Module 1. Force Diagnostics

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Force or strength and power (S & P) diagnostics in the context of rehabilitation and return to sport (RTS) refers not to the diagnosis of injury but to the assessment of range of strength or "neuromuscular" performance qualities related to force production (Taberner et al., 2020). Substantial declines in a range of neuromuscular performance qualities are observed following injury. These declines are driven by tissue damage secondary to the injury and potentially associated surgery, as well as deconditioning secondary to the reduction in loading normally associated with intense training and competition. The purpose of S & P diagnostic assessments with force platforms and technology goes beyond defining athlete status or recovery, it is information that should inform and influence reconditioning programs during the rehab pathway. Hence the concept of diagnostics - to profile status in a way that moves us more towards precision medicine in terms of exercise prescription, based on specific deficits identified.

Residual deficits / persistent interlimb asymmetries

Restoration of neuromuscular function is one of the primary goals of rehabilitation following anterior cruciate ligament reconstruction (ACL-R), and following injury per se (Palmieri-Smith et al., 2008). While the focus of this module is the use of the neuromuscular performance assessment during rehabilitation and RTS following ACL-R, a number of the concepts and fundamental principles apply to athlete assessment during recovery from all injuries.

As the majority of studies, and practitioners, do not have preinjury athlete assessments, injury-induced "deficits" are not strictly deficits i.e. with respect to the preinjury neuromuscular performance data for the injured limb, they are actually interlimb asymmetries (ILA) in a specific neuromuscular quality. Therefore, it is the performance of the healthy limb that is used to quantify the performance deficit in the injured limb. We later discuss the disadvantages of using ILA as a marker of status and the degree to which this data may mislead. Notwithstanding this limitation, persistent ILA in quadriceps muscle mass, peak strength and rate of force or torque development and activation (Maestroni et al., 2021; Thomas et al., 2015) are reported not only in non-athletic populations after rehabilitation and return to normal activities but also in high performance / professional athletes following full-time care in rehabilitation and RTS and competition (Jordan et al., 2015; Maestroni et al., 2021). One of the principal risk factors for an injury is prior injury (Cronström et al., 2021), and conceptually, biomechanical and neuromuscular deficits/asymmetries consequent to the primary injury are a modifiable component of that association. Furthermore, neuromuscular-biomechanical alterations have been shown to be associated with an increased risk of an injury to the same tissue (Hewett et al., 2005; King et al., 2021a) or elevated risk to other tissues at joints in the same or contralateral limb (Opar & Serpell, 2014; King 2021b). The

latter is thought to be driven by compensatory loading and movement patterns secondary to alterations resulting from the initial injury leading to repeated overloading and force application on the uninvolved limb (Read et a., 2020).

Before we turn to the S & P diagnostic tools of this course - isokinetic dynamometry in this module, force platforms in module 2 and kinematics in module 3 - it is important to briefly consider assessments on the other end of the spectrum in terms of access and practicality, cost and time-efficiency. As highlighted in Course 1, it is important to understand what simple output measures do and more importantly, don't give us, to put a value on the information gain provided by tools such as force platforms. In settings without access to S&P diagnostics, the staples of clinical, "functional" testing and return to sport (RTS) criteria following anterior cruciate ligament (ACL) reconstruction (ACL-R) are the single leg horizontal hop and its variations - single hop for distance, triple hop for distance, crossover hop for distance and 6-m timed hop. The full battery or as few as 1 of these components have become are - particular. Limb symmetry indexes (LSI) are calculated based on distance/time in the injured versus uninjured limb and an LSI greater than 85% (Petschnig et al., 1998) or 90% (Grindem et al., 2016) a criterion for "passing" the test and RTS following ACLR.

What underlines the value of kinetics derived from S & P diagnostic tests and kinematics is that a number of recent studies (Kotsifaki et al., 2022) and reviews (Davies et al., 2020; Kotsifaki et al, 2020) strongly challenged the concept that hop tests adequately quantify knee function/deficits post-ACL-R. This is fundamental because, post-ACL-R individuals show large biomechanical/neuromuscular deficits in the hop takeoff and landing despite having low asymmetry in hop distance and passing LSI criteria. For example, Kotsifaki et al., (2022) reported that a post-ACLR cohort achieved 97% triple hop distance symmetry but only between 51% and 66% limb symmetry for knee work in the first and second rebound, respectively. The near symmetry in hop distance was achieved with significant hip joint compensation and large compensatory strategies in the trunk and pelvis. This higher force production at the hip via increased hip flexion, which compensates for and enables avoidance of knee loading/contribution, is one of the most common of these strategies in hop tests underlying symmetry despite far less recovery of knee function (Wren et al., 2018; Kotsifaki et al, 2020). Indeed, Wren et al found that in patients post-ACLR larger hop asymmetries were related to a greater dependence on compensation at the ankle than the hip not on better knee function i.e. kinematic analysis of hops showed both those with and without hop distance symmetry off-loaded the ACLR knee. An asymmetrical hop distance was associated with a dominant ankle strategy while symmetry was associated with a hip-dominant strategy. Kotsifaki et al., (2021) also highlighted the lower knee contribution to the hop compared to that of single jump vertical jumps and single leg drop jumps and better association of these tests with knee function that with the hop. Lastly, hop distance symmetries of 92-94% are reported at 8 months post-ACL-R when isokinetic slow speed (60 degrees per second) quadricep strength symmetry was 73% (Nagai et al., 2020). Therefore, hop tests appear to overestimate knee function recovery at RTS, and overreliance on these criteria potentially

contributes to the review finding that cohorts achieving these limb symmetry index LSI criteria also show a relatively poor rate of return to competitive sport, indicating an inadequate association with RTS success (Ardern et al. 2011).

ACL injury

Anterior cruciate ligament (ACL) ruptures are devastating injuries which in the vast majority of athletes returning to multi-directional sports will result in surgical reconstruction (ACL-R). While its prevalence relative to the most common injury in team sports – hamstring strains – is not high (Dodsen et al., 2016), the biomechanics and kinetics of post-ACL-R athletes are one of the most thoroughly researched injuries. This is due to the severity of the injury – in terms of short- and medium-term consequences of time loss, with typical return to sport (RTS) timeframes and the longer-term impact on performance/careers as well as future joint health (Von Porat et al., 2004). In some cases, the injury can be career ending and athletes never return to the same level of play or performance (Dodson et al., 2016). In the longer term, athletes with ACL-R are at a higher risk of early patellofemoral and tibiofemoral osteoarthritis (Øiestad et al., 2009; Von Porat et al., 2004).

ACL rupture commonly occurs between 40 and 50 ms following initial contact during weight acceptance in the early phase of deceleration movements (Krosshaug et al., 2007; Koga et al., 2010) and results from loading on the ligament exceeding its critical capacity (Shultz et al., 2015). In soccer, the vast majority of ACL injuries occur during matches where the injury rate is 20-fold higher than during training (0.340 vs 0.017 per 1000 playing hours) (Walden et al., 2016). Rupture most commonly occurs in non-contact situations during a deceleration load on the limb (Walden et al., 2015), the majority during a change-of-direction, intense decelerations or landings (Beaulieu et al., 2023).

Females have a much higher risk of sustaining an ACL injury with female athletes involved in pivoting, cutting and jumping sports having two- to three-fold higher risk of ACL injury compared to their male counterparts at the same level of exposure. The incidence of ACL ruptures has been reported as 0.081 per 1000 athlete exposures (practice or game) in females and 0.052 per 100 athlete exposures in males across a variety of high school sports (Gornitzky et al., 2015) while a 2.67 average female to male injury ratio was reported in a meta-analysis (Ekstrand et al., 2011). Female athletes in sports such as soccer, basketball and lacrosse show the highest incidence rates, with incidences of 0.148, 0.091 and 0.070 per 1000 athlete exposures respectively (Gornitzky et al., 2015). The highest incidence rates amongst male athletes are reported in sports such as American football, lacrosse and soccer with incidences of 0.89, 0.58 and 0.40 per 1000 athlete exposures respectively (Gornitzky et al., 2015).

Athletes who undergo ACL-R are at a higher risk of suffering another ACL injury either to the same limb or the opposite limb with the incidence of a second ACL injury ranging from 15-23% and the ACL injury incidence rate is six times higher when compared to uninjured athletes (Hewett et al., 2016). In younger adults (< 25 years old), 1 in 5 will sustain either a graft rupture

or a contralateral ACL injury in the first few years after returning after ACLR (Wiggins et al., 2016). The incidence of contralateral (opposite side) ACL injury is reported to be twice as high (11.8%) when compared to ipsilateral (same side) re-ruptures (5.6%) (Wright et al., 2011). This suggests that changes to an athlete's biomechanics/neuromuscular status post-ACLR may, in part, contribute to this increased risk of reinjury with the increased mechanical loading of the contralateral limb a consistent finding (Baumgart et al., 2017a; Paterno et al., 2007;), and suspected contributor to this pattern of reinjury.

A primary ACL injury can be repaired in multiple graft types, the most common of which is the bone patella tendon bone (BPTB) and hamstring tendon and gracilis grafts (HT). More recently, there is increasing use of the quadriceps tendon. Still, it remains less common, and the majority of published epidemiological and biomechanical/kinetic data is based on BPTB and HT graft data. The pattern of risk of 2nd ACL differs substantially between these graft types with a higher risk of ipsilateral re-rupture observed after HT (Samuelsen et al., 2017) and a higher incidence of contralateral rupture following the BPTB (Thompson et al., 2016). Note that studies describing neuromuscular/biomechanical studies have not generally reported graft type differences/asymmetries or other variables according to graft type, but recent work specifically examining this have shown significant differences in kinetic outcomes (Costley et al., 2021), as discussed in module 2 of this course.

Healing rates vary following ACL rupture and reconstruction. The ligament graft, hamstring or patella tendon goes through ligamentization, a three-phase process of, early, remodelling and maturation which can take varying amounts of time, depending on graft type and individual response. Multiple studies have shown that at approximately 6 months, a considerable amount of revascularization remains, but that this process stabilises between 9-12 months and at 24 months the ligament is fully matured (Landsdown et al., 2019; Cleas et al., 2011) – this healing timeline has implications regarding the timing of strength & power diagnostic test introduction. However, as discussed below, the rate of recovery of neuromuscular characteristics varies quite widely, even in professional athletes exposed to full-time rehabilitation (Taberner et al., 2020). Therefore, milestones/criteria of time and lack of pain, while important, alone are not adequate criteria for progression / RTS. Furthermore, the high-performance athlete is often under pressure to early return. As described, clinical measures of global “function” such as the hop for distance do not appear to be sensitive enough indicators of progress/recovery in underlying neuromuscular/biomechanical deficits or accurately reflect knee function, the practitioner will need to use S&P diagnostics/kinetics – and kinematics to provide information and direction to address deficits or asymmetries / aberrant patterns of movement.

The role of kinetics in ACL rehab can be summarised as:

- Test the rehabilitation status of the athlete
- Inform the training prescription, content and targets of the rehabilitation

- Assess individual response to loading
- Objective criteria for RTS

Figure 1: The role of kinetics in ACL rehabilitation.

Source: Prepared by the author.

Isokinetic dynamometry

In this module we will focus on the role of kinetics in informing rehabilitation and RTS post-ACL-R derived from isokinetic dynamometry and refer to published evidence, the author's experience in assessing and in the rehabilitation of hundreds of post-ACL patients at the Sports Surgery Clinic (SSC) - Dublin.

While we place great emphasis on the tracking of the individual athlete's response, the availability of kinetic data for healthy athletes in a population can also provide us with a proxy benchmark/profile of the healthy athlete in that sport for comparison with the injured athlete for whom true benchmark data (preinjury healthy values for the limb) is not available. Therefore, we have several means of qualifying status (in addition to observing their trends) at every stage of the rehabilitation, reference to:

1. Their benchmark data, if available.
2. The injured limb used as a reference limb to determine interlimb asymmetry (ILA).
3. Normative data for their sport and level.

Isokinetic dynamometry

Isokinetic dynamometry testing (IKD) is widely considered the gold standard method of measuring isolated joint force production and strength testing, because of its reliability and reproducibility, at least at lower speeds and in the concentric mode. Due to these factors as well as to the involvement of the knee joint in the ACL injury and potentially in its consequences (i.e. the use of either patella or hamstring in the repair), IKD knee extension-flexion testing is a traditionally sought component of an RTS battery, used to assess the injury and deconditioning induced deficits.

Isokinetic dynamometers allow for unilateral joint testing (and training) isometrically (at one angle) or dynamically (in full or specific ranges). Joint moment and force production (torque) across the range of motion used is measured at pre-set velocities. In athletes' post-ACL-R, quadriceps and hamstring peak torque (the highest torque achieved at any point across the range of motion) –i.e. maximum strength– deficits are commonly reported and are associated with an increased risk of injury and re-rupture (Kyritsis et al., 2016).

Figure 2: Patient being prepared for knee extension assessment on an isokinetic dynamometer

Deficits in force production are associated with altered kinematics and movement strategies (Palmieri-Smith et al., 2015) and large asymmetries in landing kinetics and kinematics (Schmitt et al., 2015), patterns that may predispose to reinjury or secondary muscular injury (Kyritsis et al., 2016). Despite this data underlining the importance of achieving recovery of IKD quadricep strength in relation to reducing reinjury risk, it is reported that as few as 23-48% of people achieve the proposed target of >85-90% of the quadriceps strength of the contralateral limb (i.e. limb symmetry index) post ACLR (Kyritsis et al., 2016; King et al., 2021).

Therefore, adequate emphasis on the development of strength in these muscle groups and monitoring to ensure this is achieved are highly relevant courses of action to re-injury risk. Evidence indicates that those who do not meet key RTS criteria, (which were IKD PT tests < 10 % asymmetry; hops < 10% asymmetry; and performance of an agility t-test in < 10 s) were up to 4 times more likely to be re-injured, and that those with greater than 10% asymmetry were more likely to go on to contralateral re-rupture (Hewett et al., 2019; Webster et al., 2019; Paterno et al., 2019). Achieving an IKD quadricep limb symmetry index (LSI) of <90% was associated with significantly lower risk of subsequent knee injury in 2 year prospective study (Grindem et al., 2016). In addition, increased levels of quadriceps strength post ACLR have been shown to correlate with reduced risk of future knee osteoarthritis and specifically patellofemoral joint osteoarthritis (Øiestad et al., 2015; Culvenor et al., 2013).

IKD and ACL-R

Dynamic IKD testing can be conducted at a range of speeds in concentric and eccentric contraction modes, of which the most commonly used are 60 degrees per second (°/s), 180°/s, and 300°/s. While it is certainly of interest to test across a range of speeds to determine potential differences in capabilities across the force velocity spectrum, this has meant that research is replete with varied protocols and there is a lack of consensus on the best protocol. Although the principle "fixed" time cost of IKD assessments is the initial set-up of the athlete on the device, these tests take substantially more time than jump-land or isometric lower extremity tests - 10-15 mins to perform both limbs. Another limitation on obtaining a large number of contraction modes/muscle groups is that while in theory, one can collect agonist-antagonist data (e.g., concentric quads in one direction and concentric hams in the other, so that after 5 reps one has both), there are issues with using the dynamometer in this way (as discussed below) that also limit the implementation of these potentially time saving protocols. In addition, there are concerns with the variability/reliability of even peak torque and delay in achieving stable isokinetic velocity at these higher speeds (such as 180°/s and 300°/s), which undermine the validity of early angle-torque data, particularly in individuals with little prior experience/familiarity with the assessment (most individuals). Because of these potential reliability issues and the aim of assessing maximal strength with this test, the most commonly utilised concentric quadriceps and hamstring testing at 60◦/s may, on face value, be less "functional" due to the slower speed, when the aim is to test maximum dynamic strength, slow speeds which results in higher force outputs are recommended, showing better reliability and validity (ICC: 60°/s: 0.93 vs 180°/s: 0.43) (O'Malley et al., 2018; Undheim et al., 2015; Whilite, 1992). Note that these values refer to assessments in injured individuals without multiple testing sessions and, in our experience, they do improve with experience. Nonetheless, given that jump-land tests (using force platforms) effectively assess strength-speed qualities via force application and reduction at higher velocity and lower load and in triple extension (Treddinick, 1998; Steiner, 1993), the IKD testing protocol adds value as an isolated measure of maximal dynamic force production. Similarly, despite the valid interest in eccentric quadriceps strength, eccentric

measures have higher variability and lower reliability, especially within repetitions (Tredinnick et al., 1988). Furthermore, due to the reconstruction post ACL-R patients have increased patellofemoral pain, which is more likely to be provoked by the higher load of eccentric tests, and therefore most clinicians choose to utilise concentric testing (Wasserstein et al., 2015, Hart et al., 2020).

IKD torque data is expressed in newton-metres (N.m), and is typically adjusted for body weight (N.m/kg), to allow comparison with other athletes/athletic groups. However, when tracking the individual, absolute values can also be used. While peak torque is the most commonly reported metric from IKD tests, its exclusive use has been criticised on the basis that it describes force production at a single joint angle, which, may not be highly representative of function at differing angles across the range of motion and, in particular, at angles of interest from a performance and risk perspective (Hart et al., 2022). Indeed, recent research has shown additional diagnostic value provided by an examination of the full torque –angle curve, as discussed below.

H:Q Ratios

Another widely reported IKD metric in ACL risk and rehabilitation literature is the ratio of peak torques in the hamstrings and quadriceps (H:Q ratio) (Kellis et al., 2022). Mechanistically, as the quad increases ACL loading and through anterior translation of the femur on the tibia, the hamstrings can act as balance against this with co-contraction having been shown to prevent excessive anterior tibial translation (Yanagawa et al., 2002). Furthermore, there is consistent evidence that H:Q is significantly altered in ACL deficient and reconstructed patients (Kyritsis et al., 2016), with an important graft type influence, i.e. significantly higher H:Q ratios following BPTB grafts (Fischer et al., 2018) and the reverse following HT. Research suggests that at RTS, an H:Q ratio > 60% (0.6) is associated with lower risk (Kyritsis et al., 2016), a target more likely to be achieved following a BPTB graft, however due to the impairment of the quadricep strength as a consequence of graft harvest rather than because of higher hamstring strength. Following HT grafts achieving this H:Q target is more challenging, as semitendinosus-gracilis graft harvest leads to substantial loss of neuromuscular performance in the hamstrings. H:Q ratios have been reported to be often less than 50% even at the common RTS time point of 9 months (REF). Therefore, there is a high priority for early targeted hamstring (re)conditioning from around 3 months (once the graft can be loaded) and it should be highly emphasised across rehabilitation (Hart et al., 2022).

Whilst H:Q ratios are different post ACLR, why should we pay attention to them?

Kyritsis et al., (2016) demonstrated that those who had lower H:Q ratios were at a significantly higher re-rupture risk compared to those with higher H:Q ratios. For every 10% decrease in H:Q ratio, there was a 10.6 x higher risk of ACL graft rupture.

Graft specific differences

As mentioned above, knee flexor (hamstring) and extensor (quadriceps) deficits are strongly influenced by graft type, the most common of which are the BPTB and HT. These grafts are generally harvested from the injured limb (Holland et al., 2017), resulting in neuromuscular deficits at the site. Greater quadriceps deficits are observed following in BPTB grafts, particularly in deeper knee angles of 60-95°. In contrast, following HT grafts, hamstring strength deficits are evident throughout the range, but are highest in the inner range (i.e. higher knee angles) (Hart, 2022; Baumgart et al, 2018). The semitendinosus muscle that is harvested is mechanically advantaged in deep knee flexion and, therefore, when it is utilised for the HT graft force production in this range, it is particularly impaired. This leads to an overreliance on the Biceps Femoris (BF) muscle as indicated by altered angle of peak torque (Hart, 2022) and increased cross-sectional area (CSA) in the BF. A consequence of this shift is the recruitment of the BF in a mechanically disadvantageous position – which may partly explain the increased risk of BF injury post ACL-R (Green et al., 2020). Lastly, recovery/development of semitendinosus cross sectional area has been shown to be vital to the recovery of overall knee flexor strength, especially at angles greater than 70° (Tupernein et al., 2020).

BPTB grafts on the other hand have also been demonstrated to be associated with a significantly high level of patellofemoral pain, which can persist for 2 years after surgery. Arthrogenic inhibition is a well documented phenomena, especially in knee trauma and post-knee surgery (Rice & Mcnair, 2010). Arthrogenic inhibition is a process where the quadriceps, specifically, cannot fully activate, particularly if there is joint effusion, which is common in early-stage ACL-R rehabilitation. This causes a significant atrophy of the quadriceps muscle during the early stages of rehabilitation, with reported values of 30% loss of CSA immediately after surgery (Hopkins & Ingersoll, 2000). As anterior knee pain is most often prevalent at deeper knee angles, during rehabilitation following ACL-R with BPTB grafts significant deficits are observed at higher knee angles (Hart et al., 2022), while this is not seen in HT grafts - with smaller asymmetry at 70-85° knee flexion.

Due to these angle-specific effects, Baumgart et al. (2018) proposed phase-specific analysis to characterise hams neuromuscular function and identify deficits which might not be

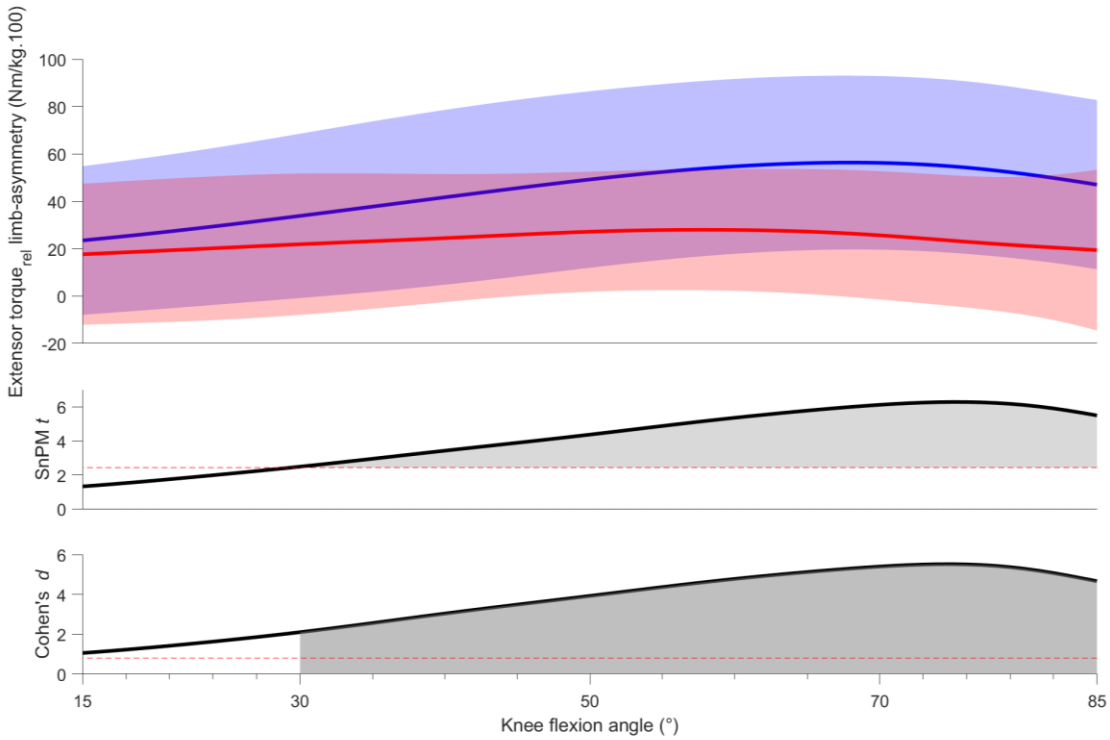
detected by peak torque alone and which might enhance rehabilitation exercise prescription and rehabilitation individualization, facilitating greater specificity of rehabilitation protocols and improved athlete outcomes.

Phase-specific analysis

One-dimensional statistical parametric mapping (SPM) is a valuable method for statistically examining differences between continuous data series. It has been widely used in the analysis of force-time and kinematic data to determine differences of changes across entire movements or phases of interest as an alternative or complement to reporting discrete variables. However, it has been recently applied to the analysis of post ACL-R isokinetic torque data for a single graft type (Baumgart, 2018). This technique has been used to identify differences in angle-specific torque and asymmetry metrics between graft types around the time of RTP, but could enable practitioners to better match the interventions to graft earlier in rehabilitation following BTPB vs HT grafts. In an ACL-R cohort, Hart et al. (2022) showed that while the angle of peak torque (52°) and the angle at which the highest interlimb asymmetry occurs (58°) only differ by 6°, the magnitude of torque asymmetry was significantly different at these two angles (24% @ 52° vs 71% @ 58°). This indicates that by using peak torque alone, angle-specific deficits are missed (not only because a graft-type interlimb asymmetry is underestimated using peak torque alone in both grafts) and that an angle/phase-specific analysis provides a more complete neuromuscular screen and additional insights, which may impact on rehabilitation protocols and RTS (Çınar-Medeni et al., 2019). Interestingly, concentric quadriceps torques at 90° and 60° of knee flexion were more strongly correlated than peak torque with single leg hop (r^2 = 0.22) and vertical jump and reach (r^2 = 0.40), respectively (Çınar-Medeni et al., 2019). This suggests a greater association with sport-specific movements.

Figure 3 shows ILA in concentric quadriceps torque across the range of motion (torque-angle asymmetry) in patients with BPTB versus HT grafts. It demonstrates significant differences in quadriceps torque ILA across the range and large differences in angle of peak asymmetry for the two graft types - BPTB grafts showing highest values at 70-85° while at this range HT tendon graft ILA is decreasing. This further highlights the issues of using peak torque alone and of ignoring graft type differences in reconditioning following ACL-R.

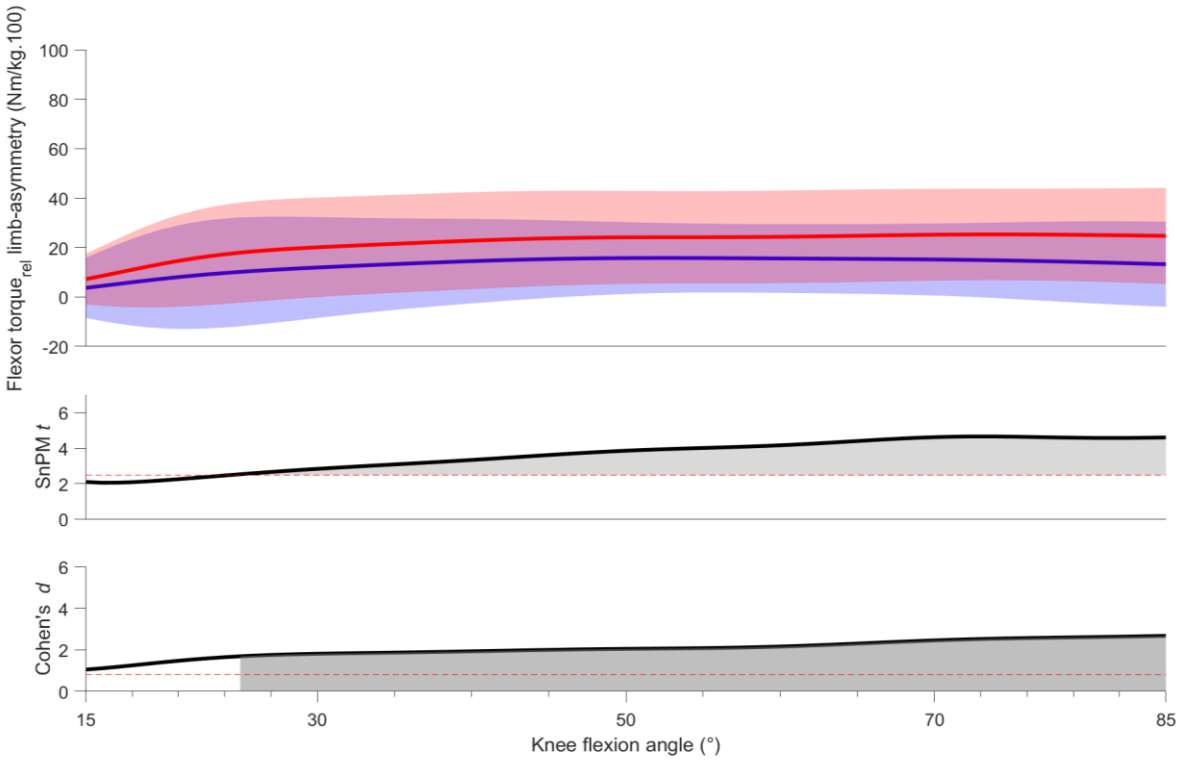
Figure 3: Quadricep (concentric knee extension) asymmetry across the range of motion



Source: Hart et al (2022). Blue line =BPTB graft; Red line=HT graft. Dashed red line is threshold for significance - therefore significant asymmetry is indicated for the area grey within the range of motion (knee flexion angle).

Figure 3 demonstrates the significant difference in hamstring asymmetry at deeper knee flexion angles following HT compared to BPTB grafts. Peak asymmetry for HT graft occurs at 70-85° flexion whilst the muscle's peak torque occurs at quite a different angle 50-60° degrees.

Figure 4: Hamstring (concentric knee flexion) asymmetry across the range of motion



Source: Hart et al (2022). Blue line =BPTB graft; Red line=HT graft. Dashed red line is threshold for significance.

Rehabilitation implications

Data derived from this IKD phase-specific analysis has important implications on the athlete rehabilitation following ACL-R. Following HT grafts, a significant inner range (higher knee flexion) deficit is observed, primarily due to the harvesting of this graft. Furthermore, (Morris et al., 2021; Jordan et al., 2015) highlighted the importance of promoting semitendinosus strength and hypertrophy in order to reduce the workload on the bicep femoris.

Thus, rehabilitation for ACLR HT grafts is important for practitioners to start knee flexion based on hamstring work (hamstring curl, hamstring sliders) early into the rehabilitation, but no earlier than 3 months post-surgery, to protect the graft. This means that conditioning programmes should prioritise these flexion exercises alongside hip-dominant outer range hamstring exercises (Romanian deadlift, hamstring bridge, deadlifts).

Rehabilitation following the BPTB graft should focus on minimising pain and swelling early in the rehabilitation, minimising the effect of arthrogenic inhibition and muscle atrophy and ensuring full muscle activation in early-stage exercises (month 0-2). After this, an emphasis on knee extension and quadriceps strength at greater angles of knee flexion should be a priority. This can be accomplished in multiple ways; however, an example of a continuum of strength exercises targeting 60 - 90° are split squat → deep leg press → single leg wall hold at 90°.

However, the benefits of using a phase-specific approach are that whilst these are the targeted adaptations taken from recent research, a phase-specific approach allows you to personalise and individualise the rehabilitation to a higher level than using peak torque measures alone, which are very limited in their use of rehabilitation prescription, bearing in mind that RTS peak torque targets are still of value.

Limitations of IKD

One of the main limitations on its use is its cost ($50,000 - $100,000), which is prohibitive for most except for the wealthiest pro-sports/institutes. These devices are therefore most commonly housed in universities, colleges, and private medical facilities, and are not portable. Therefore, all practitioners may not have access or limited access. Later in this module, we will outline other alternatives that are available. It is important to be aware of some other limitations/concerns with IKD testing. The first and most commonly cited limitation is that it is a strength test that assesses a single joint in isolation, in a predetermined and controlled range of motion and contraction speed, with a poor relationship to sport-specific movements (Goldman & Jones, 2010). This limitation could equally be cited as the advantage of IK testing relative to more functional, multi-joint, varied range of motion ballistic or plyometric jump and hop tests. Thus, it is imperative to understand the value of a test and its "limitations" in the context of the question about neuromuscular performance. You can expect it to answer, fundamentally, the reasons why you are including the test. However, it is important to realise the value that IKD testing adds to ACLR rehabilitation and the fact that RTS relates to the providing detail of isolated neuromuscular function and angle-specific force production of the muscle impaired by the operation and injury –they should not be used as a sole RTS criteria.

Summary

- Isokinetic testing should principally be utilised to test muscle maximal knee extension and flexion strength in concentric mode at 60°/s due to limitations related to other speeds and modes with features of neuromuscular performance, such as force production at high velocity, eccentric and SSC performance, and multi-joint function examined with other dynamic tests.
- If feasible, quadricep and hamstring IKD testing should be conducted throughout ACLR rehabilitation, with testing at 3, 6, and 9 months after ACLR, with more frequent testing suggested if larger strength deficits are identified.
- Key IKD peak torque should return to sport targets (minimum targets for healthy male and female competitive athletes).
    - Hamstrings and quads asymmetries of <10%
    - Concentric H:Q ratio of >60%
    - Quadriceps >260% BW

- Hamstring >160% BW

- BPTB grafts result in knee extension strength deficits which are largest at greater knee flexion angles while HT grafts (semitendinosus-gracilis). This results in greater hamstring deficits at greater knee flexion angles –following these respective graft types, the rehabilitation process should put additional emphasis on conditioning/strengthening and monitoring of these specific ranges.

Protocol:

Suggested IKD protocol for ACLR is:

- 5-minute bike warmup
- 3 x 5 reps of concentric/concentric knee extension and knee flexion at 60 degs. over 0 - 100 degrees knee flexion.
- 1 set should be warm up and familisation followed by 2 sets of 5 at 100% with strong verbal encouragement.
- If conducting the test prior to 6 months, an ACL brace pad should be utilised to limit tension on the ACLR graft (a pad placed just below tibial tuberosity).
- If using phase-specific analysis, the first and last 10 degs. of the range should be discarded, as often it will not reach >50 degs. isovelocity, which is why it is not reliable.

In ACL research, the IKD has historically been the most common method of assessing lower limb strength and function. As outlined above, there are a number of factors which limit its regular use during rehabilitation. Some of these are practical - its cost, means that for many sporting organizations access is limited to medical or university settings where it is utilized for research as opposed to in strength and conditioning facilities or gyms. The time cost relative to other force platform/jump-land tests also prevents a high frequency of evaluation. And unlike the expansion of tests battery with additional jump-land tests, adding further IKD tests at different joints or speeds is substantially more time consuming and impractical. The maximal nature of IKD testing and resulting fatigue, can interrupt the rehabilitation for up to 24hrs prior to the IKD for accurate testing (O'Malley et al., 2018) which may create some resistance to regular testing. As an open chain exercise at slow speed that bears little relation to the majority of closed chain, high speed multi joint sporting movements and specifically those that most often cause an ACL injury results in practitioners often considering that it lacks "functionality" and may show lack of interest in its use on that basis. One should however be clear on the value of a test for measuring what it is intended – isolated maximal strength with across range data in the flexor and extensor

muscles. This should always be complemented by multijoint testing but should not be rejected on the basis of lack of functionality.

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