2D KINEMATIC ANALYSIS OF KNEE FRONTAL PLANE KNEE VALGUS ANGLE: A METHODOLOGICAL APPROACH

ANÁLISIS CINEMÁTICO DEL ÁNGULO DE PROYECCIÓN FRONTAL DE RODILLA EN 2D: ENFOQUE METODOLÓGICO

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ABSTRACT

Kinematic assessment of lower limb motion in three dimensions (3D) requires the use of advanced technology, specialized training and laboratories that do not meet the requirements of the clinical and sporting environment. Two-dimensional (2D) frontal plane knee valgus angle (FPPA) assessment has demonstrated consistently its validity, accuracy and reliability in comparison with 3D analysis methodology for the detection of dynamic valgus associated with increased external hip adduction and internal rotation torques during the execution of functional movements that require eccentric muscle control. Dynamic valgus has shown to be a predictor of anterior cruciate ligament injury and patellofemoral pain syndrome especially in women. Early detection and monitoring of kinematic behavior with low cost, low complexity and basic level of expertise instruments using 2D analysis is emerging as an important assessment strategy in sports training and clinical treatments for the prevention and rehabilitation of knee injuries associated with these movement disorders. Therefore, this narrative review aims to provide essential knowledge for the correct assessment, interpretation, and analysis of FPPA in Physiotherapists and Sports Professionals.

KEY WORDS: genu valgum, anterior cruciate ligament injuries, patellofemoral pain syndrome, anterior knee pain

RESUMEN

La evaluación cinemática del comportamiento del miembro inferior en tres dimensiones (3D) requiere el uso de alta tecnología, formación especializada y laboratorios que no se ajustan a las demandas del ámbito clínico y deportivo. La valoración del APFR (ángulo de proyección frontal de rodilla)en dos dimensiones (2D) ha mostrado consistentemente su validez, objetividad y confiabilidad al ser comparada con la metodología de análisis en 3D para la detección del valgo dinámico asociado al incremento de torques externos de aducción y rotación interna de cadera durante la ejecución de tareas funcionales que exigen control muscular excéntrico. El valgo dinámico ha mostrado ser un predictor de lesión del ligamento cruzado anterior y de síndrome de dolor patelofemoral, especialmente en mujeres. La detección oportuna y el seguimiento del comportamiento cinemático con instrumentos de bajo costo, poca complejidad y un nivel de experticia básico utilizando análisis en 2D, se perfila como estrategia de valoración importante en el entrenamiento deportivo y el abordaje clínico para la prevención y rehabilitación de lesiones de rodilla asociados a estos desórdenes del movimiento. Por tanto, esta revisión narrativa pretende proveer de conocimientos esenciales para la correcta valoración, interpretación y análisis del APFR en Fisioterapeutas y Profesionales del Deporte.

PALABRAS CLAVE: valgo dinámico, rodilla, ligamento cruzado anterior, dolor patelofemoral

INTRODUCCIÓN

Currently, kinematic analysis of human movement is widely used to identify motor behavior characteristics and variations in health and sports contexts (1). Kinematic analyses can detect changes in movement patterns associated with an increased risk of injury or decreased physical and sports performance. These analyses can help to develop intervention strategies to improve these altered movement patterns (2).

Kinematic analyses are conducted in the field or laboratory settings, generally by modeling motion in three dimensions (3D) by capturing and identifying the trajectory of body segments in three planes: frontal, sagittal, and horizontal (1). The captures are performed by integrating high-speed infrared cameras with specialized software to model the trajectory of reflective markers attached to specific body landmarks according to predetermined protocols (3). These instruments are expensive, require extensive experience from the professionals who control them, and spend a lot of time performing kinematic analyses. Yet, they are the gold standard for the non-invasive identification of human body movement characteristics and variations.(1).

Validation of 3D motion capture instruments has shown high accuracy and small standard error of measurement. This methodology has demonstrated its value for identifying motion-associated risk factors that predict the likelihood of lower limb injury in physically active and athletic women, specifically anterior knee pain and anterior cruciate ligament ruptura (3). However, given the limitations in instrumentation costs, the need for the evaluator´s expertise, and time consumption in the analysis, FPPA assessment in two dimensions (2D) has recently been implemented with these same objectives, given the low instrumentation costs and ease of execution from analysis of 2D videographies (4).

The FPPA quantifies the valgus or varus movement of the knee during the execution of functional tasks that cause an additional eccentric load on the lower limb musculature, evidencing deficiencies in the dynamic stabilization capacity of the lower limb.(5). Peak FPPA values explain 58% to 64% of the between-subject variance in the average peak 3D knee abduction during dynamic tasks such as jumping and lateral displacement. This angle also correlates significantly with transverse plane knee external rotation and frontal plane coxofemoral adduction, which are the major components of the movement associated with dynamic valgus. (3).

In this regard, the identification of movement-altered patterns in the transverse and frontal plane of the knee and coxofemoral can be assumed by the cost-effective assessment of FPPA. These movement disorders can occur in subjects with pathology and healthy subjects who show a premonitory movement pattern that can predict anterior cruciate ligament injury and patellofemoral pain síndrome (6). Thus, this easily done method provides a low complexity and speed of analysis results, which allows its use in the clinical setting and the sports contexts to identify this type of movement disorder (6). However, considerations such as validity, reliability, and methodology for its elaboration have yet to be presented concisely. Likewise, the proximal and distal pathomechanics factors associated with the alteration of this angle have not been condensed clearly to health and sports professionals.

For these reasons, this paper aims to review the validity, reliability, and objectivity of this assessment, in addition to presenting the most relevant methodological aspects for its development with emphasis on the operational details for obtaining and interpreting the measurement and, finally, to provide a theoretical basis for the explanation of both distal and proximal mechanical phenomena associated with the alteration of the valgus presentation of the FPPA.

VALIDITY, INTRA-RATER RELIABILITY AND INTER-RATER RELIABILITY

3D motion capture systems are the gold standard, valid and reliable tools for measurement of the frontal knee projection angle, but their use has several limitations. These systems have the highest costs of motion capture devices and need a significant amount of time for interpretation and analysis. In addition, they need high qualifications of operators and evaluators and also require the participation of several professionals while the measurements are taken (1).

In this context, it is necessary to validate less costly options that require less qualification to perform the evaluations and can be developed quickly to respond to the high volumes of data. In addition, the transport of these devices and measuring instruments must be easy and fast both in clinical and field contexts to the sites where the subjects of analysis are located (7).

For some time now, given the needs mentioned above, several researchers have made attempts to certify the 2D video analysis methodology and correlate it with data obtained with 3D motion capture systems (1, 5, 8, 9). To this end, three test quality criteria have been determined: validity, intra-rater reliability, and inter-rater reliability.

Validity indicates that the instrument assesses what it is intended to evaluate; that is, the test reveals those characteristics it is intended to measure (10). Intra-rater reliability refers to the precision with which the results are obtained; this variable indicates the consistency or stability of the measures when the measurement process is repeated (11). Finally, inter-rater reliability expresses that there is no personal appreciation for the results; thus, if the same test is applied to a group by different examiners, the results should be very close in their values (12). These criteria are reported from statistics such as the intraclass correlation index (ICC). The results are presented from 0 to 1, with values closer to 1 being the most relevant and indicating a better agreement between measurements.

In this vein, McLean et al. (3) concluded that 2D FPPA analysis was a valid and potential method for assessing excessive valgus (0.64). They proposed that this angle could determine the risk of non-contact anterior cruciate ligament injuries from exaggerated movements at the knee joint level. Thus, this methodology is an excellent assessment option at a lower cost, with less time and personnel requirements to predict dynamic valgus..

Subsequently, Mizner et al. (13) found strong correlations between 2D video analysis and 3D motion capture. Their study reported high validity (0.918) when comparing the two methods and excellent validity (0.939) when comparing the knee-ankle separation ratio. Additionally, they revealed excellent inter-session reliability (0.95) and high inter-rater reliability (0.89) for 2D video analysis. Regarding the knee-ankle separation ratio, they reported an inter-session reliability of 0.97 and an inter-rater reliability of 0.92. At the same time, Munro et al. (5) reported excellent inter-rater reliability values (0.79 - 0.86 in men and 0.59 to 0.88 in women). On the other hand, the inter-rater reliability coefficients in this study revealed values ranging from 0.80 to 0.89 in men and 0.72 to 0.91 in women..

Subsequently, Harris-Hayes et al. (14) compared 2D video analysis versus visual analysis, obtaining good values of inter-session reliability (0.80 to 0.90) and inter-rater reliability (0.75 to 0.90). In this study, they concluded that subjective visual assessment has a high percentage of agreement with objective assessment through video analysis (90%), as long as the movement patterns of the lower extremity are previously defined. Similarly, Ortiz et al. (15), compared 2D versus 3D systems, obtaining excellent validity between measurement systems (>0.9) for both knee-ankle separation ratio and knee-to-ankle distance. Additionally, they reported excellent inter-session reliability (>0.95) and inter-rater reliability (>0.93) for FPPA assessment. This research aimed to determine the inter-rater reliability among novice raters with no experience in this measurement (16).

Recently, Herrington et al. (17) compared 2D video analysis versus a 3D motion capture system, reporting good agreement between these systems for FPPA measurement (r^2 = 0.79), as well as finding good to excellent correlations for intra-rater reliability (0.72) and inter-rater reliability (≥0.96) coefficients. For their part, Simon et al. (18) compared frontal projection angles through 2D and 3D video analysis against visual analysis in men and women (54 participants, of whom 30 were women). Their study concluded that FPPA analysis presents a moderate correlation with 3D analysis (0.521 in women and 0.528 in men). Additionally, these authors reported intra-rater reliability values ranging from 0.961 to 0.999 and inter-rater reliability values from 0.967 to 0.998.

Likewise, with the 2D motion analysis methodology, several functional motor patterns have been validated, which require high strength production during the eccentric phase of muscle contraction, demanding the stabilization of the lower extremity by the neuromuscular system (16, 19, 20). Consequently, the movement patterns evaluated through these methodologies have shown to be valuable when identifying possible alterations or movement disorders in the lower limb, not only in athletes and physically active people but also in sedentary subjects and older adults (6). Among the most used motor patterns are the single leg squat (SLS), single leg landing (SLL), drop jump (DJ), single leg hop (SLH), side step, and side jump, among others.

Specifically in the SLS, Munro et al. (5) reported good intra-rater reliability (0.86 in men and 0.59 in women) and good inter-rater reliability (0.82 in men and 0.72 in women). Herrington et al.(17), found excellent intra-rater reliability (0.97) and moderate inter-rater reliability (0.72) for this test. For their part, Alves Lopes et al. (1), evaluated 16 studies in their systematic review with meta-analysis. They concluded that the SLS has great intra-rater reliability values ranging from 0.97 to 1.00 and excellent inter-rater reliability values (0.97). More recently, Kingston et al. (21) found a moderate validity (0.70) in favor of the FPPA during the SLS and a good intra-rater reliability of (0.85) for the FPPA in this test.

Regarding the SLL, Munro et al. (5), revealed good intra-rater reliability (0.79 in men and 0.75 in women) and inter-rater reliability values of 0.80 and 0.82 in men and women, respectively. Similarly, Herrington et al. (17), found excellent inter-session reliability (0.99) and good inter-rater reliability (0.87). Subsequently, Lopes et al. (1), in their meta-analysis, concluded that intra-rater reliability for the SLL ranges from moderate to good (0.642 - 0.820) and inter-rater reliability from good to excellent (0.89 - 0.92).

Regarding the DJ, studies such as Munro et al. (5) have reported good inter-session reliability values of 0.83 in men and 0.88 in women and good to excellent inter-rater reliability values (0.89 in men and 0.91 in women). For their part, Ortiz et al. (15) revealed inter-session reliability values ranging from 0.97 to 0.99 and inter-rater reliability from 0.88 to 0.99. Concurrently, Kingston et al. (21) reported inter-session reliability values of 0.73 and 0.91 for the knee and hip FPPA, respectively.

Thus, FPPA assessment through 2D video analysis has proven to be a cost-effective tool for the initial evaluation of lower limb kinematic disorders and an excellent alternative to 3D assessment systems. Additionally, the tests used for these procedures have proven valid and have suitable intra-rater and inter-rater reliability. For this reason, this methodology allows less expensive evaluations that do not require highly qualified personnel and can be developed in less time, facilitating data collection from large population groups with less investment of time, money, and staff.

METHODOLOGICAL ISSUES

Kinematic performance assessments using high-speed motion analysis technologies allow accurate and reliable measurement of FPPA. These evaluations are developed with a seven-camera system and recorded at 250 Hz, typically using VICON (Oxford Metrics Ltd, Oxford, United Kingdom) or BTS Gaitlab system (BTS Bioengineering Corp, Quincy, U.S.A). These devices have contributed significantly to the current success of screening methods and intervention strategies in the fields of sports physiotherapy and sports science.(1). Unfortunately, these systems have significant barriers to their implementation in terms of their considerable financial costs, the need for controlled spaces, and spend time requirements for their execution (3). For these reasons, alternatives such as 2D FPPA measurement offer advantages in cost, materials, accessibility, and ease of implementation to health and sports science professionals without requiring high levels of technical training to perform and interpret these measurements. In addition, these measurements are valid, reliable, and unbiased when performed by experienced and novice professionals (5, 14).

Validity, intra-rater reliability, and inter-rater reliability of the 2D FPPA measurement require strict methodological conditions and specific protocols for it to adequately reflect the lower limb motion phenomena that occur primarily in the transverse plane for the knee and the frontal plane for the coxofemoral (22, 23). For these reasons, following the guidelines and steps offered in this section of the narrative review are of paramount importance for successful execution and subsequent interpretation.

Spatial suitability and camera positioning

The space required for the FPPA measurement should be a flat surface with an area of 6 m long by 4 m wide. The lens of the digital camera should offer at least a 30 Hz recording system and be located strictly in the frontal plane to the measurement target; any variation in obliquity to the target will determine FPPA measurement error. The background of the recording space should preferably be white, without surrounding objects that distract the subject under analysis (24).

The camera must be placed on a stable tripod with a level reading that allows for establishing a balanced image both vertically and horizontally of the frames acquired during the video recording with a distance of approximately 2.50 m to the measuring objective (3). The camera's height should be frontal and directly to the fulcrum of the FPPA, that is, the femoral inter-epicondylar midpoint. The clothing of the subject to whom the measurement is performed must make it possible to observe all the reflective markers used for marking the anatomical landmarks that will be traced later in the digital analysis of the extracted frames. The recording space must be illuminated with lateral and frontal support lamps that facilitate the clear and precise observation of the white reflective markers exposed to these light sources (24).

Positioning reflective markers

To track the anatomical landmarks movement specified to determine the FPPA, low-weight white markers should be placed, which in front of white light bulbs will appear reflective and will make it possible to track them in the free digital motion analysis applications suggested in this document.

The anatomical landmarks that should be marked bilaterally for the elaboration of the FPPA are the anterosuperior iliac spine, the anterior midpoint interepicondylar femoral, the anterior midpoint intermaleolar and the projection of an intermediate point between the anterosuperior iliac spine and the anterior midpoint interepicondylar femoral. For the determination of these points, the average distance between them is established with a tape measure for clinical use (22).

The markers should be attached to the anatomical sites described above with double-sided adhesive tape. The adhesion of the markers to the body must be ensured to allow their tracking during the execution of the different functional tasks with a high eccentric component used as risk screening of motor behavior in physically active women and athletes.

FPPA video-graphic estimation

Following the indications mentioned above, the functional tasks recorded on video must be exported to digital applications that allow the quantitative analysis of the trajectories made by the reflective markers. In the case of the FPPA, the tool that allows its analysis is the digitized goniometer, which operates under the same conditions as the analog goniometer. Two types of free software are generally used for FPPA analysis: Kinovea and Tracker. The former is a software developed for the study of human movement that allows the capture, observation, annotation, and measurement of kinematic parameters and kinetic inferences (25). The latter is an instrumental biophysical analysis software that can track the kinematic and kinetic behavior of the human body (26). Both software allows for easy frame-by-frame analysis of the angular characteristics of human movement. For the specific measurement of the FPPA, the maximum knee flexion moment must be determined during the execution of the functional tasks selected for the analysis. Subsequently, the fulcrum of the digital goniometer of the respective software should be placed at the anterior femoral interepicondylar midpoint. Thereafter, one arm of the goniometer should be taken to the intermediate point between the anterosuperior iliac spine and the femoral interepicondylar midpoint. The other arm of the goniometer should be projected to the intermalleolar midpoint (5).

Once the angle has been established, the software displays it in a mathematical spatial sense in a Cartesian plane but not in a kinesiological sense. The last is adopted for its interpretation. Since the mathematical angle offered by the software must be transformed to kinesiological, a subtraction of 180° must be made to the value of the mathematical angle identified. This math operation results in the kinesiological angle that will allow its comparison with risk scales established by the association to a knee injury.

Functional tasks used to identify FPPA

Several functional tasks of daily life and sports activities have been proposed to identify the risk of knee injury with the consequent use of the FPPA. All of these tasks have as a specific condition the solicitation of great eccentric muscular control during their execution. The ground reaction forces created during these tasks notably increase the muscular response for the correct absorption of these forces and stabilization of the body (20, 27, 28).

Among the most commonly used tasks are: Single leg squat, step down, countermovement jump, Drop jump, and single-leg landing. The particularities of each of these gestures are described below.

Single leg squat

The purpose of this test is to demand the stabilization capacity of the pelvic and lower limb musculature in single-legged support (29). The subject must perform this movement by placing the feet at shoulder width and the hands on the hips. Place himself in one-legged backing and make a deep knee flexion that reaches at least 45° degrees of flexion but no more than 60°. At this time, the FPPA measurement is performed with the trunk upright and the other lower limb suspended. Then the subject slowly returns to the initial position of knee extension with a duration of the task of 5 seconds counted by an external evaluator, ensuring that the descent lasts a minimum of 3 seconds of the total execution. The position of the toes is chosen by the person being evaluated regardless of their location relative to the knee, as long as 45°-60° of flexion is ensured (30).

Step down

The purpose of this movement is to request the stabilizing capacity of the muscles surrounding the coxofemoral joint, the knee, and the ankle in a closed kinetic chain. The control of this movement is evident when the subject descends against gravity (31). A 25 cm high step is required, and the subject is asked to place themself in two-legged support on the step and then move to one-legged backing with the other lower limb suspended in extension in the sagittal plane. Next, the subject must perform hip and knee flexion and ankle dorsiflexion of the lower limb in support until the contralateral heel makes contact with the floor. The FPPA is then measured to return to the one-legged starting position finally. During the execution, the spine must remain upright, the upper limbs suspended in front, and performed in a time of three seconds.

Countermovement jump

This test aims to solicit the neuromuscular control of the trunk, pelvis, and lower limbs during the execution of a two-legged jump with a negative phase or descent that seeks to accumulate elastic energy with a subsequent concentric positive phase. This energy storage is expected to generate additional propulsion sponsored by the muscular elastic component. During the execution of this task, the FPPA is observed at the moment of maximum knee flexion of the descent phase of the jump since it coincides with the most significant demand for eccentric control (32).

Drop Jump

A 31 cm high bench is required to perform this task. The subject should be positioned at the top of the bench in two-legged support with feet placed at shoulder width and hands on the hips, preferably towards the edge of the bench. After that, followed by a verbal command, the subject jumps from the bench and, immediately after contact with the ground, performs a jump to reach a maximum height. This rebound jump should be as fast as possible in the eccentric-concentric transition, and the FPPA should be measured at the moment of maximum knee flexion of the eccentric phase of this task (33).

Single leg landing

A 25 cm high step is required to perform this task. The subject is asked to be in one-legged support with hands on the hips. Upon verbal command, the subject must jump from the step and generate eccentric control of a one-legged fall on the lower limb that was previously in support on the step. The task will be successful if it can control the movement with a subsequent concentric recovery phase without supporting the contralateral lower limb. The FPPA is evaluated at the moment of maximum knee flexion of the eccentric descent phase(5).

PATHOMECHANICS ASSOCIATED WITH THE VALGUS ALTERATION OF THE FPPA

During functional tasks involving eccentric loading, the different segments of the lower limb are forced to generate load absorption from ground reaction forces created by external torques. These forces can cause flexion, adduction, and internal rotation of the hip, which must be counteracted by the internal torques of the musculature of this joint (34). The greater the demand for eccentric control of functional activity, the greater the external forces created, especially at the proximal level of the body. These phenomena are associated with kinematic alterations observed in both 3D and 2D motion captures, which have shown adduction and internal rotation of the coxofemoral as the main compensations, a characteristic primarily observed, particularly in women (35).

Both coxofemoral adduction and internal rotation contribute to medial migration of the knee joint center about the foot, causing tibial abduction and foot pronation resulting in the display of dynamic valgus, which has been associated with an anterior cruciate ligament injury and patellofemoral dysfunction (6). Excessive adduction of the coxofemoral causes stresses on the stabilizing soft tissue of the knee, especially in the medial aspect, such as the medial collateral ligament, medial patellofemoral ligament, and anterior cruciate ligament itself. Likewise, this movement disorder promotes an increased internal rotation of the coxofemoral about a fixed tibia. This last action stresses soft tissue structures that limit this movement, such as the medial collateral ligament, lateral collateral ligament, and popliteus muscle (36).

Now, the orientation of the resultant of the ground reaction force vector about the joint center determines the direction and magnitude of the external torques that the pelvic and lower limb musculature must resist in this type of functional task. On the other hand, the migration of the body's center of mass about the center of pressure also influences the ground reaction force vector, causing the movements of the trunk and pelvis also to modify the external torques produced by gravity, which must be counteracted by the body musculature (37).

Since excessive adduction and internal rotation movements of the coxofemoral are the main phenomena associated with dynamic valgus represented in the increased FPPA, the muscles that can counteract these movements will be the gluteus maximus, gluteus medius, and short external rotators of the hip. However, weakness of these muscles in the lower limb in support can promote a hemipelvis contralateral tilt. In turn, this provokes a migration of the center of mass away from the center of pressure toward medially increasing the varus moment in the knee joint. These phenomena generate mechanical stress on the lateral collateral ligament and iliotibial band with an increase of compressive forces in the medial compartment of the knee (36).

Thus, the weakness of the hip extensor and abductor muscles increases the lateral compartment tensile stress of the knee and its medial compressive stress. As compensation, a trunk strategy movement is generated that directs the center of mass just above the center of pressure of the supporting lower limb (37). In this way, the resultant of the ground reaction force is brought closer to the hip joint center, which reduces the demand on the abductor and extensor musculature. However, this compensatory strategy places the resultant of the ground reaction force lateral to the knee. The last promotes a valgus moment that is clearly observed in the FPPA. This dynamic valgus stresses in tension the medial collateral ligament, the medial patellofemoral ligament, and the anterior cruciate ligament. Likewise, stresses in compression the lateral compartment of the knee and the lateral facet of the patella with the lateral femoral condyle. This pathomechanics are responsible for the increased rates of anterior cruciate ligament injury and patellofemoral pain syndrome in women who exhibit a dynamic valgus expressed in increased FPPA (37) (Figura 1).

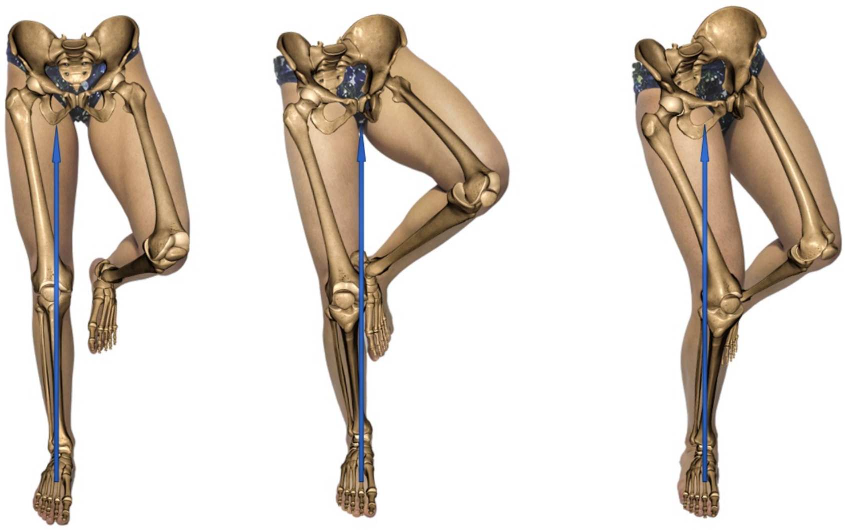

Figura 1. Mechanical alteration of the movement pattern in dynamic valgus.

It has recently been suggested that increased foot and ankle mobility, mainly increased midfoot mobility and decreased dorsiflexion, relates to dynamic valgus. But the evidence supporting the influence of distal factors in the production of dynamic knee valgus is still limited. However, these factors should be considered assessing and treating subjects with FPPA impairment (38, 39).

Kinematics disorders of the lower limb pose a challenge for preventing and rehabilitating knee injuries. These movement alterations require deep kinesiological and biomechanical knowledge to change the loads in tension and compression suffered by the anatomical structures of the knee during activities of daily living and in sports of physically active women.

CONCLUSION

The 2D FPPA analysis is an essential diagnostic and follow-up tool for possible lower limb movement disorders in functional tasks that can be implemented routinely with the use of affordable, low-cost, low-skill evaluator technology following specific guidelines such as those provided in this review. Under these conditions, an adequate APFR assessment offers a valid, accurate, and reliable approach to lower limb kinematic behavior in activities of daily living, exercise, and sport that facilitates the intervention of physical therapists and physical educators in clinical and sports settings.

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