# Rehabilitation After Anterior Cruciate Ligament Reconstruction: Criteria-Based Progression Through the Return-to-Sport Phase

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Rehabilitation following anterior cruciate ligament (ACL) reconstruction has undergone a relatively rapid and global evolution over the past 25 years. However, there is an absence of standardized, objective criteria to accurately assess an athlete's ability to progress through the end stages of rehabilitation and safe return to sport. Return-to-sport rehabilitation, progressed by quantitatively measured functional goals, may improve the athlete's integration back into sport participation. The purpose of the following clinical commentary is to introduce an example of a criteria-driven algorithm for progression through return-to-sport rehabilitation following ACL reconstruction. Our criteria-based protocol incorporates a dynamic assessment of baseline limb strength, patient-reported outcomes, functional knee stability, bilateral limb symmetry with functional tasks, postural control, power, endurance, agility, and technique with sport-specific tasks. Although this algorithm has limitations, it serves as a foundation to expand future evidence-based evaluation and to foster critical investigation into the development of objective measures to accurately determine readiness to safely return to sport following injury. *J Orthop Sports Phys Ther 2006;36(6):385-402*. doi:10.2519/jospt.2006.2222

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Advances in fixation methods and other graft reconstruction techniques have dramatically improved surgical success with anterior cruciate ligament (ACL) reconstruction.[16,21] The advances in surgical technique have resulted in consistently good surgical outcomes and may shift the potential for an athlete to return to his or her previous level of sport, to be more determined by differences in rehabilitation than by surgical procedure.[16,44,45] Traditional ACL rehabilitation that once included prolonged immobilization, non-weight bearing and slow progression to activity, now emphasizes immediate motion, early weight bearing and accelerated return to sports participation for athletic patients. Compared to past protocols, rehabilitation programs are now more aggressive and advocate the release of athletes to sports activities in as early as 8 weeks after surgery.[82,83]

Athlete return to play is often dictated by graft stability (anterior-posterior tibiofemoral motion), patient confidence, postsurgical

timeline, and subjective medical team opinion. Appropriate objective criteria that consider both graft strength and objective functional criteria to determine advancement through the end stages of rehabilitation and readiness to return to sport following ACL reconstruction remain elusive.[44] Rehabilitation and ultimate return to sport, using objective tests that quantitatively measure functional ability, may increase athlete reintegration to sports at the same competitive level as prior to the injury.

Rehabilitation following ACL reconstruction is commonly divided into early (immediate postoperative and subacute strengthening) and late rehabilitation phases (functional progression and return to sport), with specific goals and time since surgery as determinants for phase progression. Early phases of post-ACL reconstruction often utilize stringent, criteria-based guidelines for range of motion (ROM) and progression to full weight bearing and exercise selection. In contrast, the final phases of rehabilitation prescriptions are typically broader, with general categorizations of appropriate exercises and progressions, without specific milestones for when it is safe to introduce high-risk and high–joint-loading activities.[83,88,89] In addition, more conservative therapeutic approaches may limit progression to later stages of rehabilitation and possibly delay successful return to sport.

Exercise prescription for an athlete's progression through rehabilitation and back-to-sport participation should avoid stretching the graft in athletes who do not possess the strength and functional abilities necessary to protect the healing joint while undertaking high–joint-loading activities. Structurally, animal studies indicate that the graft's strength may reach its weakest point at approximately 6 to 8 weeks postoperatively[14] and may only reach failure loads between 11% and 50% of the native ACL at 1-year postoperative.[5] Controlled loading may enhance ligament and tendon healing,[3,4] while excessive loading can potentially damage the healing graft and lead to increased anterior-posterior knee laxity.[9] Graft healing properties have been studied primarily in animal models, including rabbits,[5] canines,[9] and primates.[14] These types of animal models present important information related to histological properties, stiffness, and ultimate load to failure intermittently over a 1-year span in the mammal. However, the properties of a healing graft in animal models may be limited in their generalizability to outcomes in the human ACL.[5,9,13, 14] The limited data in humans makes the determination of the optimal load to place on the healing ACL reconstruction, as well as the optimal timing to place that load, difficult to determine.[8] It is possible to return to pivoting, twisting, and rotational sports as early as 3 to 4 months postoperatively;[82,83] however, this early return to sport may not be safe for

athletes who do not have sufficient functional stability to protect the weakened, healing graft. Healing ACL grafts may be better protected if more aggressive post-ACL reconstruction rehabilitation protocols were to utilize objective measures of functional status to drive rehabilitation progression. Progression should be based on variables that determine functional stability and neuromuscular control. This may improve successful early (2-3 months) return to sport and good long-term outcomes.[76]

Concomitant with decreased biomechanical strength of the ACL graft relative to the native ligament, athletes may demonstrate decreased muscular strength, joint position sense, postural stability, and force attenuation (significant limb-to-limb landing ground reaction force differences during bilateral tasks) for 6 months to 2 years after reconstruction.[19,25,51,62,71] Deficits evident in the early stages of rehabilitation (unique to the patient and possibly to the graft type), if left unaddressed, will likely persist beyond the late rehabilitative stages.[19,51] Ongoing biomechanical deficits that contribute to neuromuscular performance during competitive sport may limit dynamic support, which may compromise the already weakened graft. This may increase the risk of ipsilateral ACL reinjury in the first year following reconstruction.[68,78]

In addition to reduced graft strength and altered functional joint control, there are other factors that make late-phase ACL rehabilitation a high-risk period for the athlete. During this phase of rehabilitation, clinicians must be especially cognizant of the potential gap between the athlete's perceived versus actual sports readiness, as subjective scores often do not correlate to quantified function and strength scores in patients with ACL injuries and reconstructions.[61,65,77] Without objective measures that identify potential deficits, it may be difficult for therapists to justify sport restriction and the associated limitations, as well as to address additional physical areas of concern. Specific progressive guidelines, based on objective measures, can provide a goal-oriented rehabilitation process that may be an appealing approach for athletes.[16]

In summary, there is currently a lack of objective criteria to reliably determine how and when to progress a patient through end stage rehabilitation. The purpose of this clinical commentary is to introduce an example of a criteria-driven progression through the return-to-sport phase of rehabilitation following ACL reconstruction. The outlined progression has yet to be validated; however, both documented and empirical evidence is provided for each component and the clinical rationale for the algorithm is outlined. The authors acknowledge that further validation is needed to formalize the use of

our criteria-driven algorithm into the mainstream clinic, but we desire to utilize the current clinical commentary to initiate critical evaluation of our current practice.

## Criteria for Progression Into the Return-to-Sport Phase

Our return-to-sport neuromuscular training incorporates a progression through specific criteria designed to provide structure and objective standardization to late-phase rehabilitation following ACL reconstruction. Figure 1 presents an algorithmic flow chart used to track the athlete's progress through the late rehabilitation stages. Prior to initiation of return-to-sport training, our recommendation is that the patient meets the following minimum baseline criteria: (1) minimum International Knee Documentation Committee (IKDC) Subjective Knee Form score of 70 (Appendix 1); (2) either no postsurgical history of giving way or a negative pivot shift; and (3) a minimum baseline strength knee extension peak torque/body mass of at least 40% (male) and 30% (female) at 300°/s, and 60% (male) and 50% (female) at 180°/s.

Carefully documented and validated subjective assessment of the patient's ability to progress in rehabilitation may be a key factor in determining an athlete's readiness to enter a return-to-sport program. The International Knee Documentation Committee (IKDC) Subjective Knee Form is a reliable and valid tool for the determination of a patient's rating of knee symptoms, function, and ability to participate in sport following knee injury—specifically, ACL injury[36] (Appendix 1). The constructs validated for the IKDC were swelling, pain level, and functional ability. Initial scoring of at least 70 on the IKDC knee subjective rating form on the involved limb is one of the requirements for our athletes post-ACL reconstruction to enter return-to-sport training. An IKDC rating of 69 or more would put athletes within 1 standard deviation of a population-based average for males and females aged 18 to 24 years (1079 limbs).[2] Athletes with increased functional abilities may achieve an IKDC rating of 70 or greater and be prepared to progress into the return-to-sport phase more rapidly (2-4 months). An IKDC knee rating below 70 may indicate that an athlete is in need of additional recovery time from postsurgical trauma and improvement in functional status prior to beginning return to sport training. Incorporation of a validated subjective knee-rating system like the IKDC may bridge the gap between patient-perceived function and objectively measured function to enhance progress through the proposed algorithm in the return-to-sport phase of rehabilitation.

Functional stability, or the ability to avoid giving way of the knee using dynamic muscular restraints, protects the healing graft following ACL reconstruction. Though mechanical stability may be restored via surgical reconstruction, the patient may continue to experience functional instability (giving-way episodes or perceived instability) or functional impairments.[34,80,85] Return to high-level sports is a high-risk period for athletes during the first year postreconstruction.[68,78,87] Return of a patient to high-level sports before functional stability is achieved may increase the potential for poor outcome. In addition, inadequate functional stability may be related to decreased confidence in the injured knee and to decreased ability to return to preinjury sports participation.[45] The inability of the patient to develop dynamic muscular joint stabilization through neuromuscular control during walking and activities of daily living (ADL) should exclude the patient from progression into an aggressive return-to-sport rehabilitation phase.[6,66] Therefore, the athlete should have no giving-way episodes prior to entering the return-to-sport phase. However, a giving-way episode may represent a deficiency in active (neuromuscular restraint) or passive (static restraint) stability or a combination of both. A positive pivot shift indicates mechanical instability and is related to subjective reports of poor functional outcome.[43,46] A patient who reports a previous history of giving-way episodes and a negative pivot shift likely possesses sufficient mechanical stability to safely enter into advanced rehabilitation exercises designed to address the functional instability.[38] Measurable functional deficits that may relate to past giving-way episodes may be correctable if the athlete participates in safe and progressive return-to-sport training.

Prior to initiation of return-to-sport training, the athlete should demonstrate sufficient strength to improve potential for success.[48] The absence of sufficient strength may result in an inability to initiate dynamic movements, to attenuate ground reaction forces, or to achieve high levels of performance during dynamic tasks.[41,48] Normative ranges for postpubescent adolescents and adults for isokinetic knee extension peak torque-body mass ratio at 300°/s are 40% to 55% for men and 30% to 45% for women, and at 180°/s are 58% to 75% for men and 50% to 65% for women.[10] We use a minimum quadriceps torque-body mass ratio of 40% for males and 30% for females at 300°/s, and 60% for males and 50% for females at 180°/s, for return-to-sport training for the athletic population. These values are the low ranges of normative data that we hypothesize are the baseline levels of strength that athletes should demonstrate for a safe and successful introduction into the initial stages of the return-to-sport program.
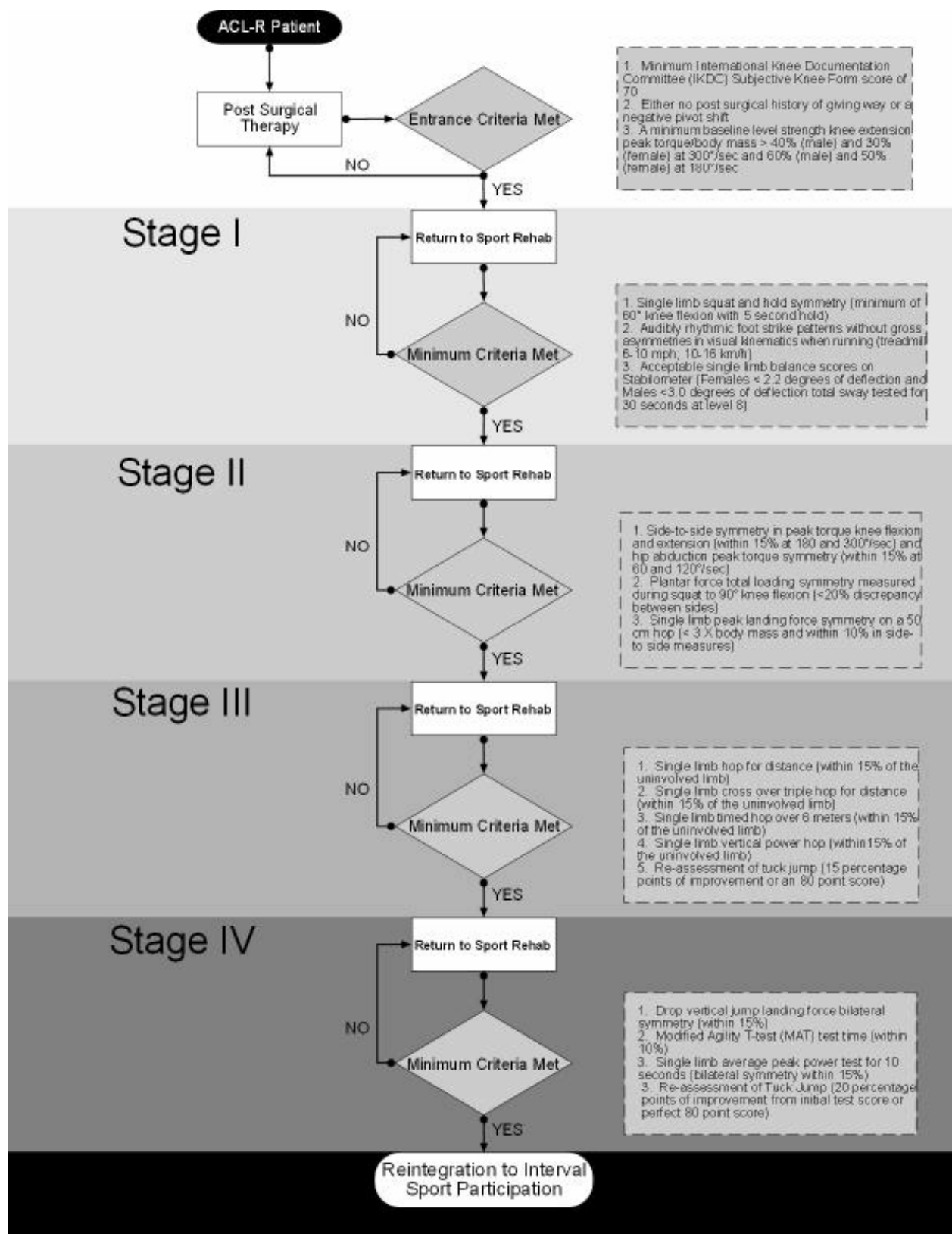
CLINICAL COMMENTARY

**FIGURE 1.** Return-to-sports activities post ACL reconstruction. Before progressing to the next rehabilitative stage in the program, the patient must meet the minimum progression criteria.

## Return-to-Sport Phases

The rehabilitation progression should take the athlete through a combination of both low-risk and high-demand maneuvers in a controlled environment. The training should balance attempts to overload and develop the functional abilities of the athlete with minimal exposure to potential injury risk positions.

The introduction of this type of training into the rehabilitation program may create acute muscle soreness and the rehabilitation team should use discretion as to the appropriate intensity and progression of exercises. Systematic criteria-driven guidelines, however, may facilitate the decision making approach towards intensity and exercise mode. The ultimate goal of the ACL return-to-sport algorithm of rehabilitation is to identify and address deficits that may inhibit the athlete from improving neuromuscular function and raise the athlete to a level that will minimize the risk of reinjury. In addition, we think this approach provides the potential for athletes with ACL reconstruction to improve their ability to manage forces and torques that may have incited the initial injury and hindered performance prior to injury.

## Stage 1: Goals

Our initial stage of return to sport targets the following specific goals: (1) to improve single-limb weight-bearing strength at increasingly greater knee flexion angles; (2) to improve side-to-side symmetry in lower extremity running mechanics; (3) to im-



**FIGURE 3.** Demonstration of clinician assessing running-gait mechanics. The clinician evaluates the athlete to determine if they demonstrate audibly arrhythmic foot strike patterns or gross asymmetries in visual kinematics when running that would limit progression onto subsequent stages.

prove weight-bearing single-limb postural balance. To improve single-limb strength we recommend that clinicians advance single-limb weight-bearing exercises with lunge and single-limb squatting exercises. In addition, treadmill training with verbal and visual feedback can be integrated to improve side-to-side limb symmetry in running kinematic and kinetic patterns. Exercise prescriptions that stress single-limb postural control, especially techniques performed on unstable surfaces, are warranted for stage 1 of the return-to-sport phase of rehabilitation. We feel that exercise prescription should be modified to address deficits specific to each individual athlete, with a primary focus on increasing the athlete's potential to meet the minimum criteria required to progress to stage 2 of return-to-sport training.

## Stage 1: Criteria for Progression

The criteria for progression to stage 2 of return-to-sport training are as follows: (1) single-limb squat and hold symmetry (minimum 60° knee flexion with 5-second hold) (Figure 2); (2) audibly rhythmic foot strike patterns without gross asymmetries in visual kinematics when running (treadmill 6-10 mph [10-16 km/h]) (Figure 3); and (3) acceptable single-limb



**FIGURE 2.** Single-limb squat test with a goniometer. Athlete is instructed to squat to 60° or more of knee flexion and hold for 5 seconds. Athletes must perform this task on both their involved and noninvolved limb.
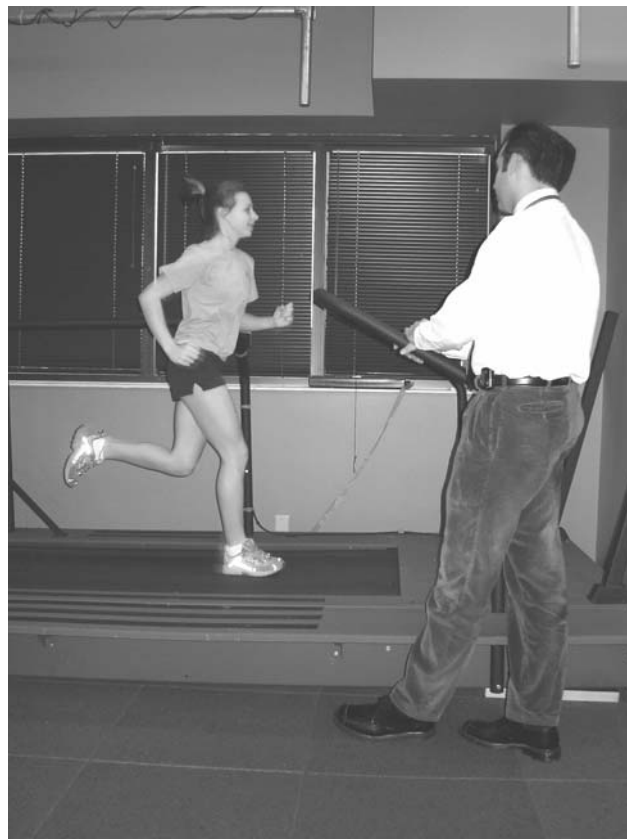
balance scores on stabilometer (females, less than 2.2° of deflection; males, less than 3.0° of deflection; total sway tested for 30 seconds at level 8) (Figure 4).

Single-limb postural stability deficits may be present bilaterally after ACL rupture and well into the postoperative rehabilitation period.[1,91] Measures of postural stability can be used as a means of assessing an athlete's recovery of functional stability after ACL reconstruction.[1,33,91] Postural balance is a complex function that relies on the interplay of several factors, including proprioception, strength and function of dynamic joint restraints, static joint restraints, and postural equilibrium. Dynamic joint restraints are muscle-tendon units that maintain limb and joint position and react to changing loads and forces. Static joint restraints include ligaments and bony architecture that limit joint motion. Measures of postural sway are often assessed on stable surfaces during single-limb standing with the knee extended or nearly extended and with variations in visual input. These measures can be accurately assessed by clinicians but may not always be sensitive to determining



**FIGURE 4.** Single-limb balance measurement taken on a Biodex Stabilometer.

deficits following ACL reconstruction.[31] Increasing knee flexion positions during dynamic tasks may be useful for the determination of side-to-side differences, because greater knee flexion may be more challenging if an athlete has continued strength deficits. In addition, improved proficiency in performing tasks at increased knee flexion may limit exposure to excessive anterior tibial shear loads that can overload weakened grafts when performing dynamic loading tasks.[17,22,50] Patients with ACL injury may not demonstrate differences when compared to controls or their contralateral limb. However, during more dynamic cutting tasks these patients utilize a cutting strategy with decreased knee flexion.[35] Progression through subsequent return-to-sport stages will incorporate safe biomechanical techniques in deep knee flexion angles that may protect the ACL graft.[57] Based on empirical evidence, we require that athletes be able to squat to 60° knee flexion in single-limb stance and maintain postural control for a minimum of 5 seconds. During this test, the athlete should demonstrate the ability to maintain the hip and trunk in an upright position during descent and to maintain the position of the center of mass along a vertical axis. Clinicians can utilize a goniometer to demonstrate the desired knee flexion angle and cue the athlete once the angle is achieved to start timing.

Straight-line jogging is often initiated early in rehabilitation programs,[83] but frequently the athlete's technique is altered due to underlying deficits.[24] Without direct assessment of a patient's running gait pattern, it is difficult to develop objective tests that can be used for progression following ACL reconstruction. However, we delay progression into the next stage of rehabilitation if the patient visually demonstrates grossly evident limb asymmetries during treadmill running. Patients with abnormalities in running gait post-ACL reconstruction may benefit from biofeedback training. Pilot work demonstrates that visual and verbal biofeedback can influence desired kinematic gait variables in normal and in patient populations.[18,52] Clinicians rehabilitating patients post-ACL reconstruction may use biofeedback techniques with treadmill training to assess and treat gross abnormalities in straight-line running technique.[18,24] Specifically, we focus on improvement of the symmetry of loading the extremity, range of motion at lower extremity joints, and obtaining normal rhythmic strides during forward running on a treadmill.[18,24] We recommend that patients demonstrate an audibly rhythmic foot strike pattern without gross asymmetries in visual kinematics when running (treadmill, 6-10 mph [10-16 km/h]) prior to progression to stage 2 of the return-to-sport rehabilitation. These recommendations for running-gait assessment and training were gained primarily from empirical evidence and warrant further investigation to determine their clinical effectiveness and validity.

Stabilometry (Figure 4) is an objective method for evaluating postural stability on more functional unstable platforms and can be diagnostic for remaining neuromuscular deficits in athletes after ACL reconstruction.[1,33] The athlete's ability to control the platform's tilt is quantified as a variance from center of pressure (increased variance scores indicating decreased postural stability). The Biodex Stability System (Biodex Corp, Shirley, NY) gives reliable measures of body sway.[73,79] Schmitz et al[79] examined the intrarater and intertester reliability of the Biodex Stability System in a cohort of 19 healthy subjects. The authors implemented a repeated-measures design with 2 testers on consecutive days. They reported intratester (ICC = 0.82) and intertester (ICC = 0.70) reliability for total stability. In a similar study that evaluated test-retest reliability on the same day, Pincivero et al[73] reported good intrarater reliability at level 8 for the nondominant (ICC = 0.78) and dominant (ICC = 0.95) limbs.

Mizuta et al[54] examined subjective complaints of functional instability following ACL injury with a stabilometric measurement of postural balance on a force plate and found impaired standing balance in the group with functional instability. They concluded that stabilometry was a useful method for evaluating functional instability of the knee.[54] Tropp et al[84] reported that athletes who could not demonstrate postural balance within 2 standard deviations of normal had a significantly higher risk of lower extremity injury. Normal female subjects demonstrate greater single-limb postural stability than males on a stabilometer.[33] However, in subjects with ACL-deficient knees, males had greater stability than females preoperatively on the involved and noninvolved limb.[33] On postoperative examination, the males continued to have greater total stability than females, with significant differences remaining between these groups at 6 months, 9 months, and 12 months postoperatively. The males' instability on the involved limb peaked at 3 months postoperatively, whereas the females had the most instability at 6 months postoperatively. If females have greater deficits in single-limb balance than males following ACL rupture, they may require more rehabilitation to recover from ACL reconstruction to regain functional stability and to be prepared to return to peak function. These findings also indicate that the clinician should stress balance and functional stability exercises in the rehabilitation for female patients to aid in a progressive return of proprioceptive abilities.[33]

On average, males and females who are 3 months post-ACL reconstruction demonstrate deficits of approximately 20% of those of normal controls in postural control, as assessed on the Biodex Stability System for 30 seconds. Our athletes who desire to progress onto stage 2 of the return-to-sport phase must demonstrate postural stability scores that are within a 20% range of control values. We require our females to score less than 2.2° of deflection and males less than 3.0° of deflection of total sway for both the involved and uninvolved limb to progress to stage 2.

## Stage 2: Goals

The second stage of return-to-sport training focuses on the following goals: (1) to improve lower extremity non-weight-bearing strength; (2) to improve force contribution symmetry during activities in bipedal stance; and (3) to improve single-limb landing force attenuation strategies.

During this stage, we recommend that clinicians continue lower extremity weight-bearing strengthening activities, high-intensity balance training, and perturbation training in the athlete's rehabilitation. In addition, the rehabilitation program can now include non–weight-bearing lower extremity exercises.[53] Our clinicians also work on improving the athlete's strength with squatting techniques, focusing on equal side-to-side limb contribution. Increased focus on appropriate force attenuation strategies with landing on a single limb may also be incorporated into the rehabilitation. Exercise prescription can be modified to address other clinically identified deficits specific to the individual athlete.

## Stage 2: Criteria for Progression

We recommend that the athlete demonstrate the proficiency in the following criteria prior to progressing to stage 3: (1) side-to-side symmetry in peak torque knee flexion and extension (within 15% at 180°/s and 300°/s) and hip abduction peak torque side-to-side symmetry (within 15% at 60°/s and 120°/s); (2) plantar force total-loading symmetry measured during bipedal squat to 90° knee flexion (less than 20% discrepancy between sides); (3) single-limb peak-landing-force symmetry on a 50-cm hop (less than 3 times body mass and within 10% in side-to-side measures).

Historically, isokinetic strength assessment has been used as criteria to progress to return-to-sport activities.[21,41,55] Despite reports that quadriceps deficit may persist up to 2 years following ACL reconstruction[41,71,75] and that only a low to moderate correlation of isokinetic strength to knee function may exist,[28,74,90] isolated quadriceps strength is still considered a critical component to safely progress athletes back to dynamic activities.[44] Typically, quadriceps weakness is a limiting factor in rehabilitative progression and failure to achieve adequate strength can potentially result in increased risk of future injury, including acute and overuse injuries such as anterior knee pain.[15,89] Decreased quadriceps function follow-

ing injury and reconstruction, coupled with the evidence of compensation with functional tasks, such as stair ascent and landing from a jump following ACL reconstruction, is of concern.[19,25] Global assessments of function, though critical to the overall assessment of the athlete, may fail to detect isolated weakness in the knee extensor muscle group. Because quadriceps and hamstring cocontraction is an important dynamic stabilizer of the knee joint,[63] adequate quadriceps and hamstrings strength is important for the safe progression of the athlete after ACL reconstruction to the next stage of the return-to-sport program, as well as to the ultimate discharge of the athlete to sport. Therefore, we recommend that patients demonstrate peak torque symmetry of the involved limb within 15% of the contralateral limb for both quadriceps and hamstring strength at 180°/s and 300°/s to progress to stage 3 of the criteria-based algorithm.

Hip abduction strength is likely to be important for both dynamic knee stability and decreasing reinjury risk. In a cohort of young healthy female athletes, Hewett et al[32] determined that measures of dynamic lower extremity valgus and asymmetries in hip abduction torque were predictive of ACL injury in this population. Padua et al[69] showed that hip abduction strength was a significant predictor of initial contact and peak knee valgus angles during a drop-landing task. Zazulak and colleagues[92] reported that female athletes who are at higher risk of ACL injury demonstrated decreased hip muscle activation during single-limb-landing tasks when compared to males. While differences between limbs have been demonstrated in sidelying isometric hip abduction torque,[37] pilot data in a larger cohort (n = 152) of young athletes indicates that these side-to-side differences are not evident when hip abduction is evaluated isokinetically in the standing position.[12] Adequate hip abduction strength is likely necessary to safely return to sport following ACL reconstruction. Therefore, we recommend that the patient demonstrate peak torque symmetry within 15% of the contralateral limb for hip abduction strength at 60°/s and 120°/s.

Side-to-side asymmetries in dynamic functional tasks, such as jumping and cutting, are risk factors for ACL injuries in young healthy athletes.[32] Following ACL reconstruction, patients frequently do not demonstrate the ability to balance forces bilaterally in the lower extremities with both high-level tasks, such as landing,[19] and less dynamic tasks, such as squatting.[62] Neitzel et al[62] demonstrated that with squatting, patients were unable to balance side-to-side loading response equal to that of controls until 12 to 15 months postoperatively. These patients demonstrated side-to-side deficits between 33% and 48% at 1.5 to 4 months postoperative and between 21% and 28% at 6 to 7 months postoperative. Considering the potential

for side-to-side biomechanical differences to increase risk for ACL injury, it may be necessary to train the patient to balance these forces prior to progression to stage 3.[32] Force platforms, insole foot pressure systems, or standard bathroom scales may be utilized to determine relative side-to-side loading discrepancies during this activity. We suggest that the patient demonstrate less than a 20% side-to-side difference in total loading during a 90° knee flexion squat maneuver.

Inability to attenuate forces during a single-limb maneuver may be related to increased risk of ACL injury.[47] Specifically, athletes that utilize decreased landing knee flexion may subject their limb to an abrupt bone-to-bone stress at the knee. Decreased knee flexion at landing may be evidenced by increased landing forces and could be a result of decreased thigh muscle strength.[47] The single-limb landing force symmetry test (less than 3 times body mass and within 10% in side-to-side measures) is performed a total of 6 times (3 randomized trials on each side) using an AccuPower portable force platform (Advanced Mechanical Technology, Inc, Watertown, MA). Subjects are instructed to initiate the movement while balancing on 1 foot, to hop forward 50 cm, and to balance for 10 seconds after landing on the same foot. Maximum vertical ground reaction force is calculated for each trial. Maximum vertical ground reaction force shows high within-session reliability on both the dominant ($r = 0.823$) and nondominant ($r = 0.877$) sides.[11] The average maximum vertical ground reaction force for the normal athletes is 2.4 times body mass.[11] It is recommended that athletes perform this test with less than 3 times body mass and a side-to-side discrepancy of less than 10%.

Finally, prior to progression to stage 3, we recommend that the athlete's lower extremity plyometric techniques be assessed. Specifically, we have the athlete perform repeated tuck jumps for 10 seconds. A standard 2-D camera in the frontal and sagittal planes may be utilized to assist the clinician. The athlete's technique (Figure 5) is then subjectively rated on an 80-point scale (Appendix 2). The athlete's baseline performance is determined at this time. This assessment will be repeated at the conclusion of each subsequent stage to objectively track improvement with jumping-and-landing technique. Pilot work in our laboratory with 10 physical therapists was conducted to determine the reliability of scoring the tuck jump assessment. These data demonstrated that intrarater within-session reliability was high $r = 0.84$ (range, 0.72-0.97). Pilot data using the tuck jump assessment tool suggest that it may be adequate for a single clinician to reassess athletes to determine changes in technical performance of the tuck jump exercise. The authors acknowledge that
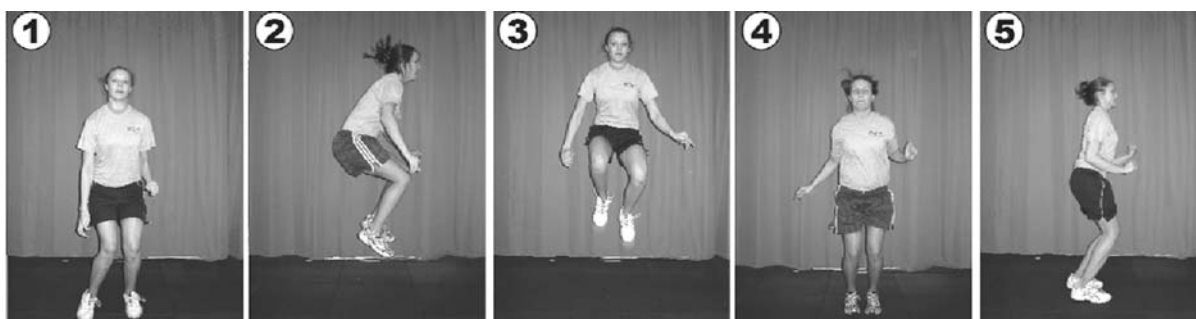
**FIGURE 5.** Examples of techniques that clinicians evaluate during the tuck jump assessment. For this test the athlete is positioned with shoulder width apart and asked to jump, pulling her thighs parallel to the ground. Jumping is repeated for 10 seconds. (1) Example of knees not in neutral alignment; (2) Example of thighs not reaching parallel at top of jump; (3) Example of thighs that are not equal side-to-side throughout the flight sequence; (4) Example of inappropriate foot placement at landing, not shoulder width apart; (5) Example of foot placement in appropriate parallel position not staggered during ground contact.

further work is needed to validate this tool when used for progression in patients following ACL reconstruction.

The tuck jump exercise may be useful for the clinician to identify lower extremity valgus and side-to-side differences (Figure 5).[57] The tuck jump requires a high effort level from the athlete. Initially, the athlete may place most of his or her cognitive efforts solely on the performance of this difficult jump. The clinician may readily identify potential deficits, especially on the first few repetitions.[57] Additionally, the tuck jump exercise may be used to assess improvement in lower extremity biomechanics as the athlete progresses through the return-to-sport training.[16,57]

Specifically, correction of lower extremity valgus at landing and improvement of side-to-side differences in lower extremity movements and foot placements is the focus of the tuck jump assessment tool. The link between valgus knee loading and resultant increases in ACL strain is demonstrated through cadaver, in vivo, and computer-modeling experiments.[27,39,49,50] Physiologic valgus torques on the knee can significantly increase tibial subluxation and load on the ACL.[27] A prospective combined biomechanical-epidemiologic study showed that knee abduction moments (valgus torques) and angles were significant predictors of future ACL injury.[32] Knee abduction moments, which directly contribute to lower extremity dynamic valgus and knee joint load, predicted ACL injury risk with high sensitivity and specificity.[32] It may be even more important to address potential lower extremity valgus measures if demonstrated by patients after ACL reconstruction, as it may have been a predisposing factor to their initial injury.[32] If the athlete can improve neuromuscular control and biomechanics during this difficult jump-and-landing sequence, the athlete may gain dynamic neuromuscular control of the lower extremity and create a learned skill that can be transferred to competitive play.

## Stage 3: Goals

We suggest that the third stage of return-to-sport training continue to focus on improving the functional abilities of the athletes with ACL reconstruction. Specifically, the goals for stage 3 of the return to sport are: (1) to improve single-limb power production; (2) to improve lower extremity muscular endurance; and (3) to improve lower extremity biomechanics during plyometric activities.

During stage 3 of the rehabilitation, we recommend the incorporation of midlevel intensity double-limb plyometric jumps and the introduction of low-intensity single-limb repeated hops into rehabilitation. We focus on proper and safe technical performance of the plyometric activities. The athlete's ability to properly perform the plyometric tasks can be used to guide the volume and intensity of the exercises selected.

## Stage 3: Criteria for Progression

To advance to the next stage, the athlete must achieve the following criteria related to athletic power development and symmetry: (1) single-limb hop for distance (within 15% of the uninvolved side); (2) single-limb crossover triple hop for distance (within 15% of the uninvolved side); (3) single-limb timed hop over 6 m (within 15% of the uninvolved side); (4) single-limb vertical power hop (within 15% of the uninvolved side); (5) reassessment of tuck jump (15 percentage points of improvement or an 80-point score) (Appendix 2; Figure 5).

One tool to assess unilateral lower limb functional power, while assessing limb symmetry, is functional performance testing. Tests such as the single-limb hop for distance, triple hop for distance, single-limb crossover triple hop for distance, and single-limb timed hop over 6 m have been previously described as tools to utilize with athletes following ACL reconstruction and those with an ACL-deficient knee.[26,64,90] The ability to demonstrate limb symmetry within 15% on these tests may be an effective tool for the

evaluation of patients for progression following ACL reconstruction.[26] Therefore, the patient's ability to successfully attain 15% limb symmetry on these hop tests may be important to safely progress in the return-to-sport phase of rehabilitation.

Side-to-side imbalances in muscular strength, flexibility, and coordination may be important predictors of increased injury risk.[7,32,42] Knapik et al[42] demonstrated that side-to-side balance in strength and flexibility is important for the prevention of injuries and when side-to-side differences are present, the athlete is more injury prone. Baumhauer et al[7] also found that individuals with muscle strength imbalances exhibited a higher incidence of injury. Hewett et al[32] developed a model to predict ACL injury risk with high sensitivity and specificity. Approximately half of the parameters in the predictive model were side-to-side differences in lower extremity kinematics and kinetics. Side-to-side imbalances may increase risk for both limbs. Overreliance on the noninvolved limb can put greater stress and torques on that knee, while the involved limb may be at risk due to an inability of the musculature on that side to effectively absorb the high forces associated with sporting activities.

The single-limb vertical power hop test can be used to assess the athlete's ability to perform work (force × displacement) over a given time. The athlete is instructed to stand in unilateral stance and hop as high as possible from a single limb and land on both limbs. Peak power generated during the push-off phase is calculated from each hop and averaged over 3 trials to assess asymmetries between limbs. The athlete must attain an average symmetry value within 15% to meet the requirements for stage progression with this test. In addition, the athlete can be reassessed with the standardized tuck jump assessment tool (Appendix 2; Figure 5). At this point, we recommend that the athlete demonstrate 15 percentage points of improvement (or a perfect score of 80 points) relative to their initial test to meet the requirements for progression of this task.

### Stage 4: Goals

The final stage of return-to-sport training focuses on skill reacquisition related to the athlete's sport and to maximize athletic development during training. More specifically, stage 4 of the return-to-sport protocol will focus on the following: (1) equalizing ground reaction force attenuation strategies between limbs; (2) improving confidence and stability with high intensity change of direction activities; (3) improving and equalizing power endurance between limbs; and (4) using safe biomechanics (increased knee flexion and decreased knee abduction angles) when performing high-intensity plyometric exercises.

In this stage we recommend that clinicians incorporate power, cutting, and change-of-direction tasks that are modified to be related to the athlete's individual sport.[57,59] We suggest emphasis of the performance of power movements equally well in both directions, with sufficient hip and knee flexion angles with decreased knee abduction.[57,58] Extensive verbal and visual feedback are utilized to help the athletes following ACL reconstruction develop safe biomechanics during power movements.

### Stage 4: Criteria for Progression

Successful completion of stage 4 and ultimate clearance for integration back into sporting activities is dependent upon the athlete's ability to achieve the following criteria related to sport-specific movements: (1) drop vertical jump landing force bilateral symmetry (within 15%) (Figure 6); (2) modified agility T-test (MAT) test time (within 10%) (Figure 7); (3) single-limb average peak power test for 10 seconds (bilateral symmetry within 15%) (Figure 8); (4) reassessment of tuck jump (20 percentage points of improvement from initial test score or perfect 80-point score) (Appendix 2; Figure 5).

Limb asymmetries with athletic tasks may be potential risk factors for ACL injury and, therefore, should be minimized prior to return to sport. All stages of the ACL return-to-sport program attempt to minimize these asymmetries, not only with strength, but with athletic maneuvers. Athletes who demonstrate side-to-side differences in biomechanical measures during a drop vertical jump are at increased risk of ACL injury when compared to subjects with more symmetrical lower extremity biomechanics.[32] Limb-to-limb asymmetries are evident during drop landing[19] and drop vertical jump[71] in patients following ACL reconstruction. Addressing side-to-side differences may decrease risk of injury once athletes are allowed unrestricted return to sport following ACL reconstruction. Thus we assess an athlete's ability to demonstrate symmetry (within 10%) with vertical ground reaction force during a drop-landing maneuver at this stage of progression for return-to-sport rehabilitation.

While the T-test is standard for the assessment of agility,[29,72,86] it may not adequately measure side-to-side differences due to the equalization of cutting directions in performance of the test. For this reason, the modified agility T-test was developed. The modified agility T-test may more accurately identify the differences between an athlete's involved and noninvolved side than the standard T-test. This modification to the standard T-test incorporates four 90° cuts isolated to a single direction during the trial. This modification is aimed to isolate involved-side deficits during a multidirectional agility test. Agility testing similar to the MAT can provide high retest reliability ($r$ = 0.94-0.98).[72] The goal of this test is for the athlete to attain a 10% symmetry in the time taken to complete the task.

The ability to generate and maintain single-limb power is important during single-limb cutting maneuvers in sport. Also, improved ability to attenuate force on a single limb and to regenerate and redirect motion may be relevant to a reduction in injury risk in various single-limb positions in sports.[47,56,67] The single-limb average peak power test for 10 seconds, which can be used to measure single-limb ground reaction force attenuation and force generation, may be useful to identify athletes who are prone to injury and possible reinjury after ACL-reconstruction.[32,48,67] To execute this test the athlete performs a single-limb vertical hop for 10 seconds and the average of the peak power generated during push-off for each jump is calculated. The single-limb power hop for 10 seconds demonstrates high within-session ($r = 0.97$) and moderate between session reliability ($r = 0.76$).[23] Athletes following ACL reconstruction demonstrate deficits up to 20% or more on their involved limb.[70] We recommend that athletes achieve 85% or better side-to-side symmetry in the average force production to progress beyond this stage of rehabilitation. Athletes unable to perform the single-limb power hop with symmetry (greater than 15% deficit) may be affected by residual pain or strength deficits that warrant further rehabilitation prior to re-entry into sport activities.[70]

## Return to Sport

Once athletes meet the stage 4 criteria, they should be prepared to leave therapy and begin reintegration into their respective sports. However, we do not suggest that this is the time for unrestricted full participation in competitive events; rather, it is suggested that athletes resume practice activities and begin to prepare themselves for competitive play. Return to sport following ACL reconstruction can be a high-risk period for athletes after ACL reconstruction because of both the risk of graft failure and the increased risk of injury to the contralateral limb, which may be higher than the involved side.[30,82] Retear rates may reach as high as 20% in young patients.[81] There is also the potential for long-term osteoarthritic changes that occur in the majority of both ACL-deficient and ACL-reconstructed knees.[60] Successful execution of the suggested criteria of return-to-sport training may more objectively determine an athlete's readiness to return safely to sports participation and indicate that dynamic restraints are sufficient to limit both pathologic gross motion and micromotion in both the involved and uninvolved knee joint. Systematic progression through these objective testing protocols may provide the athlete with both increased neuromuscular control and in-
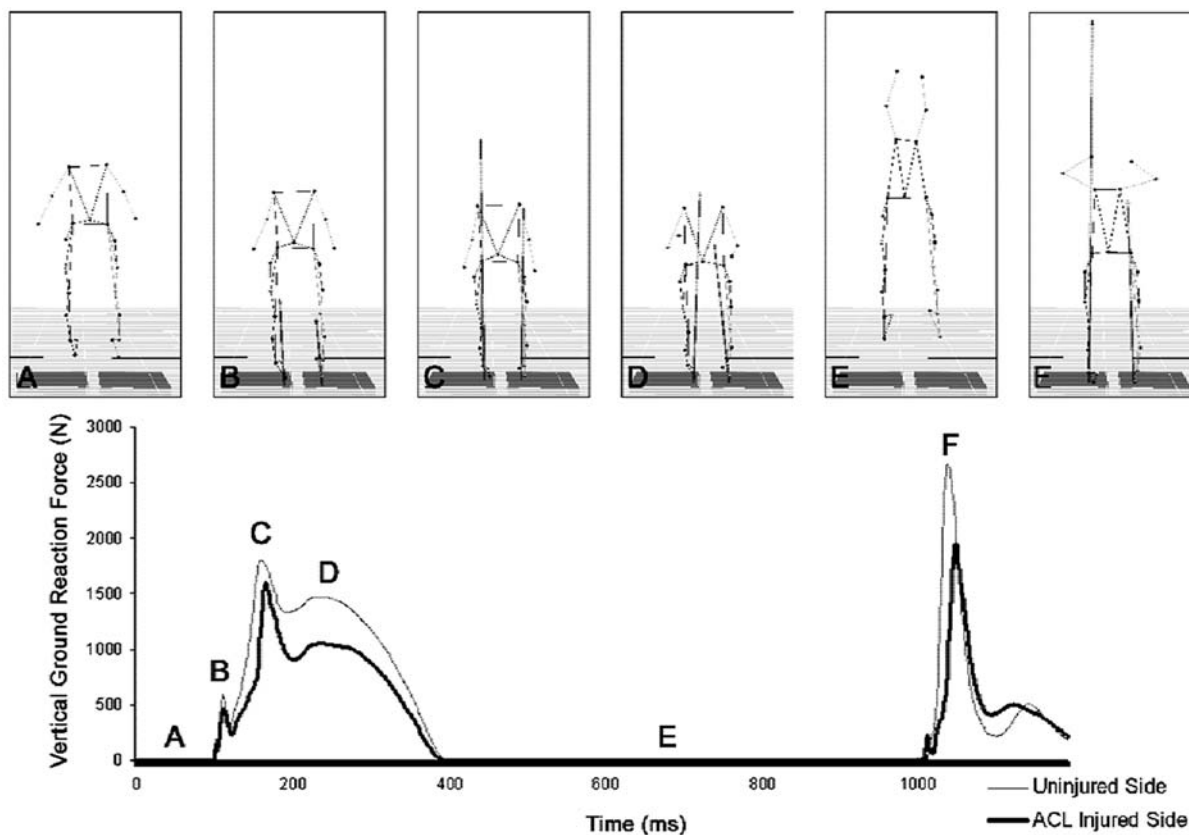


**FIGURE 6.** Example of a patient post ACL reconstruction performing a drop-vertical jump maneuver. Image sequence on the top shows the higher ground reaction forces on the uninjured side (right) at specific time points. Two force curves (right and left side) over time are displayed on the bottom. Force measures are customarily taken from the first initial contact, but the second landing can also be analyzed for a more in-depth analysis.
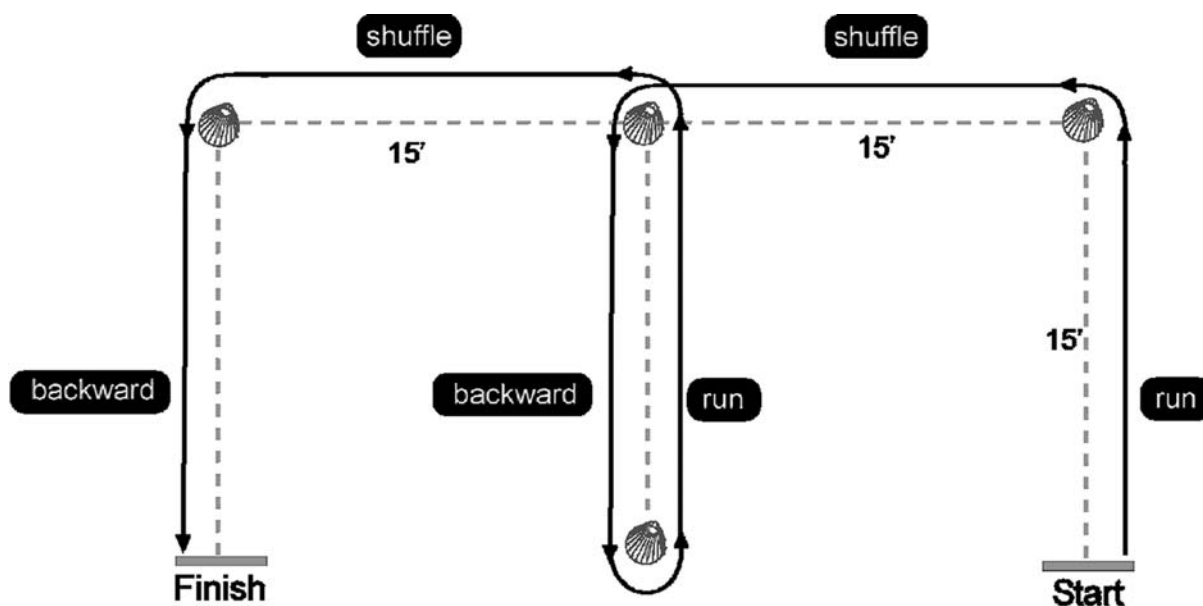
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**FIGURE 7.** Layout of modified agility T-test (MAT) used as part of a progression criteria back into interval sport activities. Athlete should perform the maneuver from each direction by starting from the finish line and repeating the pattern.

creased confidence, which will facilitate successful and safe return to sports after ACL injury.[16,45]

## Limitations of Applying These Protocols to a Standard Practice

Further study is required to determine the clinical relevance, reliability, validity, and long-term outcomes of this algorithmic approach to the return-to-sport phase of rehabilitation. Measurement of the described criteria for transition to each subsequent stage in the return-to-sport phase requires the utilization of equipment that may not be available in the majority of sports medicine clinics. Future research may provide evidence as to whether or not less equipment-intensive return-to-sport algorithms are

warranted. The stringent exit criteria are designed to ensure adequate strength, power, agility, symmetry, and stability prior to participation in high-risk activities. Ultimately, this can translate into successful return to sports; however, long-term outcome studies are necessary to validate the described criteria based progression to return to sport.

## CONCLUSION

Late-phase rehabilitation following ACL reconstruction without criteria-based guidelines may allow for deficits in lower extremity proprioception, strength, and ground reaction force attenuation and production to persist beyond rehabilitation
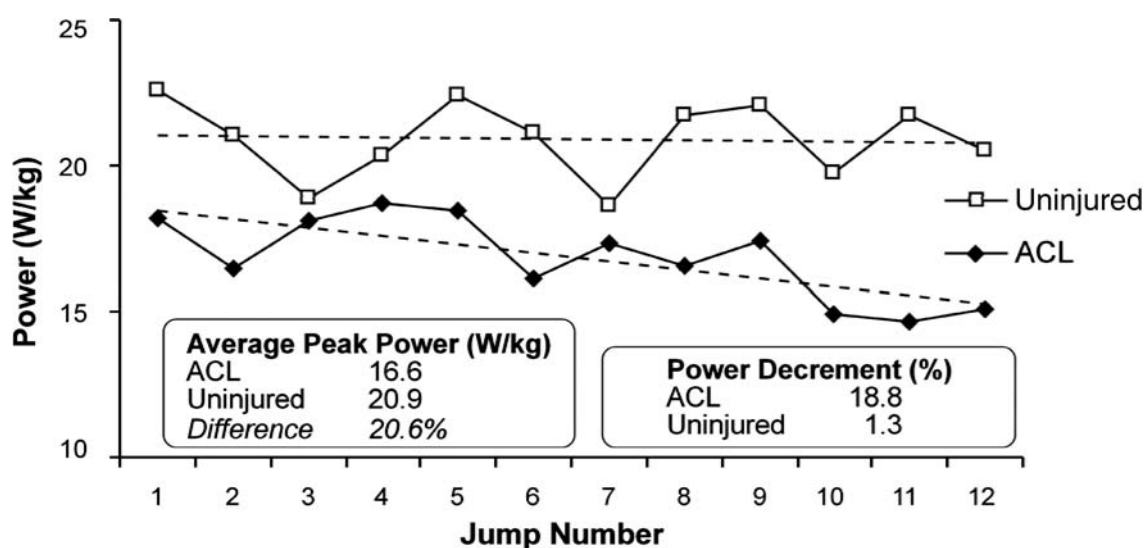


**FIGURE 8.** Example of an actual single-limb vertical jump power degradation over time for an athlete in ACL return-to-sport training. Athlete starts the trial standing on a single limb and repeatedly executes maximum vertical hops for 10 seconds.

phases.[1,19,33,40,62,71] These deficits may transfer into competitive play and increase the risk of reinjury or limit the achievement of optimal performance levels. The developed algorithm has the potential to identify postsurgical deficits and address them through systematic progression throughout the stages of the return-to-sport phase of rehabilitation. This approach may improve the potential for athletes to return to sport at optimal performance and minimal risk of reinjury.

## ACKNOWLEDGEMENTS

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# Appendix 1

## IKDC Subjective Knee Evaluation Form

First Name _____ Last Name _____ Today's Date _____ Date of Injury _____ Side of Injury  R   L

SYMPTOMS(*): (*)Grade symptoms at the highest activity level at which you think you could function without significant symptoms, even if you are not actually performing activities at this level.

1. What is the highest level of activity that you can perform without significant knee pain?

- ❑ Very strenuous activities like jumping or pivoting as in basketball or soccer
- ❑ Strenuous activities like heavy physical work, skiing or tennis
- ❑ Moderate activities like moderate physical work, running or jogging
- ❑ Light activities like walking, housework or yard work
- ❑ Unable to perform any of the above activities due to knee pain

2. During the past 4 weeks, or since your injury, how often have you had pain?

|  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Never | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | Constant |

3. If you have pain, how severe is it?

|  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No pain | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | Worst pain imaginable |

4. During the past 4 weeks, or since your injury, how stiff or swollen was your knee?

- ❑ Not at all
- ❑ Mildly
- ❑ Moderately
- ❑ Very
- ❑ Extremely

5. What is the highest level of activity you can perform without significant swelling in your knee?

- ❑ Very strenuous activities like jumping or pivoting as in basketball or soccer
- ❑ Strenuous activities like heavy physical work, skiing or tennis
- ❑ Moderate activities like moderate physical work, running or jogging
- ❑ Light activities like walking, housework or yard work
- ❑ Unable to perform any of the above activities due to knee swelling

6. During the past 4 weeks, or since your injury, did your knee lock or catch?     ❑ Yes     ❑ No

7. What is the highest level of activity you can perform without significant giving way in your knee?

- ❑ Very strenuous activities like jumping or pivoting as in basketball or soccer
- ❑ Strenuous activities like heavy physical work, skiing or tennis
- ❑ Moderate activities like moderate physical work, running or jogging
- ❑ Light activities like walking, housework or yard work
- ❑ Unable to perform any of the above activities due to giving way of the knee

8. What is the highest level of activity you can participate in on a regular basis?

- ❑ Very strenuous activities like jumping or pivoting as in basketball or soccer
- ❑ Strenuous activities like heavy physical work, skiing or tennis
- ❑ Moderate activities like moderate physical work, running or jogging
- ❑ Light activities like walking, housework or yard work
- ❑ Unable to perform any of the above activities due to knee

9. How does your knee affect your ability to:

| | | Not difficult at all | Minimally difficult | Moderately difficult | Extremely difficult | Unable to do |
|---|---|---|---|---|---|---|
| a. | Go up stairs | ❑ | ❑ | ❑ | ❑ | ❑ |
| b. | Go down stairs | ❑ | ❑ | ❑ | ❑ | ❑ |
| c. | Kneel on the front of your knee | ❑ | ❑ | ❑ | ❑ | ❑ |
| d. | Squat | ❑ | ❑ | ❑ | ❑ | ❑ |
| e. | Sit with your knee bent | ❑ | ❑ | ❑ | ❑ | ❑ |
| f. | Rise from a chair | ❑ | ❑ | ❑ | ❑ | ❑ |
| g. | Run straight ahead | ❑ | ❑ | ❑ | ❑ | ❑ |
| h. | Jump and land on your involved leg | ❑ | ❑ | ❑ | ❑ | ❑ |
| i. | Stop and start quickly | ❑ | ❑ | ❑ | ❑ | ❑ |

## FUNCTION:

10. How would you rate the function of your knee on a scale of 0 to 10 with 10 being normal, excellent funtion and 0 being the inability to perform any of your usual daily activities which may include sports?

Function prior to your knee injury:

|  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cannot perform daily activities | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | No limitations in daily activities |

Current function of your knee:

|  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cannot perform daily activities | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | No limitations in daily activities |

**Scoring Instructions for the 2000 IKDC Subjective Knee Evaluation Form**

The responses to each item are scored using an ordinal method such that a score of 1 is given to responses that represent the lowest level of function or highest level of symptoms. For example, item 1, which is related to the highest level of activity without significant pain is scored by assigning a score of 1 to the response "Unable to Perform Any of the Above Activities Due to Knee" and a score of 5 to the response "Very strenuous activities like jumping or pivoting as in basketball or soccer". For item 2, which is related to the frequency of pain over the past 4 weeks, the response "Constant" is assigned a score of 1 and "Never" is assigned a score of 11.

The IKDC Subjective Knee Evaluation Form is scored by summing the scores for the individual items and then transforming the score to a scale that ranges from 0 to 100. **Note**: The response to item 10 "Function Prior to Knee Injury" is not included in the overall score. The steps to score the IKDC Subjective Knee Evaluation Form are as follows:

1.  Assign a score to the individual's response for each item, such that lowest score represents the lowest level of function or highest level of symptoms.
2.  Calculate the raw score by summing the responses to all items with the exception of the response to item 10 "Function Prior to Your Knee Injury"
3.  Transform the raw score to a 0 to 100 scale as follows:

$$\text{IKDC Score} = \left[ \frac{\text{Raw Score} - \text{Lowest Possible Score}}{\text{Range of Scores}} \right] \times 100$$

Where the lowest possible score is 18 and the range of possible scores is 87. Thus, if the sum of scores for the 18 items is 60, the IKDC Score would be calculated as follows:

$$\text{IKDC Score} = \left[ \frac{60 - 18}{87} \right] \times 100$$

$$\text{IKDC Score} = 48.3$$

The transformed score is interpreted as a measure of function such that higher scores represent higher levels of function and lower levels of symptoms. A score of 100 is interpreted to mean no limitation with activities of daily living or sports activities and the absence of symptoms.

The IKDC Subjective Knee Score can still be calculated if there are missing data, as long as there are responses to at least 90% of the items (i.e. responses have been provided for at least 16 items). To calculate the raw IKDC score when there are missing data, substitute the average score of the items that have been answered for the missing item score(s). Once the raw IKDC score has been calculated, it is transformed to the IKDC Subjective Knee Score as described above.

**Adapted from:** Irrgang JJ, Anderson AF, Boland AL, et al. Development and validation of the international knee documentation committee subjective knee form. *Am J Sports Med* 2001;29(5):600-13.

CLINICAL COMMENTARY

# Appendix 2

Athletes perform repeated tuck jumps for 10 seconds while the clinician scores the performance for each category on the visual analog scale. Each category is measured in centimeters from the NEVER (0 score) to the ALWAYS (10 score) with each incremental increase (1 cm) towards ALWAYS equal to 1 point increase in their score. Scores for each category are summed to provide the total score for the assessment. The scores will range from 0 to 80 total points.

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**Tuck Jump Assessment**

## KNEE AND THIGH MOTION

(1) KNEES NEUTRALLY ALIGNED AT LANDING
NEVER                                    ALWAYS

(2) THIGHS REACH PARALLEL (Observed at highest point of jump)
NEVER                                    ALWAYS

(3) THIGHS EQUAL SIDE-TO-SIDE (Throughout sequence)
NEVER                                    ALWAYS

## FOOT POSITION

(4) FOOT PLACEMENT SHOULDER WIDTH APART
NEVER                                    ALWAYS

(5) FOOT PLACEMENT NOT STAGGERED (Side view)
NEVER                                    ALWAYS

(6) TOE-TO-MIDFOOT ROCKER UTILIZED (No heel strike)
NEVER                                    ALWAYS

## PLYOMETRIC TECHNIQUE

(7) RAPID REBOUND BETWEEN JUMPS (No visible delay)
NEVER                                    ALWAYS

(8) LANDS IN SAME FOOTPRINT (From point of take-off)
NEVER                                    ALWAYS

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