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Masterclass

Task based rehabilitation protocol for elite athletes following Anterior Cruciate ligament reconstruction: a clinical commentary

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ABSTRACT

Anterior Cruciate ligament (ACL) injuries are one of the most common and devastating knee injuries sustained whilst participating in sport. ACL reconstruction (ACLR) remains the standard approach for athletes who aim to return to high level sporting activities but the outcome from surgery is not assured. Secondary morbidities and an inability to return to the same competitive level are common following ACLR. One factor which might be linked to these sub-optimal outcomes may be a failure to have clearly defined performance criteria for return to activity and sport. This paper presents a commentary describing a structured return to sport rehabilitation protocol for athletes following ACLR. The protocol was developed from synthesis of the available literature and consensus of physiotherapists and strength and conditioning coaches based in the home country Institute of Sports within the United Kingdom.

1. Introduction

Anterior Cruciate ligament (ACL) injuries are one of the most common and devastating knee injuries sustained whilst participating in sport. ACL reconstruction (ACLR) remains the standard approach for athletes who aim to return to high level sporting activities (Hewett, Di Stasi, & Myer, 2013). Less than half of athletes who undergo ACLR are able to return to sport within the first year post surgery (Ardern, Webster, Taylor, & Feller, 2011), on return around 25% of the athletes returning to sport will have a subsequent second ACL injury (Hui et al., 2011; Leys, Salmon, Waller, Linklater, & Pinczewski, 2012), with the outcomes from second surgery being considerably worse (Spindler et al., 2011). Not only do these athletes returning to sport have a 1 in 4 chance of re-injuring an ACL, but regardless of whether they return to sport or not have a 1 in 2 chance of developing significantly clinical and radiological osteoarthritis (OA) of both the tibiofemoral and patellofemoral joints within 10–15 years (Crossley & Hinman, 2011; Culvenor, Cook, Collins, & Crossley, 2012; Oiestad, Holm, Gunderson, Myklebust, & Risberg, 2010). It would appear despite the advances in surgical technique and rehabilitation that the post-operative problems of these patients are not being fully addressed (Hewett et al., 2013).

Current practice around ACLR rehabilitation is quite disparate and inconsistent due to the lack of clear consistent sequential functional progressions aimed at achieving task specific goals. The current criteria for return to sport are both vague and rely on personal interpretation with the literature lacking empirically based criteria (Schmitt, Paterno, & Hewett, 2012). There is an absence of, or clear criteria for progression within the rehabilitation literature, a typical example would be from Wilk, Macrina, Cain, Dugas, and Andrews (2012) "once satisfactory strength and neuromuscular control has been demonstrated……functional activities such as running and cutting may begin 12 weeks and 16–18 weeks after surgery respectively". Rarely if ever are the terms "satisfactory strength and neuromuscular control" defined. When objective criteria for return to sports such as hop tests and strength symmetry ratios of hamstrings and quadriceps compared to contralateral side, are offered as a minimal standard to achieve, these are clearly not detailed enough when dealing with athletes aiming for return to high level competitive sports after ACLR (Bizzini, Hancock, & Ellizzeri, 2012; Van Grinsven, van Cingel, Holla, & van Loon, 2010). The present criteria used for return to sport would appear to need to be revisited, especially as recurrent injury seems to be an increasing problem (Renstrom, 2013).

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In the absence of clear goals any exercise rehabilitation intervention lacks focus and is likely to be less efficient and effective at returning the athlete both safely and quickly (on time) to sport and with reduced risk of re-occurrence or secondary morbidity. Establishing clear goals should aid both the athlete and the coach in seeing progression during what is a prolonged rehabilitation period, it allows those delivering the rehabilitation to the athlete to progress when targets are being met and hold and/or consolidate when they are not. It also removes the current practice of time based goals which often do not reflect the athlete's functional ability at the time they are reached. An example of this being that often athletes following UK based ACLR post-operative protocols, are not allowed to run in any form until 3 months post-operation. In terms of graft healing and maturation, the often cited reason for determining this figure, this is an irrelevant date (Claes, Verdonk, Forsyth, & Bellemans, 2011; Woo, Abramowitch, Kilger, & Liang, 2006), however this becomes a fixed point in the athlete, coaches, surgeons and rehabilitation specialists minds with the athlete failing if they cannot run at that point and on track if they are running at this time. Yet, as all practitioners realize the ability to return to running successfully is related not to healing time post-operation but on the attainment of a number of task specific skills and functional goals, if rehabilitation is geared toward these then this would allow this the athlete to be "ready when they are ready" and the multitude of intermediate markers will allow the practitioner to know exactly when they can achieve this safely.

In their reflection current issues relating to ACL injury and reconstruction Hewett et al. (2013) commented that the majority of athletes who have ACL reconstruction do not successfully return to sport and even those that do rarely are able to perform at the same level in subsequent seasons after they have returned (Ardern et al. 2011). Often the literature reports outcomes from American collegiate or varsity athletes, though often training full time and receiving full medical and rehabilitative support, these athletes may still not fully represent high performance "professional' athletes.

The data on elite as opposed to varsity or collegiate sport presents a more mixed picture with Busfield, Kharrazi, Starkey, Lombardo, and Seegmiller (2009) reporting only 22% of national basketball association (NBA) players failed to returned to play, but of the 78% who returned, 44% were not performing at the same level, based on match statistics. Similarly, in the national football league (NFL) Shah, Andrews, Fleisig, McMichael, and Lemak (2010) found 63% of players returned to play. In a more detailed analysis of NFL players Carey, Huffman, Parekh, and Sennett (2006) found just under 80% of players returned to sport but this on average took over 12 months, and these players had typically performances deficits in the region of 30% based on match statistical data. In women's professional basketball Namdari, Scott, Milby, Baldwin, and Gwo-Chin (2011) found 78% of players returned to sport, but again there was a significant reduction in a number of sport specific game skill statistics. Athletes in high performance professional sport would appear to return to sport in greater numbers than their counterparts in varsity or collegiate sport, there is insufficient data to comment on the comparative longer term outcomes. But, what appears to be clear is that these athletes even on return to sport do not have the same impact on the games they play.

One of the main reasons for this could be the failure of the athletes to regain their pre-injury neuromuscular function (Paterno et al., 2010; Thomee et al., 2011). In a recent review paper Ardern et al. (2011) concluded that even though 85–90% of athletes obtained normal (or near normal) strength values the return to sport rate was still low. The failure to return may be related to fear of re-injury or lack of confidence with both Lentz et al. (2012) and McCulloch et al. (2012) in a similar group collegiate and varsity athletes reporting these factors to be significant in 50% of patients who failed to return to the same level of sport. Furthermore, with Lentz et al. (2012) finding the other major factor being continued knee symptoms, it may be that the patients' rehabilitation is failing to meet their needs for a complete non-problematic return to sport. This could be either in terms of the components of the rehabilitation programmes, the way they are monitored and progressed or the criteria used to measure aspects such as suitability to return to sport. There seems to be a disconnect between patients self-reported outcomes, rating their performance and their muscle functional capacity (Thomee et al., 2011). This could be because of a lack of sensitivity of the methods currently used in testing muscle function or the need for more exacting and challenging performance tests (Thomee et al., 2011).

Insufficient neuromuscular control during dynamic movements has been suggested to be a major factor in both primary (Hewett et al., 2005; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007) and secondary (post-surgical) (Paterno et al., 2010) ACL injury risk. During various landing and cutting tasks excessive knee abduction moments (Hewett et al., 2005) and frontal plane trunk displacement (Zazulak et al., 2007) have both been predictive of ACL injury. Paterno et al. (2010) found these motion asymmetries and poor movement strategies persisted even following return to sport and were highly predictive of secondary ACL injury. It would appear that rehabilitation needs to be geared at least in part to regaining symmetrical motion and appropriate movement strategies to reduce risk of re-injury and improve function.

The literature around the outcome from ACLR surgery would appear to indicate that a high proportion of athletes do not return to the same level of sport, in the medium term, have increased risk of re-injuring the reconstructed or the contralateral knee and in the longer term of developing osteoarthritis within both the tibiofemoral and patellofemoral joints. It may be in part that these relatively poor outcomes are due to a failure to fully rehabilitate these athletes and assess them with sufficiently rigorous criteria before they pass through the stages of rehabilitation on route to return to sport. Here the failure to rehabilitate could either expose the athlete to deleterious loads they are not physically able to control, not prepared for the demands of the sport so they are physically incapable of returning or alternately the lack of rigor in the testing has left the athlete lacking confidence in their ability to return.

This contention is strongly supported by the literature which indicates that with the rate of return to sport being low, it would suggest that the tests commonly used as criteria to return athletes to unrestricted sports activities are not demanding enough or variables more important for safe return to unrestricted sports activities are not being evaluated post-surgically (Angelozzi et al., 2012; Chmielewski, 2011). Currently, based on objective criteria, there is no consensus as to when athletes should safely return to their pre-injury sport level after ACLR, especially in sports activities that require high levels of dynamic neuromuscular control coupled with power generation and absorption (Angelozzi et al., 2012; Myer, Brent, Ford, & Hewett, 2011; Myer, Paterno, Ford, Quatman, & Hewett, 2006). With this in mind a consensus group was set up representing physiotherapists and strength and conditioning coaches from the United Kingdom Institutes of Sport chaired by a recognized international expert in the field of ACL injury and rehabilitation research. The aim of this consensus group was to develop a robust set of progression criteria and concurrently running rehabilitation guidelines for the management of ACLR patients within the UK Institute of Sport Environment. The specific goal being to agree on a series of generic markers for progression for each of rehabilitation stages along with monitoring tools to assess loading stress on the athlete's knee.

2. Rehabilitation stages

The consensus group identified the following stages for the ACLR patient to progress through in their journey to return to their sport.

- Pre-operative
- Post-operative recovery
- Progressive limb loading
- Unilateral load acceptance
- Sport specific task training
- Unrestricted sport specific training

For each of these phases the group identified key criteria (and specific tests) which were to be achieved prior to the athlete being released to move on to the next rehabilitative phase. Within each of these phases the group also identified typical rehabilitation activities required to achieve these goals.

2.1. Monitoring

Alongside the end of rehabilitation stage criteria, the athlete whilst undertaking the rehabilitation programme needs to be monitored within each session, daily and weekly for certain key performance indicators. These measurements relate to the impact of the rehabilitation exercises on the patients knee, assessing if the knee is becoming stressed by the level of loading. The athlete is monitored continuously both for the effect of the quantity of rehabilitation activity and the quality of performance of the rehabilitation activities.

2.2. Monitoring the effect of rehabilitation exercise load

Pain and swelling can be used to determine exercise progression as these factors will relate to the loading stresses which have been placed on the knee (Myer, Brent, Ford, & Hewett, 2008). Measurement of knee circumference at the patella has been shown to have strong intra-tester reliability and good sensitivity to change (Jakobsen, Christensen, Christensen, Olsen, & Bandholm, 2010); therefore the impact of rehabilitation and activities of daily living are monitored by changes in knee circumference. Jakobsen et al. (2010) showed changes of greater than 1 cm to be clinically significant. In practice the patient measures knee circumference on first rising and at the end of the day, the change in this score (greater than 1 cm) being an indicator of a significant increase in effusion within the knee (Jakobsen et al., 2010). Similarly, pain can be monitored using a 10 point numeric rating scale (0 = no pain, 10 = worst imaginable pain), this has been shown to be sensitive to changes in pain which effect function (Krebs, Carey, & Weinberger, 2007) with a reduction or increase by 1 point being regarded as the minimal clinically important change (Salaffi, Stancati, Silvestri, Ciapetti, & Grassi, 2004). In practice the patient reports pain on first rising and weight bearing, following any and all rehabilitation sessions and prior to going to bed. Any change in score from the previous day is noted and significant increases in post rehabilitation scores (>1) which do not resolve by the evening.

2.3. Monitoring of performance quality; single-leg loading qualitative assessment tool (QASLS)

Insufficient neuromuscular control during dynamic movements has been suggested to be a major factor in both primary (Hewett et al., 2005; Zazulak et al., 2007) and secondary (post-surgical) (Paterno et al., 2010) ACL injury risk. During various landing and cutting tasks excessive knee abduction moments (Hewett et al., 2005) and frontal plane trunk displacement (Zazulak et al., 2007) have both been predictive of ACL injury and so also may relate to increase stress loading and potential graft failure in the ACLR patients. Paterno et al. (2010) found these motion asymmetries and poor movement strategies persisted even following return to sport and were highly predictive of secondary ACL injury.

It would appear that rehabilitation needs to be geared at least in part to regaining symmetrical motion and appropriate movement strategies to reduce risk of re-injury and improve function. In order to carry this out a means of monitoring limb alignment during functional tasks is required. Within the literature limb alignment control has been assessed using what has been regarded as the "gold standard" 3D motion capture (Hewett et al., 2005). These systems although accurate are expensive and the assessments time consuming (Onate, Cortes, Welch, & Van Lunen, 2010), and not practical to use in the clinical environment for monitoring within session performance. This has led a number of authors to develop qualitative means of assessing lower limb alignment (Chmielewski et al., 2007; Crossley, Zhang, Schache, Bryant, & Cowan, 2011; Ekegren, Miller, Celebrini, Eng, & Macintyre, 2009; Onate et al., 2010; Whatman, Hing, & Hulme, 2012).

The findings of these studies have shown their scoring systems to be both reliable (Chmielewski et al., 2007; Crossley et al., 2011; Ekegren et al., 2009; Onate et al., 2010; Whatman et al., 2012) and valid (Ekegren et al., 2009; Onate et al. 2010; Whatman, Hulme, & Hing, 2013) and thus show considerable promise when assessing patients. To date these qualitative scoring systems have either assessed bilateral drop jumps (Ekegren et al., 2009; Onate et al., 2010; Padua et al., 2009) or single-leg squatting (Chmielewski et al., 2007; Crossley et al., 2011; Whatman et al., 2012), with

Qualitative analysis of single leg loading

Date: Patient:

Condition: Left Right Bilateral

QASLS	Task: Single leg squat Single leg step down Single leg hop for dist	Left	Right
Arm strategy	Excessive arm movement to balance		
Trunk alignment	Leaning in any direction		
Pelvic plane	Loss of horizontal plane		
	Excessive tilt or rotation		
Thigh motion	WB thigh moves into hip adduction		
	NWB thigh not held in neutral		
Knee position	Patella pointing towards 2nd toe (noticeable valgus)		
	Patella pointing past inside of foot (significant valgus)		
Steady stance	Touches down with NWB foot		
	Stance leg wobbles noticeably		
	Total		

Fig. 1. Qualitative scoring sheet for all single-leg loading tasks.

none assessing single-leg landing tasks or using a single system to assess diverse tasks. Having a single assessment system across all single-leg loading tasks is likely to improve usability for the clinician as well as reliability as experience and practice improve reliability (Whatman et al., 2012).

A qualitative scoring system was devised by one of authors (LH) based on the previously reported scoring systems of Crossley et al. (2011) and Whatman et al. (2012, 2013). It involved dichotomous scoring of the movement strategy occurring in individual body regions (arm, trunk, pelvis, thigh, knee, foot). Scoring was defined as a zero for appropriate strategy and one for inappropriate movements, for each region with best overall score being 0 and worst 10 points. The scoring sheet is shown in Fig. 1 and examples of appropriate and inappropriate movement strategies in Fig. 2. The qualitative scoring system used was based on those previously reported in the literature which had attempted to analyze single-leg squat and had shown good to excellent intra and intertester reliability (Crossley et al., 2011; Whatman et al., 2012). The scheme incorporated region criteria similar to that used by both Crossley et al., 2011 and Whatman et al. (2012), following the assertion from both Chmielewski et al. (2007), Onate et al. (2010) and Whatman et al. (2012) that this increased content validity. The scheme used was modified from those studies to also take into account trunk and pelvis motion which Crossley et al. (2011), Myer et al. (2008) and Whatman et al. (2013) regarded as a significant factor in the alteration of lower limb alignment and load. Similarly, a dichotomous scale was used when classifying motion within each of the regions which was shown to increase reliability (Whatman et al., 2012).

The qualitative scoring system used (QASLS) has been shown to have excellent validity when compared to 3D motion capture kinematics during single-leg squatting and landing (Herrington & Munro, in press), excellent intra and intertester reliability (Almangoush, Herrington, & Jones, in press; Dawson & Herrington, in press) and strong reliability when assessing real time versus video analysis of single-leg squat (Dawson & Herrington, in press).

Fig. 2. Examples of optimal and sub-optimal strategies during single-leg loading tasks.

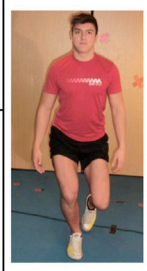
	NWB thigh not held in neutral		
Knee position	**Patella pointing towards 2nd toe (noticeable valgus)**		
	Patella pointing past inside of foot (significant valgus)		
Steady stance	**Touches down with NWB foot**		
	Stance leg wobbles noticeably		

Fig. 2. (*continued*).

The qualitative assessment of the athlete performing their rehabilitation exercises would then be informally assessed during all rehabilitation sessions using the criteria and formal assessed as a progression criterion within the stages outlined below.

2.4. Pre-operative phase

2.4.1. Aim

Prepare the athlete for surgery, normalizing knee function through minimizing knee effusion, gaining full quadriceps activation and normal gait.Typical rehabilitation activities

- Effusion control
- Muscle activation
- Range of movement
- Gait re-education
- Limb loadingTargets for the patient prior to surgery
- Full quadriceps activation (no lag on straight leg raise (SLR))
- Full range of movement (symmetrical)
- Minimal activity related effusion (<1 cm change supra patella circumferential measurement)
- Leg press limb symmetry index (LSI) equals less than 5%
  - LSI = (involved side/uninvolved side) × 100
- Normal gait walk and straight line jogging (8–10 min/mile)
- Functional questionnaire score (Knee Outcome Osteoarthritis Score (KOOS), International Knee Documentation committee (IKDC) subjective form etc.) equal to or greater than normative valuesRationale for pre-operative phase targets
- Full quadriceps activation (no lag on straight leg raise (SLR))

Activation failure of the quadriceps has been shown to contribute to profound strength deficits in patients with knee joint pathology and may serve as a barrier to rehabilitation of quadriceps post-operatively (Adams, Logerstedt, Hunter-Giordano, Axe, & Synder-Mackler, 2012; Lynch, Logerstedt, Axe, & Snyder-Mackler, 2012).

- Full range movement (symmetrical)

Limited pre-operative range of movement has been shown to significantly limit the progression of post-operative rehabilitation (Adams et al., 2012; Quelard et al., 2010)

- Minimal increase in activity related effusion (<1 cm change knee circumference over patella)

Changes in knee joint effusion are frequently associated with irritation of intra-articular structures, articular disorders and clinically active knees (Hurley, 1997). The level of effusion has been strongly associated with quadriceps inhibition; increasing effusion creating greater inhibition (Palmieri-Smith, Thomas, & Woitys, 2008). The level of pre-operative joint effusion has been implicated in development of early post-operative quadriceps activation failure (Lynch et al., 2012) and increased risk of post-operative arthrofibrosis (Rubin, Yeh, & Medvecky, 2009). The subjective grading of effusion (Sturgill, Snyder-Mackler, Manal, & Axe, 2009) would appear to show no relationship to central activation ratio of the quadriceps (Lynch et al., 2012) hence might not be sensitive enough to detect changes. Therefore the use of alternate within

subject measurements for changes in such as knee circumference (Jakobsen et al., 2010) have shown good reliability and a real clinical change value of greater than 1 cm (Jakobsen et al., 2010) and hence changes or differences in circumference of greater than 1 cm are likely to be significant.

- Leg press limb symmetry index with less than 5% difference

Pre-operative quadriceps weakness (greater than 20% difference between sides) has been shown to predict poor quadriceps strength and low self-reported function after surgery (Adams et al., 2012; Eitzen, Eitzen, Holm, Synder-Mackler, and Risberg, 2010).

- Normal gait walking and straight line jogging (8–10 min/mile)

Small deviations in normal gait patterns if not corrected have the potential to become exaggerated when the patient starts to run and return to more complex functional activities (Myer et al., 2008).

- Functional questionnaire score equal to or greater than normative values

Patient derived subjective assessments of symptoms and function are often more robust when evaluating the outcome of ACLR than clinical measurements such as arthrometers (Kocher, Steadman, Briggs, Sterett, & Hawkins, 2004). The goal pre-operatively for the athlete then would be to have functional scores equal to or greater than that of the normal "non-athletic" population. For the IKDC subjective questionnaire a score of greater than 89% for males and 86% for females would exceed the reported norm values (Anderson, Irrgang, Kocher, Mann, & Harrast, 2006; Collins, Misra, Felson, Crossley, & Roos, 2011). Ideally, for the KOOS questionnaire a score equal to or greater than normal values for each of the following individual domains: pain 90–95%; symptoms 84–91%, activities of daily living 92–98%, sport/recreation 80–91%, quality of life 80–90% (Collins et al., 2011; Paradowski, Bergman, Sunden-Lundius, Lohmander, & Roos, 2006) would be required.

2.5. Post-op recovery phase

2.5.1. Aim

To overcome the effects of the operation, regain range of movement and muscle activation, control effusion and achieve normal walking gait.Typical rehabilitation activities

- Effusion control
- Muscle activation
- Range of movement
- Gait re-education
- Limb loadingTarget criteria to be achieved prior to progression to the progressive limb loading activity phase
- Full quadriceps activation (SLR no lag × 10 repetition)
- Range of movement 0–120° (minimum)
- Minimal effusion (<1 cm change at patella with activity and diurnal variation)
- Bilateral squat to parallel (thighs relative to floor) with even symmetrical weight bearing
- Gluteal muscle activation (undertake a bilateral short lever bridge)
- Hamstring muscle activation (flex the knee in standing to 90° and undertake a bilateral straight leg bridge)
- Normal symmetrical gait
- Static cyclingRationale for targets to be achieved prior to progression to the progressive limb loading activity phase
- Full quadriceps activation (SLR with no lag through 10 repetitions)

Persistent quadriceps lag on SLR has been shown to indicate an inability to actively fully extend the knee. If this is not achieved by week 5 post-operation this would be considered a predisposing factor for significant quadriceps weakness at 6 months post-operation (Potter & Foo, 2006). This activation failure of the quadriceps is likely to serve as a major barrier to rehabilitation (Lynch et al., 2012) limiting rehabilitation progress and increasing the risk of developing patellofemoral pain (Myer et al., 2006).

- Range of movement with full extension and a minimum of 120° flexion

Early joint motion is beneficial when it comes to avoiding capsular contractions, reducing swelling and pain, and early full passive and active extension would appear to have no adverse effect on knee laxity (Isberg et al., 2006). Even small losses of knee extension (3–5°) appear to adversely affect subjective and objective outcome markers later in the rehabilitation phase (Adams et al., 2012). Establishing at least 120° of knee flexion allows the patient to undertake static cycling the benefits of which are explained later. Within the criteria establishing normal patella motion is also an important component, because of its relationship to both loss of flexion (Wilson, Press, Koh, Hendrix, & Zhang, 2009) and extension.

- Minimal effusion (<1 cm change at patella with activity)

As stated above changes in knee joint effusion are frequently associated with irritation of intra-articular structures and articular disorders in clinically active knees (Hurley, 1997) the level of effusion being strongly associated with quadriceps inhibition, with increasing effusion creating greater inhibition (Palmieri-Smith et al., 2008). Pain and swelling should therefore be used to determine exercise progression (Potter & Foo, 2006) as it will relate to the loading stresses which have been placed on the knee (Myer et al., 2008). Measurement of knee circumference at the patella has been shown to have strong intra-tester reliability and good sensitivity to change (Jakobsen et al., 2010), therefore it is suggested that the impact of rehabilitation and activities of daily living is monitored by changes in knee circumference. Jakobsen et al. (2010) showed changes of greater than 1 cm to be clinically significant. In practice the patient would measure knee circumference on first rising and at the end of the day. The aim is that the measure should not have changed by greater than 1 cm over the day. Greater changes than this may be indicative of increasing joint effusion and so joint stress, which may mean changing the loading the patient undertakes to settle the irritation.

- Bilateral squat to parallel (thighs relative to floor) even symmetrical weight bearing

Neitzel, Kernozek, and Davies (2002) found that some ACLR patient's failed to symmetrically load their legs during squat up to 12 months post-op and this was related to poor functional outcomes.

- Gluteal muscle activation

This is demonstrated by being able to undertake bilateral short lever bridge exercise (10 repetitions to neutral hip extension). Decreased gluteal muscle activity has been associated with increased knee valgus during a variety of functional tasks (Zazulak et al., 2007). Improvements in hip abduction and lateral rotation

strength and activation have lead to the attainment of superior neuromuscular alignment and control of the lower limb (Khayambashi, Mohammadkhani, Ghaznavi, Lyle, & Powers, 2012; Philippon et al., 2011).

- Hamstring muscle activation

This is demonstrated by flexing the knee in standing to 90° actively and being able to undertake a bilateral straight leg bridge (heels on 30 cm high box) for 10 repetitions to neutral hip extension. Seto, Orofino, Morrissey, Medeiros, and Mason (1988) found increased hamstring muscle activation and strength to be associated with superior outcomes (functional scores and return to sport).

- Normal symmetrical gait

Abnormal gait patterns have been associated with quadriceps weakness (Bush-Joseph et al., 2001), low patient satisfaction with outcome after ACLR (Kocher et al., 2002), decreased functional performance (Decker, Torry, Noonan, Sterett, & Steadman, 2004), post-operative complications including osteoarthritis (Dye, Staubli, Biedert, & Vaupel, 1999). Patients following ACLR have been shown to have significantly different gait patterns 12 months post-operation (Hall, Stevermer, & Gillette, 2012) with these changes being associated with articular cartilage matrix degeneration (Haughom et al., 2012) and so osteoarthritis risk. The gait abnormalities also often become further exaggerated when the patient returns to running (Myer et al., 2008).

- Static cycling

Kutzner et al. (2012) found tibiofemoral joints shear stresses to be considerably lower in cycling than walking. Low load cyclical loading of articular surfaces promotes chrondrocyte activity (Arokoski, Jurvelin, Vaatainen, & Helminen, 2000) and reduces the potential compromise of articular cartilage during future loading activities (Kviranta, Tammi, Jurvelin, Saamanen, & Helminen, 1988). The cycling should also aid in resolution of the often present bony bruise reducing the risk of developing on going degenerative issues within the joint (Davies-Tuck et al., 2010).

2.6. Progressive limb loading

2.6.1. Aim

Progressing the athlete from bilateral weight bearing activities to full unilateral weight bearing activities in conjunction with being able to undertake limited load acceptance activities (bilateral jump landing and jogging). Together with progressing strength training and work capacity of key lower limb muscles.Typical rehabilitation activities

- Muscle strengthening and work capacity training
- Static movement dissociation
- Dynamic movement control (closed chain)
- Bilateral load acceptance
- Cardiovascular trainingTarget criteria to be achieved prior to progression unilateral load acceptance activity
- Full range of movement
- Minimal activity related effusion (less than 1 cm change knee circumference around the patella, diurnal variation)
- Maintain single-leg stance without significant postural sway at 5, 45 and 90° knee flexion (10 s hold) on a soft yielding surface.
- Star Excursion Balance Test (SEBT)
  - Anterior and Posterior reach directions are symmetrical
  - Medial and Lateral reach distance has less than a 10% difference in limb symmetry index (LSI)
  - Composite score (total anterior, posterior, medial and lateral) has less than 10% difference in LSI
- Single-leg squat to 90° (alignment control × 10 repetitions; QASLS score 0–1)
- Bilateral drop jump test [alignment control; QASLS score 0–1] from 30 cm box
- Tuck jump test (score <3)
- Single-leg press 1.5× body weight (BW) (10 repetitions) – 0–90° knee flexion
- Gluteal muscle work capacity
  - Unilateral short lever bridge on box (hip 45°) (×25 + each leg no greater than 5 repetition (rep) difference between sides)
- Hamstring muscle work capacity
  - Unilateral long lever bridge on box (hip 45°) (×25 + each leg no greater than 5 rep difference between sides)
- Calf muscle work capacity
  - Unilateral heel raise (×25 + no greater 5 rep difference between sides)
- Function
  - Straight line running (8–10 min/mile)
  - Stair ascent and descent (30 cm); alignment control symmetryRationale for the target criteria to be achieved prior to progression unilateral load acceptance activity
- Full range of movement

The benefits of achieving full range of movement were discussed earlier, with respect of regaining full range of flexion this also is indicative of an appropriately tracking patella and is associated with a reduced risk of the development of patellofemoral joint pain (Wilson et al., 2009). The regular monitoring of range of movement for any significant change (>10° for flexion; >5° for extension) may provide an early sign of the development of intra-articular pathology such as arthrofibrosis (Shelbourne & Gray, 2009). Changes in range of movement may also reflect changes in the level of joint effusion (Potter & Foo, 2006)

- Minimal activity related effusion (<1 cm change patella)

The impact of rehabilitation and activities of daily living is to be continually monitored by change in knee circumference. Jakobsen et al. (2010) showed changes of greater than 1 cm to be clinically significant, indicating the levels of load applied were causes of joint stress.

- Single-leg stance 5, 45 and 90° knee flexion (10 s hold) on deformable pad

Multi angle static balance forms the pre-requisite to any dynamic activity (Myer et al., 2006), without good static balance performance during dynamic tasks is likely to be significantly compromised.

- Single-leg squat to 90° (alignment control × 10 reps; QASLS score 0–1)
- Bilateral drop jump test [QASLS score 0–1] from 30 cm box
- Tuck jump test (score <3)

Athletes who demonstrate symmetry in relation to limb alignment control during limb loading activities after ACLR may significantly reduce their potential for future ACL injury (Paterno et al., 2010).

- Star Excursion Balance Test (SEBT)

During anterior reach of the SEBT there is a significant increase in quadriceps EMG activity (Earl & Hertel, 2001) and the distance

has a moderate correlation to concentric strength (Thorpe & Ebersole, 2008), symmetry of reach providing good indicator of quadriceps function. The posterior reach direction generates significantly greater hamstring muscle activity (Earl & Hertel, 2001) and has a moderate correlation to concentric hamstring strength (Thorpe & Ebersole, 2008), providing good indicator of hamstring muscle function. Deficits in medial and lateral reach distances have been associated with ACL deficient knees (Herrington, Hatcher, Hatcher, & McNicholas, 2009) and furthermore both Fridén, Zätterström, Lindstrand, and Moritz (1989) and Goldie, Bach, and Evans (1989) reported increased postural sway (decreased stability) in the medio-lateral direction to be significantly related to ACL injury. Plisky, Rauh, Kaminski, and Underwood (2006) reported deficits in composite reach distances of greater than 6% were related to a significant increase in global lower limb injury risk.

- Single-leg press 1.5 BW (10rep) – 0–90° knee flexion

A typical level of loading during a vertical jump landing is around 1.5× body weight (Cleather, Goodwin, & Bull, 2013) in order for progression to these activities it would be appropriate to have force generation (and absorption) capabilities equal to those tasks.

- Gluteal muscle work capacity

As demonstrated by unilateral short lever bridge on box (hip 45°) (×25 + each leg no greater than 5 rep difference between sides). Decreased gluteal muscle activity has been associated with increased knee valgus during a variety of functional tasks (Zazulak et al., 2007). This is further exaggerated when the muscles become fatigued with repetitive loading (Herrington & McKenna, in press).

- Hamstring muscle work capacity

This is shown by achieving a unilateral long lever bridge on box (hip 45°) (×25 + each leg no greater than 5 rep difference between sides). Increased hamstring muscle activation and strength have been associated with superior outcomes (functional scores and return to sport) (Seto et al., 1988) increased work capacity is likely to aid this relationship further.

- Calf muscle work capacity

As demonstrated by unilateral heel raise (>25 reps and no greater 5 rep difference between sides). Schlumberger (2002) reported an average of an 8% strength deficit in calf muscle strength 6 months following ACLR. Lack of strength in this muscle group is likely to affect both load absorption and propulsion significantly during running gait.

- Function
  - Straight line running (8–10 min/mile)
  - Stair ascent and descent (30 cm); alignment control symmetry (QASLS score 0–1)

Roewer, Di Stasi, and Snyder-Mackler (2011) found reduced peak extensor moments and reduced knee flexion angle during walking at 6 months post-operation, with peak knee extensor moment and peak knee power absorption significantly less in involved knee at both 6 and 24 months post-operation, despite having symmetrically equal quadriceps strength at 6 months post-operation. They concluded that abnormal movement strategies during gait can still be present 2 years post-op despite symmetrical quads strength, it then becomes important to specifically assess walking and running gait along with functional activities such as stair ascent and descent, to address any abnormalities which could otherwise persist for a prolonged period.

2.7. Unilateral load acceptance activity

2.7.1. Aim

Progressing athlete from bilateral load acceptance activities to full unilateral load acceptance activities in multiple planes of movement. Alongside progressing strength and force development training and work capacity of key lower limb muscles.Typical rehabilitation activities

- Muscle strengthening and work capacity training
- Unilateral load acceptance activities in multiple planes and reactive landings situations
- Bilateral multi-plane and unilateral single plane plyometric activitiesTarget criteria to be achieved prior to progression to sport specific task training activities
- SEBT symmetry and within norms
- Single-leg hop landing (alignment control; QASLS score 0–1)
  - Single-leg hop for distance (LSI for distance <5%)
  - Forward and side hop from 30 cm box
- Tuck jump test (score 0–1)
- Cross over hop LSI <5%
- Lower limb closed chain strength
  - 10 RM Single-leg press >2.0 BW – 0–90° knee flexion
  - 10 repetition unilateral leg press to 90° within 5% of contralateral leg
  - Overall weight lifted <10% down on pre-injury level 3–6 RM of squat and deadlift.
- Isolated (open chain) quadriceps and hamstring strength
  - Isokinetic extensors total work >300%BW
  - Isokinetic flexor eccentric peak torque >130% of concentric flexor peak torque
  - No breaks in extensor or flexor isokinetic curve during testing
- Rate of force development; vertical hop test LSI <5%Rationale for target criteria to be achieved prior to progression to sport specific task training activities
- SEBT symmetry and at upper end of normal values

As there is only a weak association between static balance–stability activities and ability to dissociate movement (Riemann & Schmitz, 2012) it is important that patients have symmetrical and normal movement dissociation skills, not only to allow unrestricted movement but also as a decreased performance is associated with reduced injury risk (Plisky et al., 2006).

- Single-leg (hop) land (alignment control; QASLS score 0–1)
  - Single-leg hop for distance (LSI for distance <5%)
  - Forward and side hop from 30 cm box
  - Tuck jump test (score 0–1)

Athletes who demonstrate symmetry in relation to limb alignment control during limb loading activities after ACLR may significantly reduce their potential for future ACL injury (Paterno et al., 2010).

- Cross over hop LSI <5%

There is a strong relationship between cross over hop performance and functional outcome (Trulsson, Roos, Ageberg, & Garwicz, 2010) correlating significantly to IKDC subjective and KOOS questionnaire scores (Reinke et al., 2011). The work of Munro and Herrington (2011) showed LSI needs to be in excess of 90% to be deemed normal.

- Lower limb closed chain strength
  - 10 RM Single-leg press >2.0 BW – 0–90° knee ROM
  - 10 rep unilateral leg press to 90° within 5% of contralateral leg
  - Overall weight lifted <10% down on pre-injury level 3–6 RM of squat and deadlift.
- Isolated (open chain) quadriceps and hamstring strength
  - Isokinetic extensors total work >300%BW (60°/s concentric)
  - Isokinetic flexor eccentric peak torque >120–130% of concentric flexor peak torque (60°/s)
  - No breaks in extensor or flexor isokinetic curve during testing (60°/s)

Lewek, Rudolph, Axe, and Snyder-Mackler (2002) compared post ACLR strong group (>90%LSI) weak group (<90%LSI) and found strength to have a significant effect on early stance phase knee angles and moments and quadriceps strength during walking and jogging, showing strength plays significant role in functional performance (Schmitt et al., 2012). Breaks within the isokinetic knee extensor torque curve have been shown to be associated with patellofemoral pain (Anderson & Herrington, 2003) and even osteochondral lesions of the patellofemoral joint (Herrington, Williams, & George, 2003) and are likely to be related to quadriceps inhibition (Dvir, Halperin, Shaklar, & Robinson, 1991), which will need to be overcome prior to successful return to full unrestricted activity. Similarly, breaks within the flexor curve have been associated with poor functional scores in ACL deficient patients (Herrington, Turner, & Horsley, 2003).

- Rate of force development; vertical hop test LSI <5%

Both Angelozzi et al. (2012) and Myer et al. (2012) showed significant deficits in rate of force development in patients post ACLR which had an impact of functional performance and obviously will affect the ability to performance sport specific speed and agility based tasks.

2.8. Sport specific task training activities

2.8.1. Aim

Improving athlete's work capacity in the ability to undertake unilateral load acceptance activities in multiple planes of movement with a reactive random element. Develop athlete's ability to carry out specific multi-directional running and landing tasks which are aligned to needs of their sport, along with any other sport skill based tasks.Typical rehabilitation activities

- Muscle strengthening and work capacity training
- Unilateral load acceptance activities in multiple planes and reactive landings situations (with fatigue element)
- Sports specific aligned running agility tasks
- Sports specific aligned skill tasksTarget criteria to be achieved prior to progression to unrestricted sport specific training
- Limb alignment control following fatiguing task
  - SEBT symmetry and within norms
  - Single-leg (hop) land (alignment control; QASLS score 0–1)
    - Single-leg hop for distance (LSI <5%, and <5% pre-op score)
    - Forward and side hop from 30 cm box (alignment control; QASLS score 0–1)

- Running speed
  - A flying run (10 m) through Optojump system and speed gates, with outcome measures of L v R side symmetry of contact and flight times within 5–10%
  - Agility run time symmetrical (modified T or alternate sport specific) <10% pre-op time
- Function
  - Sport specific tasks with alignment control under random practice and fatigue scenarios (video analysis of alignment control; QASLS score 0–1)Rationale for the target criteria to be achieved prior to progression to unrestricted sport specific training
  - Limb alignment control following fatiguing task (sport specific intensity-duration)
    - SEBT symmetry and within norms
    - Single-leg (hop) land (alignment control; QASLS score 0–1)
      - Single-leg hop for distance (LSI <5%, and <5% pre-op score)
      - Forward and side hop from 30 cm box (alignment control; QASLS score 0–1)

Fatigue has been shown to have a significant effect on limb alignment control during a variety of loading tasks (Herrington & McKenna, in press; Khayambashi et al., 2012) the athlete is expected to show near perfect control after a fatiguing activity.

- Running speed
  - A flying run (10 m) through Optojump system and speed gates, with outcome measures of L versus R side symmetry of contact and flight times within 5–10%
  - Agility run time symmetrical (modified T or alternate sport specific) <10% pre-op time
- Function
  - Sport specific tasks with alignment control under random practice and fatigue scenarios (video analysis of alignment control; QASLS score 0–1)

To more appropriately reflect motor learning practices appropriate neuromuscular control needs to be undertaken whilst carrying out tasks of progressively increasing complexity, where more open skill elements become incorporated in a more and more random fashion, once the closed skill tasks have been mastered (McCormick, 2012; Verstegen, Falsone, Orr, & Smith, 2012). The athlete needs to be able to demonstrate transference of the neuromuscular control strategy into the "real world".

3. Discussion

Barber-Westin and Noyes (2011) in their review of return to sport criteria following ACLR noted only 13% of the studies reported any criteria for returning the athlete to sport. These criteria include muscle strength or thigh circumference (28 studies), general knee examination (15 studies), single-leg hop tests (10 studies), Lachman rating (one study) and validated questionnaires (one study). All of these criteria would seem insufficient when compared to the loading stresses the knee is exposed to during normal sporting activities. This clinical commentary has attempt to produce a progressive series of targets for the athlete following ACLR with the goal of gradually increasing the stress the athlete and their knee are exposed to, in order to develop the robustness required to return to sport.

Conflict of Interest

The authors have no conflicts of interest related to this paper.

Ethical Approval

The study was literature based and no ethical approval was sort.

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