Clinical Review: Focused

# Biomechanical Evaluation of the Athlete's Knee: From Basic Science to Clinical Application

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Clinical screening to assess knee biomechanical dysfunctions and its comorbidities has been of interest for researchers and clinicians in recent years. Although research in the area of knee injury mechanics has elucidated some of the biomechanical predisposing factors that lead to knee injury, clinicians are still puzzled on how to translate these findings to their clinical practice. Highly instrumented, costly equipment and time-consuming data analyses are some of the difficulties of using 3-dimensional biomechanical analysis in the clinic. However, several biomechanical lower-extremity assessment tools are available and feasible to use in the clinic to guide proper clinical decision making that may impact prevention of knee injuries in the physically active population. The purpose of this article was to review screening techniques for assessment of lower extremity biomechanics and to translate these findings to clinical practice and to bridge the gap between basic science and clinical application. After reading this article, clinicians should be able to (1) identify lower-extremity factors related to knee injury, (2) appropriately select functional tasks to evaluate patients, and (3) make intervention recommendations or appropriate referral to address altered lower-extremity biomechanics related to knee injury.

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## INTRODUCTION

Screening assessments for knee injury in the clinical setting, especially anterior cruciate ligament (ACL) tears and patellofemoral pain syndrome (PFPS) has received much attention by clinicians. The estimated financial burden associated with ACL injuries per individual in the United States and Mexico is more than $5000 for surgery alone, rising to approximately $16,000 when including rehabilitation [1,2]. The estimated direct and indirect medical costs for PFPS in Scandinavia are approximately $1500 per year [3]; thus, it could be assumed to be higher in North America. Several functional tasks, such as squats, hops, and drop jumps, are advocated to serve as screening tools within the clinic to identify poor biomechanical control of the lower extremities during sports or activities of daily living. Although these functional tasks have been used for years, assessment of these activities that lead to appropriate clinical decisions is unclear. The purpose of this review is to evaluate recent literature that covers the topics of biomechanical analyses and aims at screening and detecting poor biomechanical knee mechanics during closed kinetic chain activities. After reading this review, clinicians should be able to (1) identify lower extremity factors that have been related to injury during several closed kinetic chain functional tasks, (2) use appropriate functional tasks to assess their patients, and (3) prepare evidence-based recommendations on how to correct poor dynamic biomechanical mechanics of the lower extremity.

## KNEE INJURY MECHANICS

Patellofemoral disorders and ACL injuries account for the vast majority of knee injuries within the athletic population [4-6]. Generally, women are 6-8 times more predisposed to knee injuries than male counterparts in sports that require jumping, landing, cutting, and pivoting maneuvers [7]. The mechanisms of PFPS and ACL pathology are multifactorial in nature, including anatomic and biomechanical factors of which the biomechanical factors

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seem to be the most important. In addition, these biomechanical mechanisms of injury, such as knee valgus and weakness of hip muscles, are similar for both clinical conditions; however, the forces required to injure the ACL are much higher, thus resulting in an acute injury [8]. Some of the biomechanical factors associated with PFPS and ACL pathologies are large knee abduction angles [7], large knee abduction moments [9,10], increased hip adduction and hip internal rotation [11], increased knee valgus [12,13], weakness of the hip and core musculature [12-14], altered landing patterns [15], ankle and foot malalignments [16-18], and lower hip and ankle range of motion [11]. In general, PFPS is characterized by a chronic mechanical derangement that occurs between the retropatellar surface and femoral condyles when forces at the knee are relatively low but absorbed with poor mechanics, such as hip adduction and hip internal rotation, among others [9,10,19]. During ACL injuries, the force imparted to the joint exceeds the threshold of force absorption of the ligament, which causes it to rupture. When the forces at the knee are excessively high with a combined rotational component, not only the ACL is damaged but structures such as the menisci tear simultaneously [20].

PFPS is a disabling condition that primarily affects women and those participating in sports and activities of daily living performed in closed kinetic chain, such as ascending and descending stairs, hopping, and squatting. Women have been shown to be 2.23 times more likely to developed PFPS than male counterparts [21]. Common factors associated with PFPS include hip weakness [12,14], patellar malalignment [9,10], increased femoral internal rotation [9,10], and ankle and foot malalignments [16-18]. Repetitive activities performed with these biomechanical malalignments predispose soft tissue around the knee joint to increased pressure that leads to inflammation and pain [9,10,14].

ACL is one of the most disabling injuries that occur at the knee joint, with long-term neuromuscular deficiencies [22,23], with approximately 70% of patients, especially women, not returning to sporting activities [24]. Women have higher ACL injury rates than men (1.0-9.5 times) during sports participation across multiple sports [25]. ACL injuries occur in noncontact or contact manners. Contact mechanisms are clearly understood because there is a direct trauma to the knee joint caused by external forces. However, noncontact injuries account for 80% of all ACL injuries, with 70% that occur during ground contact after landing from a jump and the other 30% that occur while decelerating to change direction while evading an opponent [24,25].

Assessment of dynamic stability as an injury-prevention strategy or return-to-sports readiness depends upon appropriate functional tasks selection. The functional tasks selected to be used in the clinic should challenge the knee joint in all planes of motion and mimic the maneuvers encountered by the athlete's sport [26]. To be able to assess the complex nature of the knee and its stability, it is recommended that a battery of tests should be used [26-28]. Of all the functional tasks available to assess knee dynamic stability, this review will consider 3 functional tasks that have shown to discriminate specific knee biomechanical deficits related to knee pathology. These tasks were selected because they can be performed in small examination rooms and do not require expensive, highly instrumented equipment. We will discuss them from the least demanding to the one with the highest level of difficulty and technique.

## FUNCTIONAL TASKS

### Squat

Bilateral- and single-leg squats are two of the mostly commonly used functional tasks within the research and clinical community (Figure 1). Investigators have found, by using dynamic magnetic resonance imaging, that the femur tends to move into adduction and internal rotation, which gives the impression of patellar lateralization during the eccentric phase of a squat [9,10,19]. This evidence suggests that patellofemoral disorders could be related to increased patellofemoral compression forces [9,10], weakness of the musculature that controls hip adduction and internal rotation [12,14], dynamic patellar malalignments [9,10], or ankle and foot complex pronation [16-18]. The femur is the longest bone in the human body capable of creating high torques that move the knee into a medial direction [10,19]. Therefore, control of the femur closer to its center of rotation (hip joint) seems the most appropriate dynamic control mechanism to prevent medial deviation [19]. The single-leg squat is a low-level task that could assist in the assessment of medial knee deviation without the excessive stress associated with drop jumps or hops. During this maneuver, hip muscles, such as the gluteus maximus and gluteus medius, and hip external rotators are tested for their ability to eccentrically control hip adduction and internal rotation [19].

To perform the double- or single-leg squats, the patient is asked to stand with the feet shoulder-width apart. The position of the feet (toes in or out) is self-selected by the patient. The patient is then asked to squat to 45°-50° and return slowly to the fully extended position. Only a range of motion from 45°-50° is required because this range of motion is where most of the medial femoral rotation occurs during this maneuver [9,10,19]. This task could be evaluated by qualifying the movement as a high-risk or low-risk position [29]. A high-risk position in the frontal plane is considered when the patella moves inward and ends up medial to the first toe (Figure 1C). This medial deviation of the knee joint occurs because the foot is fixed on the floor while the femur is adducting and internally rotating [8]. Conversely, if the knee ends in line with the first toe or more lateral, then the position is considered low risk (Figure 1B). In the sagittal plane, assessment of the trunk is important. An erect trunk posture

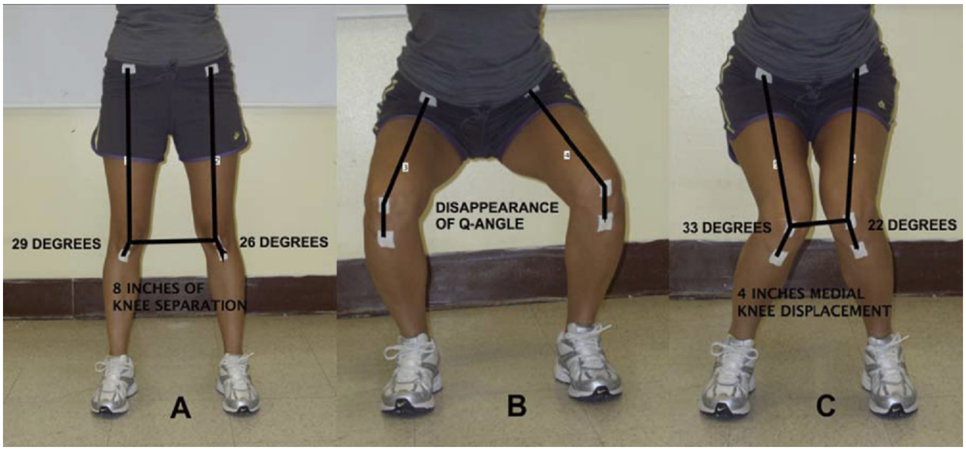


**Figure 1.** Bilateral squat. (A) The patient starts by standing up straight, with legs shoulder-width apart. The patient is then asked to squat down as far down as possible. (B) Proper squatting technique, with a knee alignment lateral to the anterior superior iliac spine. (C) An improper squatting technique is represented by a medial collapse of both knees, which is a combination of hip internal rotation, hip adduction, and knee valgus.

moves the vector of ground reaction forces posteriorly, which increases the demand on the knee extensors and on the knee joint [8]. However, a forward trunk posture increases the demand on the hip extensors and decreases the load on the knee joint by moving the ground reaction force vector anteriorly [8].

## Step Down

The step down (Figure 2) is a broadly used clinical functional task to assess lower-extremity biomechanical deficiencies because its slow motion makes it easier to observe [30] . Still, it is important for clinicians to recognize what to observe during this task. Although the step down seems to be a low-demand task, it is one of the best tests to assess hip strength in a closed kinetic chain. Performance of the step down from a 23-cm step increases knee-hip adduction and hip internal rotation, while decreasing knee flexion. The biomechanical dysfunctions to observe during this task are a contralateral pelvic drop or contralateral pelvis elevation, ipsilateral hip adduction, ipsilateral hip internal rotation, and, consequently, ipsilateral knee valgus. These dynamic imbalances could occur in a single plane or in combination when the hip musculature is not capable of producing sufficient stability in the frontal and transverse planes [12,19]. During this task, the hip joint (femur) begins in a neutral position, moving toward adduction if improper contraction

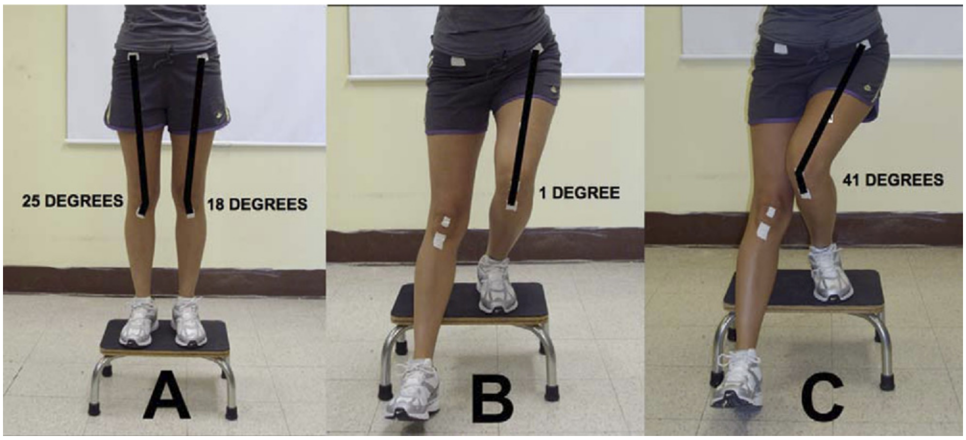


**Figure 2.** Single-leg step down. (A) During this task the patient starts by standing on a 23-cm high step, with legs shoulder-width apart; the patient is asked to keep one leg on the step and touch down on the floor with the opposite heel and come back up to the step. (B) Shows proper lower-extremity biomechanics. (C) Weakness of the hip abductors and external rotators will allow the leg on the step to move into valgus.

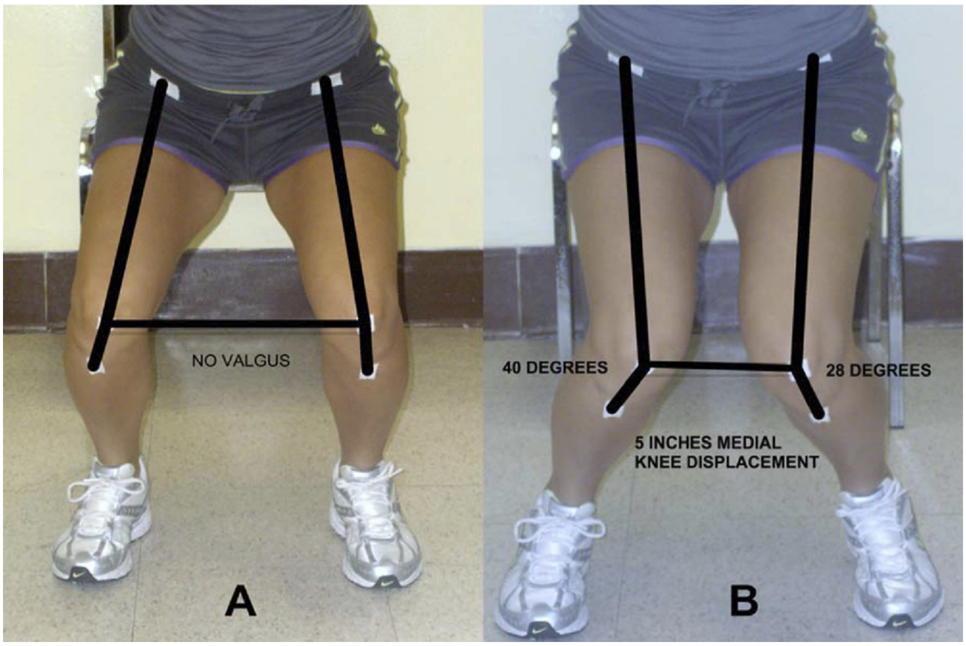


**Figure 3.** Drop jump. The patient is asked to drop from a box higher than 40 cm and to land with both legs; the patient must attempt a maximal vertical jump upon landing. The difference between good (A) and poor (B) landing mechanics is a dynamic medial collapse of the knees during the landing phase.

of the hip abductors and external rotators do not control the applied body weight to the flexed knee. In addition, because this task is performed with the leg in a closed kinetic chain, a contralateral pelvic drop will give the impression of hip adduction of the stance leg, which creates what is known as a Trendelenburg sign. To the contrary, some patients elevate their contralateral hip as a compensation for their weakness in the hip abductors (compensated Trendelenburg). These movements occur while the patient moves the trunk toward the stance limb with the purpose of decreasing the load on the hip abductors by displacing the patient's center of mass closer to the hip joint [8]. Typically, women will present greater hip adduction and hip internal rotation than men during this task [29,30]. Therefore, special attention needs to be given to the movement patterns exhibited from the pelvis to the knee for the most appropriate assessment, especially in women.

To perform this task, a 23-cm step will be required. The patient will be asked to stand up on the step with both legs. Upon the command to start the task, the patient will stand on one leg and bend the knees slowly until the opposite (nonstance) heel touches the floor. The patient will return to the standing position. Similar to the squat, this task could be evaluated by qualifying the movement as a high-risk or low-risk position [29]. A high-risk position is considered when the patella moves inward, ending up medially to the first toe (Figure 2C). If the patella ends in line with the first toe or more lateral, then the position is considered low risk (Figure 2B).

## Drop Jump

The drop jump (Figure 3) is a functional task widely used to detect lower-extremity mechanical dysfunction and lower-extremity weakness because of its capacity to create high eccentric loading during its landing phase [27,28]. It has been clearly documented that women tend to present greater hip and knee injury, predisposing factors after landing from a jump [31]. Small hip and knee flexion angles, in combination with large hip adduction and hip internal rotation angles, as well as large knee valgus joint angles are some of the predisposing factors that lead to knee injury [31]. Several researchers have concluded that, during the landing phase after a jump, these valgus forces increase the load to the knee joint and the risk for ligamentous injury [32].

The risk for knee injuries during landing has been found to depend upon the height of the jump. Women begin exhibiting straighter knees when compared with men during landing from heights higher than 40 cm [32]. Therefore, a drop box of 40 cm or higher should be used to detect faulty lower-extremity biomechanics. Specifically, the drop jump should be used to identify knee joint valgus and not mechanical hip deficiencies [30]. As previously stated, the drop jump creates high eccentric loads on the lower extremity, which makes this task only appropriate for physically active individuals who are familiar with performing jumping and landing tasks or asymptomatic individuals during preparticipation examinations. Therefore, this test is not appropriate for patients who present with a limp, exhibit difficulty walking, or are in the acute phase of their injury. Unfortunately, the landing phase after a drop jump is a very rapid movement easier identified by high-speed cameras. However, the equipment needed to perform 3-dimensional motion analysis is expensive, and the data analysis is time consuming and not feasible in the clinical setting [29,30]. As a result, the clinician depends upon his observational skills to perform the evaluation of the patient's landing mechanics.

The performance of this task will require a box equal or higher than 40 cm. The patient will be asked to stand up on top of the box, with the feet at shoulder-width apart and toward the edge of the box, with the feet in full contact with the surface. The patient will be given a command to get ready to drop from the box as soon he or she is ready to do so. Upon landing, the patient needs to perform a countermovement jump (vertical jump) and try to touch the ceiling during the jump. The patient needs to be encouraged to drop and not to jump vertically during the task. During landing, factors related to knee injury are evaluated. To evaluate these factors, the landing error scoring system can be used [33,34]. This form is easy to use by giving a score of "yes" or "no" to several items that represent the predisposing factors. This evaluation tool has proven to possess good reliability (intraclass correlation coefficient $> 0.71$) and validity when compared with a 3-dimensional motion analysis system.

## CLINICAL APPLICATION

After briefly understanding the mechanics involved during the performance of the squat, step down, and drop jump, the next step would be appropriate selection of functional tasks for the assessment of lower-extremity injury that predisposes biomechanics in the clinic. As previously mentioned, PFPS occurs in most cases because the femur rotates underneath the patella, which increases friction forces between the retropatellar cartilage and lateral femoral condyles [9,10,12]. However, other factors, such as weakness of core and hip muscles [13], lesser hip and ankle range of motion [11], and altered landing neuromuscular patterns [15,19], need to be kept in mind as possible sources of PFPS. The squat and single-leg step down would be the tasks of choice for patients with suspected PFPS or for those, for example, older adults, not capable of performing high-impact tasks. This task provides information regarding weakness of the hip abductors and external rotators. Typically, hip weakness will present as a dynamic valgus (medial deviation of the knee) while the patient is in the eccentric phase of the task (Figures 1, 2) [19]. The decision of using the drop jump in patients with PFPS must be examined carefully because the pressure at the knee joint might increase to levels not tolerable and cause pain or injury. Conversely, for the assessment of predisposing factors to ACL injury, the drop jump will help assess muscle weaknesses at the hip and knee extensors (Figure 3). In this case, stress increases because the hip and knee lack sufficient flexion to absorb ground reaction forces, simultaneously increasing knee rotation and valgus. Lack of strength at the hip and pelvis to absorb the impact during the landing phase would be observed as a stiff landing (small knee and hip flexion) and both knees getting closer to each other (Figure 3B), which indicates a lack of neuromuscular control throughout the kinetic chain [27]. In addition, as previously mentioned, the drop jump can be used in asymptomatic patients in a preparticipation evaluation with the purpose of designing an injury-prevention program.

The most important characteristics of these 3 functional tasks are their capability to challenge specific dynamic neuromuscular strategies within the lower extremity and their practicability to use in the clinic without highly instrumented equipment. The squat is characterized by being able to increase internal femoral rotation, shear, and compressive loads underneath the patella [9,10,19]. The step down can be characterized by its slow movement, which makes this task easier to observe and detect poor biomechanics in the frontal and transverse plane for the pelvis and hip [30]. Therefore, it is appropriate for identifying hip abductors, hip external rotators, and possible quadratus lumborum weakness. The drop jump can be characterized by its ability to create large eccentric loads in the lower extremities [28,30,31]. These high loads will cause the knee to move into valgus (knocking of the knees), which is a leading factor for injuries during jumping and landing activities [7,11,30]. Therefore, the drop jump is a task suitable only for those patients accustomed to high-impact activities.

After performing a proper clinical evaluation, the most suitable recommendations need to be based on thorough observation and assessment. As previously stated, biomechanical dysfunctions at the knee joint are multifactorial in nature, including weakness of the hip musculature [12,14], increased torques toward valgus [7,11], impaired hip and ankle range of motion [11], and altered landing motor patterns [15]. Therefore, we need to be clear that functional tasks cannot represent a single deficiency and that the inability to perform them correctly is related to multiple factors within the kinetic chain.

The interventions to be prescribed for our patients need to be based on the specific impairments identified during the evaluation. Neuromuscular training [35], landing instructions [15], and custom orthotics [17] are among the most evidence-based interventions proven to decrease biomechanical impairments that lead to knee injury. The main muscles targeted in these neuromuscular injury prevention or rehabilitation programs are the gluteus maximus, gluteus medius, quadratus lumborum, multifidi, transversus abdominis, and hamstrings. Thus, neuromuscular rehabilitation must be an essential part of the treatment and injury prevention program of all athletes, especially women. Nevertheless, when teaching these exercises to our patients, it is very important to provide the appropriate feedback during practice to appropriately correct deficiencies.

## CONCLUSION

Knee injuries are mainly related to multifactorial causes, which require broad and comprehensive evaluation and rehabilitation strategies. Functional tasks are a great asset to the rehabilitation professional evaluation and assessment processes. The inclusion of functional tasks helps assess and identify a variety of biomechanical deficiencies, especially in closed kinetic chain activities that cause knee injuries. The squat, single-leg step down, and the drop jump are functional tasks that can be used in the clinic because of their ease of administration, evaluation, and space required. These tasks are used in the clinical evaluation of the lower extremity with the purpose of detecting impaired weight-bearing biomechanics associated with knee pathology, such as PFPS and ACL injury. Several evaluation methods have been developed when using these functional tasks with the purpose of standardizing evaluation and assessment procedures. When biomechanical deficiencies of the lower extremities are identified through our functional evaluation, an appropriate rehabilitation program should encompass neuromuscular and motor control training programs, and correction of ankle and foot biomechanical malalignments.

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