shift test was conducted with the hip flexed and abducted to 30º, applying a valgus force to the knee. A positive test was identified by a sudden subluxation of the lateral tibial condyle.[7]

Sit and reach test: the subjects sat with their feet approximately hip-width apart against a graduated mat. They kept their knees extended, placed their right hand over the left, and slowly reached forward as far as they could by sliding their hands along the mat. They performed the stretch three times, with the third attempt counting as the valid measurement.[27]

Internal and external tibial rotation were measured using PhidgetSpatial Precision inertial sensors,[29,30] positioned 5 cm below the patella at the midline. Controlled rotational movements were performed, and data were recorded using specialized software *(Figure 3)*.

Bone frame size assessment: bone frame size was evaluated by measuring wrist circumference in relation to height, classified according to the Grant Index as small, medium, or large, based on established cut-off points[31] *(Table 1)*.

All tests were conducted by two trained examiners and performed on both knees. These tests were repeated three times, and the average value was then recorded. Simultaneously, interobserver and intraobserver tests were also conducted to ensure consistency and reliability throughout each test.

Ethical considerations

This study complies with the principles outlined in the Declaration of Helsinki, the Mexican Official Standard NOM-012-SSA3-2012, Good Clinical Practice guidelines, and the provisions of the General Health Law on Research. It was approved by the Research Ethics Committee and the Research Committee of the «Dr. José Eleuterio González» University Hospital under approval number FI24-00004.

Statistical methods

To calculate the proper sample size of our population, the *finite population sample size* formula was used. As a result, the sample size necessary was established at an estimated 110 participants. This sample size was properly reached as a total of 114 participants were included in the study.

To assess data normality, the Kolmogorov-Smirnov test was applied. Variables with a parametric distribution were summarized as mean and standard deviation, whereas those with a non-parametric distribution were reported as median and interquartile range.

For inferential statistical analysis, the Student's t-test was used for parametric variables, with a p-value ≤ 0.05 considered statistically significant. All statistical analyses were performed using GraphPad Prism (GraphPad Software Inc.), version 9 (2020).

To assess intraobserver and interobserver reliability, three trained observers were selected. Each observer performed repeated measurements of the variables of interest on three consecutive occasions. The intraclass correlation coefficient (ICC) was used for continuous data, calculated using a two-way model with absolute consistency. The results were interpreted according to Cicchetti's (1994) classification. All analyses were performed using SPSS Statistics (IBM), version 25 (2020).

Table 1: Cut-off points for the grant index.

	Small	Medium	Large
Men	> 10.40	10.40-9.60	< 9.60
Women	> 10.90	10.90-9.90	< 9.90

The grant index is calculated by dividing height (cm) by wrist circumference (cm), resulting in a unitless ratio.

Table 2: Bioimpedance measurement results and physical activity levels (Tegner score).

Variable	All N = 114	Men n = 55	Women n = 59
Age (years)	21.04 ± 2.20	21.20 ± 2.30	20.90 ± 2
Height (cm)	164 ± 9	172.20 ± 5.90	157.90 ± 5
Weight (kg)	67.50 ± 16.40	77.51 ± 15.80	58.20 ± 10.70
BMI (kg/m²)	24.70 ± 4.70	26.10 ± 4.90	23.30 ± 3.90
% Body fat	30.50 ± 9.40	25.70 ± 8.10	35.60 ± 8.30
% Skeletal muscle	31.20 ± 70	36.90 ± 4.80	25.80 ± 3.70
Tegner > 6	35	19	16

BMI = body mass index.

Results

A total of 114 participants were included in the study, comprising 55 men and 59 women. The mean age was 21.04 ± 2.2 years. Significant differences were found in height (men: 172.2 ± 5.9 cm, women: 157.9 ± 5 cm; p < 0.001) and body weight (men: 77.51 ± 15.8 kg, women: 58.2 ± 10.7 kg; p < 0.001). BMI was significantly higher in men (26.1 ± 4.9) compared to women (23.3 ± 3.9; p = 0.002) *(Table 2)*.

Body fat percentage was significantly higher in women (35.6 ± 8.3%) than in men (25.7 ± 8.1%) (p < 0.005). Conversely, skeletal muscle percentage was greater in men (36.9 ± 4.8%) compared to women (25.8 ± 3.7%) (p < 0.005). Regarding physical activity levels, 35 participants had a Tegner score > 6, with a similar distribution between sexes *(Table 2)*.

Women exhibited significantly greater internal rotation (28.7º ± 1.4º vs 20.8º ± 1.8º in men; p < 0.001) and external rotation (27.76º ± 2.1º vs 18.5º ± 1.6º in men; p < 0.001).

Anterior translation of the ACL, measured using the KNEELAX 3® arthrometer, increased with higher applied forces, becoming statistically significant at 88N and 132N (p = 0.47 and p = 0.001 respectively). At 40 N, translation was greater in men (5.2 ± 2.1 mm) compared to women (4.3 ± 1.8 mm) (p = 0.246). At 60N, men exhibited 6.7 ± 2.5 mm of translation, while women showed 5.8 ± 2.2 mm (p =

0.257). At 88N, the values were 7.9 ± 3.1 mm for men and 6.9 ± 2.4 mm for women, showing a statistically significant difference (p = 0.047). Similarly, at 132N, anterior translation was significantly higher in women (8.9 ± 3.7 mm) compared to men (7.6 ± 2.5 mm) (p = 0.001) *(Table 3)*.

A higher Beighton score was associated with increased knee laxity, as measured by arthrometry. Participants with generalized joint hypermobility (Beighton score ≥ 5) exhibited significantly greater anterior tibial translation (8.4 ± 2.1 mm) compared to those with lower Beighton scores (< 5) (6.9 ± 1.8 mm) (p = 0.003).

Additionally, participants with a body fat percentage > 30% exhibited greater ACL translation (8.77 ± 1.3 mm) compared to those with < 30% body fat (7.5 ± 1.3 mm) (p = 0.002). Similarly, individuals with smaller bone frame size showed greater ACL translation (8.67 ± 2.3 mm) compared to those with larger bone frame size (7.4 ± 2.3 mm) (p = 0.002) *(Table 4)*.

Furthermore, participants with higher physical activity levels (Tegner score > 6) demonstrated lower ligament laxity (7.26 ± 2.6 mm) compared to those with a Tegner score < 6 (8.23 ± 2.4 mm) (p = 0.001).

In addition to the findings related to knee joint laxity, flexibility was assessed using the Sit and Reach test, which measures hamstring and lower back flexibility. Participants with higher physical activity levels (Tegner score > 6) exhibited significantly greater flexibility, with an average Sit and Reach score of 21.4 ± 4.2 cm, compared to those with lower physical activity levels (Tegner score < 6), who had an average score of 16.8 ± 3.9 cm (p = 0.004). These results suggest that individuals with higher physical activity levels not only demonstrate lower ligament laxity but also superior flexibility, which may contribute to better overall joint function and injury prevention.

Overall, these results suggest that femorotibial joint laxity is greater in women, individuals with smaller bone frame size, higher body fat percentage, and lower levels of physical activity.

Interobserver and intraobserver reliability

The results showed an ICC of 0.91 (95% CI: 0.85-0.96) for inter-observer reliability and 0.93 (95% CI: 0.88-0.97) for intra-observer reliability, indicating excellent consistency in both cases.

Discussion

The main finding of our study was that ACL laxity, as measured by the KNEELAX 3® arthrometer, is significantly greater in women compared to men, particularly at higher applied forces (88N and 132N). Additionally, increased ACL translation was observed in individuals with higher body fat percentage and smaller bone frame size, while greater physical activity levels were associated with lower ligament laxity.

The results of this study reinforce the notion that knee joint laxity is influenced by multiple factors, including sex, body composition, bone frame size, and physical activity level.[9] The greater ACL translation observed in women aligns with previous studies indicating a higher predisposition to knee instability and ACL injuries, particularly in high-impact or contact sports.[19] This finding may be attributed to anatomical, biomechanical, and hormonal differences, as elevated estrogen levels have been associated with reduced ligament stiffness and an increased risk of injury.[30,32]

Similarly, the observed relationship between higher body fat percentage and increased ACL translation suggests that excess adipose tissue may negatively impact joint stability, potentially due to a lower proportion of muscle mass, which plays a key role in dynamic knee stabilization. Additionally, adipose tissue is an active endocrine organ

Table 4: Anterior cruciate ligament translation by body fat percentage, bone frame size and physical activity. Greater translation was observed in participants with higher body fat, smaller bone frame size and lower physical activity.

	Translation 132N	p
> 30% Fat body (mm)	8.77 ± 1.30	0.002
< 30% Fat body (mm)	7.50 ± 1.30	
> 6 Tegner (mm)	7.26 ± 2.60	0.001
< 6 Tegner (mm)	8.23 ± 2.40	
Small bone frame size (mm)	8.67 ± 2.30	0.002
Large bone frame size (mm)	7.40 ± 2.30	

Table 3: Comparison of internal and external rotation angles and ACL anterior translation between men and women. Women showed significantly greater rotation and ACL translation (measured with KNEELAX 3® arthrometer).

	Men	Women	p	95% CI
Internal rotation	20.80° ± 1.80	28.70° ± 1.40	0.001	−8.50 - −7.30
External rotation	18.50° ± 1.60	27.76° ± 2.10	0.001	−9.95 - −8.57
Translation 40N (mm)	5.20 ± 2.10	4.30 ± 1.80	0.264	0.17 - 1.63
Translation 60N (mm)	6.70 ± 2.50	5.80 ± 2.20	0.257	0.02 - 1.78
Translation 88N (mm)	7.90 ± 3.10	6.90 ± 2.40	0.047	−0.03 - 2.03
Translation 132N (mm)	7.60 ± 2.50	8.90 ± 3.70	0.001	−2.46 - −0.14

ACL = anterior cruciate ligament.

that secretes pro-inflammatory cytokines, such as leptin and adiponectin, which have been implicated in altered collagen metabolism and reduced ligament integrity.[20] This hormonal influence may further contribute to increased ligament laxity and a higher risk of ACL injury. Two main mechanisms have been proposed through which increased body fat may influence joint laxity. The first involves low-grade systemic inflammation, mediated by adipokines such as leptin, which may disrupt connective tissue homeostasis and promote increased ligamentous compliance.[33] The second mechanism relates to muscular disuse, where excess fat may reduce physical activity levels, leading to decreased muscle tone and dynamic joint support, thereby allowing for greater passive laxity.[34] Both factors may act synergistically, contributing to an increased risk of joint instability.

In this context, the lower ACL translation observed in individuals with higher physical activity levels may indicate that muscle strengthening and improved neuromuscular control play a crucial role in preventing excessive laxity and, consequently, ligament injuries. Moreover, the stability of the posteromedial and posterolateral corners of the knee is critical in controlling excessive rotational movement and preventing secondary ligamentous injuries.[15,16,17] These structures, including the posterior oblique ligament, arcuate ligament, and popliteofibular complex, play a significant role in resisting rotational forces that may contribute to ACL and PCL instability. Deficiencies in these stabilizing structures can lead to excessive tibial rotation, increasing the risk of ligament and meniscal injuries. Strengthening and proprioception training should incorporate elements that enhance the stability of these knee regions, particularly in athletes engaged in pivoting and high-impact sports.

Our findings are consistent with those reported by Shalhoub et al.,[32] who identified that knee bone morphology, including femoral epicondylar width, femoral curvature, and tibial concavity, significantly influences joint laxity.[26] In our analysis, we observed that greater bone frame size in the knee is associated with lower laxity, suggesting that increased geometric restriction may contribute to greater joint stability. This reinforces the importance of considering bone frame size when assessing knee laxity, particularly when designing injury prevention and treatment strategies.

The use of the KNEELAX 3® arthrometer and inertial sensors allowed for objective quantification of ACL and PCL laxity, reinforcing their diagnostic utility in evaluating femorotibial stability. A study comparing the KNEELAX 3® and KT-1000 arthrometers found that, while absolute values of anterior tibial translation differed between devices, the side-to-side differences were not significantly different, indicating comparable effectiveness in assessing knee laxity.[24] Combined with clinical tests such as Lachman and Pivot-Shift, these measures could improve the early identification of individuals at higher risk of ligament injuries, enabling the early implementation of preventive strategies.

From a clinical and sports medicine perspective, these findings highlight the importance of an integrated approach to ACL and PCL injury prevention. Evaluating factors such as body composition and physical activity level could be crucial in identifying high-risk individuals, allowing for the implementation of strengthening and neuromuscular control programs aimed at improving joint stability.[31,35]

Given the increased risk of ACL injuries in women, injury prevention programs have been developed to enhance neuromuscular control and reduce knee joint instability. The FIFA 11+ program, designed for soccer players, incorporates dynamic warm-up exercises that improve strength, proprioception, and landing mechanics, significantly reducing ACL injury rates in female athletes.[36] Similarly, the ACTIVATE program, developed for rugby players, focuses on progressive neuromuscular training, including balance and agility drills, to decrease lower limb injuries, including ACL tears.[35] These initiatives are particularly relevant in light of findings from a Brazilian population-based study by Astur et al., which reported a higher incidence of ACL injuries in women and noted that such injuries are frequently associated with significant functional limitations.[23]

Another effective program is GAA 15, tailored for Gaelic football and hurling athletes, which emphasizes plyometric exercises, core stability, and proper landing techniques to mitigate ACL injury risk.[33,37] These structured injury prevention programs highlight the importance of targeted training interventions in reducing ACL injuries in female athletes. Integrating such evidence-based programs into training routines could be a key strategy for minimizing injury risk and enhancing long-term joint health.

The FIFA 11+, ACTIVATE, and GAA 15 programs are primarily designed to prevent ACL injuries but also help reduce the risk of injuries to other knee structures, such as the menisci and collateral ligaments, by focusing on muscle strengthening, proprioception, joint stability, and improved movement mechanics.[33,35,36,37]

Athletes with a small build may have anatomical differences and lower muscle mass that influence joint biomechanics, making it necessary to personalize prevention programs. Employing low initial levels of load and intensity, focusing on strengthening the posterior chain and core muscles, and correcting landing techniques will enable athletes with low body mass to achieve a high neuromuscular level, compensating for their structural disadvantages.[34,38,39]

Finally, the evidence from this study underscores the necessity for further research on the biomechanical and structural factors influencing ligament laxity, particularly in young and active populations. Future studies should explore additional variables such as lower limb alignment, muscle fatigue, hormonal influences, bone morphology, and genetic predispositions affecting joint stability. Investigating these factors could help refine injury prevention and treatment strategies for the knee joint, leading to more personalized and effective interventions.

Limitations

One of the main limitations of this study is the lack of direct measurements of soft tissue structures, such as muscles and the joint capsule, which are fundamental to knee stability. This aligns with the observations of Shalhoub et al.,[36] who highlighted that variability in joint laxity is influenced not only by bone morphology but also by soft tissue characteristics such as ligament length and insertion points. Additionally, the study did not include dynamic, load-bearing assessments, that are essential for evaluating knee behavior under functional conditions. This limits the extrapolation of the findings to real-life activities where neuromuscular control plays a critical role. Moreover, the exclusive inclusion of medical students as participants introduces a potential selection bias, as this population may be more physically active and health-conscious than the general population, reducing the external validity of the results. Future studies should incorporate a more diverse sample and include dynamic testing protocols alongside direct soft tissue measurements to better understand the complex factors influencing knee laxity.

Conclusion

Knee joint laxity is greater in women, individuals with higher body fat percentages, and those with smaller bone frame sizes. This increased laxity represents a significant risk factor for ligament ruptures and other joint injuries. Promoting physical activity and implementing targeted strengthening exercises for the hamstrings and quadriceps are essential strategies to reduce the risk of ligament injuries.

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