12-15-2020 9:00 AM

Assessment of Landing Biomechanics and Rehabilitation after Anterior Cruciate Ligament Reconstruction

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A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Health and Rehabilitation Sciences

Recommended Citation

Gagnon, Sheila S., "Assessment of Landing Biomechanics and Rehabilitation after Anterior Cruciate Ligament Reconstruction" (2020). *Electronic Thesis and Dissertation Repository*. 7590.
https://ir.lib.uwo.ca/etd/7590

Abstract

Aberrant landing biomechanics increase the risk of anterior cruciate ligament (ACL) injury and are a focus of rehabilitation after ACL reconstruction. The purpose of the present thesis was to develop and evaluate methods of assessing landing mechanics and investigate the effects of different rehabilitation strategies after ACL reconstruction. Three studies were conducted. The first study used a Delphi process to develop the content of a Clinician-Rated Drop Vertical Jump Scale to evaluate jump landing mechanics during rehabilitation after ACL reconstruction. Twenty experts participated in four rounds of questioning, resulting in 92% agreement for knee valgus collapse, lateral trunk lean, insufficient trunk and/or knee flexion, and asymmetry as undesirable movements included on the Scale. An instruction booklet to accompany the Scale was also developed and presented in the thesis.

The second study evaluated the reliability and sensitivity to change of several biomechanical parameters during a drop vertical jump measured using a motion capture system, completed by 46 patients after ACL reconstruction. Intraclass correlation coefficients ranged from 0.58-0.90 for peak knee flexion and abduction moments, 0.45-0.85 for knee flexion and abduction angles, 0.61-0.93 for forces and loading rate, and 0.42-0.61 for hip impulse. The standardized response mean for knee flexion angles were 0.38 (peak) and 0.35 (displacement), while other biomechanical measures on the drop vertical jump were ≤0.27. The present results support the interpretation of various landing biomechanics assessed during repeated assessments of patients undergoing rehabilitation after ACL reconstruction. A technical note on the determination of optimal filtering frequency of biomechanical analysis of jump landing was also completed to complement study two and is also presented in the thesis. Residual analysis resulted in a filtering frequency of 14 Hz for markers and 50 Hz for forces.

The third study was a randomized clinical trial comparing biomechanics of functional outcome measures in patients undergoing staged (home-based and in-clinic) rehabilitation after ACL reconstruction versus usual care. 125 patients completed a drop vertical jump at 6 and 12 months after ACL reconstruction. Results suggested the staged rehabilitation program can be effective for patients who have the motivation and resources to complete their exercises at home, when detailed instruction by a qualified therapist is provided beforehand.

Overall, the findings from this thesis provide an assessment tool to help guide rehabilitation after ACL reconstruction, describe the measurement properties of biomechanical measures in patients undergoing rehabilitation after ACL reconstruction, and supports the implementation of a novel Staged physiotherapy program.

Keywords

Anterior cruciate ligament, knee abduction moment, rehabilitation, drop vertical jump, dynamic knee valgus collapse, biomechanics

Summary for Lay Audience

Anterior cruciate ligament (ACL) reconstruction knee surgery is a commonly used procedure to replace a torn ACL and regain stability and function in the knee. An assessment tool for evaluation of jump landing performance during the ACL rehabilitation process was developed by mimicking typical sporting maneuvers where ACL injuries frequently occur. This new tool can help clinicians identify and address faulty movements that increase the risk of ACL injury. The measurement properties of the biomechanical motion analysis assessment of jump landing were subsequently evaluated to ensure concise evaluation methods were possible and reproducible. Finally, a novel strategy for rehabilitation after ACL reconstruction that shifts focus to later rather than earlier phases of recovery was tested. Biomechanical and functional outcomes were assessed to compare a combined home followed by clinic rehabilitation strategy (Staged) to Usual Care. A series of biomechanical tests, including jump landing, over a 12-month period following surgery were carried out to evaluate stability, strength and function of the reconstructed knee. Biomechanical and functional outcomes between these two groups were similar, supporting the implementation of a Staged rehabilitation process. The information contained in this thesis will help improve rehabilitation strategies and optimize the care received.

Co-Authorship Statement

This thesis contains material from a published manuscript (Chapter 2) and published supplemental material (Chapter 2 Supplement), and two manuscripts that will be submitted to peer reviewed journals (Chapters 3 and 4). Sheila S. Gagnon was the primary author on all chapters in this thesis. Chapters were co-authored by T.B. Birmingham, a Professor in the School of Physical Therapy, Faculty of Health Sciences, Western University (Chapters 2, 3 and 4); D.M. Bryant, an Associate Professor in the School of Physical Therapy, with adjunct appointment in the Department of Surgery, Faculty of Health Sciences, Western University (Chapters 2, 5 and 6); J.R. Giffin, a Professor of Orthopaedic Surgery, Schulich School of Medicine and Dentistry, Western University (Chapters 2, 3 and 4); B.M. Chesworth, an Associate Professor in the School of Physical Therapy with adjunct appointment in the Department of Epidemiology and Biostatistics, Faculty of Health Sciences, Western University (Chapter 2); M. Werstine a Physiotherapist at the Fowler Kennedy Sport Medicine Clinic, Western University (Chapter 2); K.M. Leitch, Laboratory Manager, Wolf Orthopaedic Biomechanics Laboratory, Western University (Chapter 3); J.P. Dickey, an Associate Professor in the School of Kinesiology, Faculty of Health Sciences, Western University (Chapter 3); L. O’Neil, a MSc. Student in the Wolf Orthopaedic Biomechanics Laboratory, Faculty of Health Sciences, Western University (Chapter 3).

Acknowledgments

There are a lot of individuals to acknowledge over this 10-year endeavor. Firstly, I would like to thank my supervisor, Dr. Trevor Birmingham. He has shown trust in my abilities and work, and provided me a great example, especially in literary skills. I have learnt new types of research with his guidance, which has broadened my horizons. To my co-supervisor, Dr. Dianne Bryant, for providing support and unwavering confidence. To my co-advisor Dr. Bob Giffin, for acknowledging my capabilities and believing in me. A separate thanks for your advice on my own complicated potential knee surgery requirements. To all three, thank you for your patience, it has been a long and unusual journey.

I would also like to thank my fellow students and colleagues at the Wolf Orthopaedic Biomechanics Laboratory, for helping with data collection when necessary, providing support with data analysis and the grad club sessions. Also, for patience with the unattended computer access I required. Thank you to Ian, for showing me the ropes for data collection and analysis in biomechanics. Thank you Rebecca Moyer for jumping so many times for our “photo shoot” of the drop vertical jump process. To the Fowler Kennedy Sport Medicine Clinic, especially Kim O’Neil and Jamie Wilson for helping with hop testing, and Greg Alcock and Mel Werstine for their guidance and assistance on the main project.

Thank you to all co-authors for your invaluable feedback and critique. Dr. Bert Chesworth for helping significantly with the Delphi manuscript, and Dr. Jim Dickey for helping me understand and apply residual analysis. To all the participants involved in the studies. Thank you for your time in the lab for measurements. I hope your knees have recovered well.

To Kristyn Leitch, thank you for all your brainstorming sessions regarding the motion analysis procedures, troubleshooting Cortex, helping with indefinite macros, the Butterworth filter macro, and just venting about… everything. Thank you for the Coffee and English Breakfast tea breaks. Most of all, thank you for being a good friend.

Thank you to Nicole Kaniki, for your empathy and support, for your friendship, for your help with my family, and giving me a place to stay when I was in London on many occasions.

I would also like to mention the three Professors that initiated my interest in academia and research: Dr.'s Gordon Giesbrecht, Marion Alexander and Elizabeth Ready from the University of Manitoba. Dr. Giesbrecht gave me the opportunity to work in his Laboratory for Exercise and Environmental Medicine as a research assistant. Dr. Alexander suggested I consider graduate studies and provided me with rigorous learning in Human Anatomy and Kinesiology, with quotes I still remember to this day. Dr. Liz Ready for providing me many reference letters, support and trust as an undergraduate teaching her Exercise Physiology laboratories.

A special thank you to Dr. Bruce Oddson, for giving me motivation in the final stretch of my doctoral studies, including stories from your own adventures as a doctoral student. Your advice and assistance helped me stay on track and keep focus.

To my family and friends, for the unending questions of "When are you going to be done?" and "Are you done yet?". This was most definitely, the motivation I needed to hear without end. Regardless, you have all been supportive every step of the way, believing I would make it, eventually.

To Dom and the kids. It has been a long adventure. Dom, there are no words, you were a pillar, guidance, yet increased pressure and stress, and a mentor, a friend, and always beside me, "*no matter what*" (Segara *et al.* 1996). There was nothing sharing a good pint and a heated discussion with you couldn't fix, along with a dash of *sisu*. To Eljas, my happy daydreamer, to Sini, my tough cookie and "Sinisimpukka", and to my energetic and talkative Lumea; your smiles and laughter are the reason I have persevered. To Tähti, you will always be remembered. To the new Gagnon adventure ahead, we are excited to meet you. *Te olette minun elämäni, ja rakastan teitä enemmän kuin mitään muuta. Oma maa mansikkaa, muu maa mustikkaa.*

Finally, to hockey and sauna… the only ways to really stop thinking for a second about writing a thesis. *"Vihtoen viha viilenee, saunoen sappi sammuu".*

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List of Abbreviations

2D – Two-dimensional

3D – Three-dimensional

ACL – Anterior Cruciate Ligament

BMI – Body Mass Index

CI – Confidence Interval

CoM – Center of Mass

CMJ – Countermovement Jump

DVJ – Drop Vertical Jump

DVJS – Drop Vertical Jump Scale

f' – Optimal Cut-Off Filtering Frequency

FKSMC – Fowler Kennedy Sport Medicine Clinic

GRC – Global Ratings of Change

GRF – Ground Reaction Forces

IC – Initial Contact

ICC – Intraclass Correlation Coefficients

IKDC – International Knee Documentation Committee

KAA – Knee Abduction Angle

KAA disp – Frontal Plane Knee Displacement

KAM – Knee Abduction Moment

KFA – Knee Flexion Angle

KFA disp – Sagittal Plane Knee Displacement

KFM – Knee Flexion Moment

LESS – Landing Error Scoring System

LP – Landing Phase

LSI – Limb Symmetry Index

MDC – Minimal Detectable Change

OA – Osteoarthritis

RCT – Randomized Clinical Trial

ROM – Range of Motion

RTS – Return to Sport

SEM – Standard Error of Measurement

SP – Staged Physiotherapy

SRM – Standardized Response Mean

TO – Toe Off

UC – Usual Care Physiotherapy

VGRF – Vertical Ground Reaction Forces

WOBL – Wolf Orthopaedic Biomechanics Laboratory

Chapter 1

1 Introduction: Background and Rationale

The purpose of this chapter is to provide the background and rationale of the thesis objectives. The consequence and long-term ramifications of anterior cruciate ligament (ACL) injury are considered, and objective means to evaluate risk for ACL injury. Finally, a brief description of Chapters 2-5 is presented.

1.1 Consequence of Anterior Cruciate Ligament Injury

It has been largely documented that a tear or rupture of the ACL is the most common and serious knee injury, with a reported 200,000 injuries annually in the United States alone[8,22], and rising[54]. Of these, over 175,000 reconstructions are performed per year, at a cost of approximately 11,500$ per ACL reconstruction, resulting in a cost exceeding 2 billion annually[17,54]. Notwithstanding, ACL injuries are costly, and the long-term prognosis is less than adequate. It is now being recognized that the rate of return to participation is less than initially reputed[1,13], and of greater concern are the alarming statistics on the development of osteoarthritis (OA) as a result of ACL injury[11,44,52].

Using magnetic resonance imaging, Culvenor et al[11] found that 31% of patients that had had ACL reconstruction, developed OA already at 1-year post-ACL reconstruction. There is also a high incidence of OA documented at 10-15 years post ACLR where Øiestad et al[44] found that 71% of patients had developed OA in the ACL reconstructed limb. A review by Simon et al[52] also reported that as many as 80% of ACL injured knees developed OA between 5-15 years post injury.

This incidence of OA following ACL injury is alarming, yet it is even more detrimental when we consider the age of the initial ACL injury. Many injuries occur in young populations, particularly young adolescent females[21]. Furthermore, a study by Gianotti et al[16] reported that in New Zealand, the highest rate of ACL injury in males and females occurred between the age brackets of 15 to 34 years of age. Meanwhile, Shea et al[51] and Paterno et al[46] reported that the highest incidence of ACL injury occurs at a mean age of

16 years, and Barber-Westin and Noyes[2,3] reported that the majority of patients with ACL injury that have ACL reconstruction are under 25 years of age. These individuals will unfortunately most likely develop premature knee OA, which can be debilitating. These are unfortunate lifelong and costly consequences for many victims of ACL injury and subsequent ACL reconstruction.

1.2 Treatment of ACL Injury

After ACL injury, there are two courses of treatment and intervention: surgery to reconstruct the ACL or conservative management. Most patients, especially active individuals, are advised to have ACL reconstruction[31]. In the United States, 90% of patients with ACL injury will eventually have ACL reconstruction[30,48]. Surgery aims to replace the torn ACL with a new graft ACL usually using either an autograft or allograft. An autograft is tissue from taken from the patient’s own body, such as a hamstrings autograft typically harvested from the gracilis or semitendinosus tendons, or a bone-patella-bone graft. An allograft is tissue taken from a cadaveric human donor, or a synthetic substitute. Conservative management is non-surgical treatment including exercise such as strength and balance training, ice, mobilization, and electrical muscle stimulation[34]. Both treatments require rehabilitation to help individuals safely return to their regular activities, including activities of daily living, recreative or competitive sport, maintain quality of life, and delay the onset of OA. The objective of both treatment options is to regain stability and function in the knee and reduce pain[34]. With ACL reconstruction stability is regained by replacing the torn ACL with a graft. With conservative treatment, stability is regained by training the musculature to support the knee as a substitute for the missing ligament[34].

Regardless of intervention strategy, both options require rehabilitation for successful return to cutting and jumping activities. Rehabilitation after ACL injury typically is divided into early and later postoperative phases[23,42]. Pain management, reducing inflammation and recovery of range of motion (ROM) and strength in the affected limb are the primary objectives of the early phase. A shift in focus to regaining dynamic stability of the limb and preparing the patient for return to high level function, including pre-injury level of sport are the main objectives of the later phase[23,42]. The later phase involves placing progressively increasing loads on the ACL affected limb, with the goal of attaining optimal dynamic stability safely returning the patient to pre-injury levels of function and performance.

Despite the course of surgical or conservative intervention after ACL injury, the success of current treatment and rehabilitation strategies is discouraging and there is a paucity of objective criteria for determining readiness for return to activity. Furthermore, during the return-to-sport phase, ACL graft failure and injury to the contralateral limb[20] are greatly elevated[42,43]. Re-injury rates are alarmingly high, especially within the first year of return to sport (RTS) where injury risk is reportedly 15 times greater after ACL reconstruction than in healthy controls[46,48]. Paterno et al[48] reported that within the first year after ACL reconstruction, over 25% of athletes succumbed a contralateral or ipsilateral ACL injury. Meanwhile, a follow-up of 24 months by Paterno et al[46] reported a failure rate as high as 29.5%, and an injury risk 6 times greater than healthy controls. A study by Leys et al[29] reported that at 15 years post-ACL reconstruction, there is an ACL rupture rate of around 30% (29% for hamstrings and 32% for bone-patella-bone autograft). The highest rate of re-injury occurred within the first 3 years following ACL reconstruction. According to these studies, approximately 1 in 3 patients will go on to a subsequent ACL injury in either the ipsi- or contralateral limb.

In secondary ACL injury, it seems most injuries occur to the contralateral limb. In the study by Paterno et al[48], of the patients that succumbed a second ACL injury within 24 months of ACL reconstruction, 69.6% were to the contralateral limb. Leys et al[29] reported that of the 56 ruptures seen in the 15-year follow-up, 34 (60.7%) were contralateral and 15 were ipsilateral graft ruptures. Following ACL reconstruction, both limbs are at higher risk for secondary ACL injury.

1.3 Rehabilitation Strategies

Typically, ACL rehabilitation occurs in a clinical setting over a long period of time. However, for many patients, there are barriers to attending in-clinic rehabilitation for prolonged periods. Previous studies[6,10,14,18,19,25,50] have investigated alternative ACL rehabilitation strategies, such as variations in home *vs.* supervised in-clinic rehabilitation programs. All these studies have concluded that there are little-to-no differences in a variety of measures such as ROM, Lysholm, ACL Quality of Life, laxity etc., and at various time points including 3, 6, 12 and 24 months post-operatively. Although promising, the ability of alternative rehabilitation to achieve the same biomechanical and functional outcomes that are the focus of later-stage physiotherapy remains unknown.

1.4 Return to Sport

The primary reasons for ACL reconstruction are to prevent re-injury and RTS; or more precisely, return to pre-injury level of competition[2,3]. While the rate of re-injury is alarmingly high, the rate of RTS is also troubling. While reports vary widely, in general, 82% of ACL patients RTS, of which only 63% return to pre-injury level of play, and 44% to competitive sport by 3 years[1]. At 1-year post-ACL reconstruction, only 33% of patients return to competitive sport[1]. Kvist et al[28] reported that only 53% of patients returned to their pre-injury level of sport 3-4 years post-ACL reconstruction. Similarly, a review by Kvist[27] reported that only 56% of ACL reconstruction patients returned to pre-injury activity levels. Unfortunately, patient satisfaction is also reported to be less than adequate. Ingelsrud et al[26] reported that only 66% of ACL reconstruction patients from the Norwegian Knee Ligament Registry found the outcome of their ACL reconstruction as ‘acceptable’ at 12 – 24 months post-operatively, while 12% felt the treatment had failed.

The most commonly used criteria for release to sport is time since surgery, however time is not necessarily indicative of a patients’ readiness to return[2,9]. Few studies report objective criteria when determining readiness for RTS[2,9]. Impairment criterion such as pain, effusion, ligament stability, thigh circumference and ROM are reported, though infrequently, as is subjective evaluation, such as patient reported outcomes[2,9]. Some studies have reported the use of measures such as muscle strength. A review by Barber-Westin and Noyes[2] on RTS found that only 9% of the RTS studies included in their review (25 of 264 studies) reported muscle strength as a RTS criteria. Of these, a range of criteria from 80 – 90% of the contralateral limb was required for quadriceps or hamstrings isokinetic strength. A more recent review on RTS by Burgi et al[9] reported 41% of the RTS studies included in their review included muscle strength as a RTS criteria, yet only about 20% of these studies required a limb symmetry index (LSI) of at least 85% to allow RTS. The inclusion of functional performance measures is also sometimes considered. Barber-Westin and Noyes[2] reported that 4% of the studies in their RTS review evaluated the single leg hop test, and one study required four hop tests. This has improved as Burgi et al[9], reported that 14% of the studies in their review required at least one hop test for RTS. The minimum required LSI was either not reported or ranged from 85 - 90%. There is clearly a lack of consensus on safe RTS criteria following ACL reconstruction. With the reported high rate of re-injury and dismal return to pre-injury activity levels, there is an obvious need to reconsider objective and functional performance measures to improve patient satisfaction and long-term outcomes after ACL injury.

1.5 Dynamic Knee Valgus Collapse and Drop Vertical Jump

Noncontact ACL tears are the most common and often involve dynamic knee valgus collapse[3,7]. A dynamic knee valgus collapse pattern involves hip adduction, hip internal rotation, knee abduction and ankle eversion[38,49]. There is a resultant external knee abduction moment directing the distal tibia away from the midline, as illustrated in Figure 1.1.

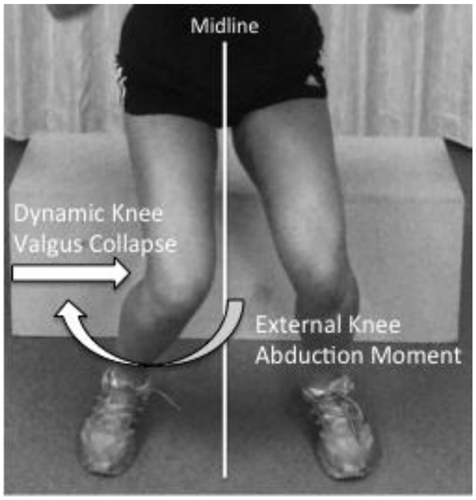

Figure 1.1: Pattern of dynamic knee valgus collapse with a resultant external knee abduction moment.

The drop vertical jump (DVJ) specifically evaluates dynamic knee valgus collapse and can help identify neuromuscular deficits within the movement pattern, especially at the knee and hip[21,49]. The DVJ involves having a subject drop off a box ~ 31 cm high with both feet, land, and immediately perform a maximum vertical jump[15,21]. Using motion analysis, a thorough evaluation of movement properties, including kinetics, kinematics and force attenuation and production can be completed on the performance of the DVJ.

Work, such as that by Myer et al[42], Paterno et al[49], and Di Stasi et al[55] have indicated that neuromuscular control in landing should be a major focus in rehabilitation following ACL injury or reconstruction. Various publications have recommended exercises to include in ACL rehabilitation, and ACL injury prevention programs, to develop good neuromuscular control in the knee and hip and promote good biomechanics to help reduce the risk for reinjury[3,35,36,41,42,55,56]. The effect of these types of rehabilitation protocols can be evaluated via the DVJ and help evaluate change of risky biomechanics. Particularly, since neuromuscular deficits are the only currently known modifiable risk-factors for secondary ACL injury[49,55], it is imperative that these are included and monitored in rehabilitation protocols following ACL reconstruction.

Performance on the DVJ can be used to predict those at risk for ACL injury[4,5,12,21,40,49], to detect neuromuscular deficiencies following ACL reconstruction, and after RTS[47,49]. Regular evaluation of quality of movement when performing the DVJ is suggested as an important objective task to be implemented in the later phase of ACL reconstruction rehabilitation to evaluate progress and determine readiness for safe RTS[42,47,55]. Movement patterns of jump landing mechanics evaluated using three-dimensional (3D) motion analysis provides an important tool for rehabilitation specialists as it can help identify compensatory movements that increase the risk for injury. This can help guide the rehabilitation process and monitor patient progress.

Important movement patterns that have been indicated as predictors of primary ACL injury risk are greater dynamic knee valgus and higher abduction loads at the knee[21,37,39]. Predictive risk factors for secondary ACL injury, in addition to the primary ACL injury risk factors, include a net hip internal rotator moment of the contralateral limb, asymmetry in sagittal plane knee moment at initial contact, and postural stability deficits[24,49]. Furthermore, asymmetry in vertical ground reaction forces (VGRF) and loading rate during the landing and take-off phases during the DVJ are observed 2 years post ACL reconstruction[47]. This can increase the risk for secondary ACL injury in the contralateral limb[47]. Identification of these neuromuscular deficits and modifiable risk factors are possible with the DVJ and are important considerations when evaluating readiness for safe RTS and reducing injury risk following ACL reconstruction.

Whether the DVJ can be reliably used in the ACL deficient population, and whether it can be used to measure change over time, requires test-retest data to be determined within this population. Reliability measures for within- and between-sessions evaluating landing mechanics during the DVJ using motion analysis in a young, healthy population are available[15]. Sufficient reliability was also demonstrated in healthy elite female athletes completing the DVJ[33]. However, since the DVJ is highly implicated in evaluating risk factors for subsequent ACL injury, and it is suggested as an objective tool to evaluate rehabilitation progress and readiness for RTS, longitudinal validity and reliability data on the DVJ task in the ACL reconstructed population is also required.

While complete analysis of the biomechanics of performance on the DVJ in rehabilitation would be ideal, access to costly motion capture equipment and time for analysis is not often possible. A means for clinicians to subjectively, quickly and confidently evaluate performance on the DVJ and evaluate risk factors in clinic, without the use of motion capture, would be beneficial to help guide therapy, provide immediate patient feedback, and assist in determining readiness for RTS. Currently a few evaluative methods have been proposed for the DVJ[12,32], and for a Landing Error Scoring System (LESS) on a jump landing task similar to the DVJ[45,53], although all require video recording and evaluation of the video at a later time.

Ekegren et al[12] found substantial intra- and interrater agreement evaluating frontal plane knee motion in healthy young competitive soccer female athletes using 2D-video analysis, however they lacked sensitivity. They believed better sensitivity may have been achieved if raters could have viewed patient performance live as opposed to on video. Mizner et al[32] evaluated 2D frontal plane projection angle and knee-to-ankle separation ratio analyzed by one evaluator *vs.* 3D motion analysis of knee abduction moment and valgus in healthy female collegiate athletes. They determined that knee-to-ankle separation may be a technique applied to evaluate ACL injury risk as a surrogate for 3D motion analysis. The LESS was found to have good-to-excellent intra- and inter-rater reliability on a jump landing task similar to the DVJ when evaluating military academic varsity/collegiate athletes[45], however it was not able to predict ACL injury in high school and college athletes[53]. All three tests require the use of 2D video analysis, and the latter requires specialized image-processing software. The development of a clinician-rated tool for use in clinic, providing immediate feedback with the ability to monitor progress or change over time within a rehabilitation program, and without further processing required, would be advantageous.

1.6 Thesis Outline

The overall purpose of this thesis was to examine rehabilitation strategies after ACL reconstruction and provide tools for evaluating patient progress and reducing secondary ACL injury risk. The thesis consists of three studies, an instruction booklet and a technical note. All studies were completed in the Wolf Orthopaedic Biomechanics Laboratory (WOBL) and Fowler Kennedy Sport Medicine Clinic (FKSMC) at Western University.

1.6.1 Chapter 2: Study 1

Biomechanical parameters measured during a DVJ task are risk factors for ACL injury and are targeted during rehabilitation after ACL reconstruction. A clinically feasible tool that quantifies observed performance on the DVJ would help inform treatment efforts. The objective of this study was to establish consensus on the content and scoring of a Clinician-Rated Drop Vertical Jump Scale (DVJS) for use during rehabilitation after ACL reconstruction, using a Delphi process. Results from this study lead to a Beta version of a DVJS where expert consensus was achieved on its content and scoring to support further clinical testing of the scale.

1.6.2 Chapter 2 Supplement: Instruction Booklet and Clinician-Rated DVJS

An instruction booklet was written to accompany the Clinician Rated DVJS (Study 1) to provide instructions for its' use. It includes examples of what to observe when using the scale, and provides instructions, a brief rationale and potential interpretation for each component. A summary of the instructions also appears on the back of the scale, included in the instruction booklet.

1.6.3 Chapter 3: Study 2

Joint biomechanics at the hip and knee assessed during a DVJ can be used to evaluate individual patient performance during ACL rehabilitation. Information about measurement properties of the DVJ assessed via motion analysis is beneficial for clinicians and researchers. The objective of this study was to estimate the test-retest reliability, standard errors of measurement, minimal detectable change and longitudinal validity of several biomechanical measures assessed during a DVJ completed by patients undergoing rehabilitation after ACL reconstruction. Results from this study revealed test-retest reliability of VGRFs, knee kinetics and kinematics during the DVJ test vary from poor-to-excellent depending on the point of landing assessed.

1.6.4 Chapter 3 Supplement: Technical Report

Three-dimensional motion analysis techniques are used to evaluate biomechanics in jumping analysis. The collected raw data has inherent error that must be filtered, often using a Butterworth filter. Residual analysis is an objective means to determine filtering cut-off frequency. This technical report provides results from a residual analysis that was completed for jumping analysis in this cohort of ACL reconstructed patients. A filtering cut-off frequency of 14 Hz for movement and 50 Hz for forces was acceptable to ensure physiological data is kept in the filtered signal.

1.6.5 Chapter 4: Study 3

Late-stage rehabilitation after ACL reconstruction is crucial for neuromuscular training and injury prevention. However, supervised physiotherapy is costly, and many patients are unable to continue. An alternative approach to ACL rehabilitation to facilitate patient adherence to late-stage physiotherapy is therefore warranted. The objective of this study was to evaluate whether a staged physiotherapy program (e.g. home-based rehabilitation followed by late supervised physiotherapy) leads to similar functional measures, including biomechanical measures of DVJ, hop testing, and strength, as a usual care physiotherapy protocol in patients following primary unilateral autograft ACL reconstruction. The results of this study revealed that completing home-based physiotherapy in the early-stages of rehabilitation, followed by supervised in-clinic therapy, can be effectively implemented.

1.6.6 Chapter 5

This final chapter provides a general discussion of the findings of these studies.

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Chapter 2

2 Development of a Clinician-Rated Drop Vertical Jump Scale for patients undergoing rehabilitation after anterior cruciate ligament reconstruction: A Delphi approach

2.1 Summary

The objective of this study was to establish consensus on the content and scoring on a Clinician-Rated Drop Vertical Jump Scale (DVJS) for use during rehabilitation after anterior cruciate ligament (ACL) reconstruction. Biomechanical parameters measured during a drop vertical jump task are risk factors for ACL injury and are targeted during rehabilitation after ACL reconstruction. A clinically feasible tool that quantifies observed performance on the drop vertical jump would help inform treatment efforts. The content and scoring of such a tool should be deliberated upon by a group of experts throughout its development. Using a modified Delphi process, experts (researchers and/or clinicians) on the risk factors, prevention, treatment and/or biomechanics of ACL injury anonymously critiqued versions of a DVJS that were developed iteratively based on the feedback from the panel, using Likert-like scale responses to questions and by providing written comments. Three-to-five rounds were planned *a priori* with the requirement of 75% agreement on included items after the final round. Twenty of the 31 invited experts (65%) participated. Approximately, 92% agreement was achieved after the fourth round. Final items on the scale included the rating of knee valgus collapse (No collapse to Extreme collapse) and the presence of the following other undesirable movements: lateral trunk lean, insufficient trunk flexion, insufficient knee flexion and limb-to-limb asymmetry. The Delphi process resulted in a Beta version of a DVJS. Expert consensus was achieved on its content and scoring to support further clinical testing of the scale.

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2.2 Introduction

Anterior cruciate ligament (ACL) injury is the most common serious knee injury resulting in compromised function, increased risk for knee osteoarthritis and large economic burden, including substantial resources expended on rehabilitation[14,25,50]. The reported level of sport participation after injury[1,10,13,16] and the rate of re-injury[15,16,18,23,40,46], suggest improvements in commonly used rehabilitation strategies after ACL injury would be advantageous.

Knee, hip and trunk motions observed during a drop vertical jump (DVJ) have proven to be important factors that contribute to the biomechanical mechanisms involved in ACL injury[21,22,33,34,49]. In particular, dynamic knee valgus is a predictive risk factor for primary ACL injury[17], and re-injury after ACL reconstruction[18,40]. The rate of subsequent ACL injury is high with approximately 1 in 4 to 1 in 6[18,23,40,46] injuries in young athletes. Furthermore, modifiable risk factors, such as dynamic knee valgus and its associated movement patterns are more highly implicated with a second ACL injury[18,40]. Accordingly, the DVJ is suggested as a functional task relevant to ACL injury that may help guide ACL rehabilitation efforts[18,29,50]. If implemented as an objective tool to be used during ACL rehabilitation, the DVJ may help therapists quantify a patient's landing mechanics that should be targeted with therapy, and evaluate change in those mechanics with treatment.

Performance on the DVJ is most commonly measured using three-dimensional (3D) motion analysis laboratories capable of quantifying joint angles and moments. Unfortunately, the use of 3D motion analysis systems in clinical settings is typically not feasible due to the costs associated with the equipment and the time required to collect and process data. Therefore, an alternative means to quantify performance during the DVJ may prove to be advantageous. Specifically, a clinician-rated tool designed to quantify performance during the DVJ may facilitate the evaluation of progress through rehabilitation efforts aimed at improving DVJ mechanics after ACL reconstruction. Previous investigators have shown that clinicians can use alternative methods to observe and rate landing mechanics[3,11,26,30,36]. These studies have typically used two-dimensional video analysis to screen for individuals at risk for ACL injury in healthy individuals.

While clinicians involved in the care of patients after ACL reconstruction have expertise in observing suggested undesirable movement patterns during functional activities and performance tests, and frequently use various outcome measures to evaluate patient progress, there is a need for greater standardized and objective criteria to evaluate an athlete's progress through rehabilitation following ACL reconstruction[3,4,31]. With respect to the DVJ, the literature suggests that it is essential to detect undesirable movement patterns that lead to dynamic knee valgus and address those mechanisms during rehabilitation[17,18,29]. Accordingly, to enable clinicians to confidently quantify the jump landing biomechanics in a clinical environment, a clinician-rated tool must include the most important movement patterns, yet also be standardized and feasible to use. It would be advantageous to have minimal-to-no equipment requirements, be easy to score, and enable prompt quantitative feedback. Additionally, it would be useful if the tool could be scored in a way that enabled sound measurement properties that supported its use in evaluating change during rehabilitation and in the statistical analyses carried out in clinical studies. Ideally, such a clinician-rated tool should be deliberated upon by a group of experts throughout its development. Therefore, the objective of this study was to establish consensus on the content and scoring of a Clinician-Rated DVJ scale (DVJS).

2.3 Methods

2.3.1 Study Design

A Delphi method was used to establish consensus from a panel of experts on the content and scoring of the DVJS. A scale development group, the study authors, created an initial version of the scale, drawing from selected studies from the DVJ literature[17,39,40] including studies that relied primarily on clinician observation[8,11,26,30,35,36]. The initial version was subsequently sent to the panel of experts who anonymously provided Likert-like scale responses to questions and written comments. The scale development group then revised and redistributed the scale based on the responses received after each round of the Delphi. Experts were invited to participate by email and provided their input through electronic fillable forms and/or online survey tools (SurveyMonkey Inc., California, USA). Completion of Round 1 of the survey indicated consent to participate, included in the letter

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of information. All participants that responded to Round 1 were subsequently contacted for each of the following rounds. A specific cut-point of ‘consensus’ for Delphi studies is not reported in the literature and varies between studies[42,51]. Terms such as *most, implied* [42], or “*majority of view*”[51] can be applied, or a criterion of 51%[44] can be used to determine consensus in a Delphi. Alternatively, a criterion for consensus in the Delphi process can be a Kappa statistic of > 0.61, or 61% termed *substantial agreement*[20]. We decided *a priori* to require ≥ 66% agreement (i.e. two thirds of the respondents) to represent adequate consensus in Rounds 1 and 2. As responses in a Delphi tend to converge towards consensus as rounds progress[41], we opted to inflate our agreement criteria for consensus in Rounds 3 or greater to be ≥ 75% (i.e. “Agree” and “Somewhat Agree” on the Likert scale used). With each subsequent round and survey, participants were first provided with a summary of the results and modifications made to the DVJS from the previous round of review. All experts remained anonymous to each other. Participants’ responses were coded to avoid bias and to blind the scale development group. Only the study coordinator in contact with the Delphi participants was not blinded. The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects granted ethical approval. Our Delphi process is summarized in Figure 2.1. The survey questions for each round (Appendix D), the final (Beta) version of the scale (Chapter 2 Supplement; Figure 2.10) and its instruction booklet (Chapter 2 Supplement) are available online in the supplemental material.

2.3.2 Expert Participants

We used purposive sampling to invite 31 potential participants on a Delphi panel consisting of experts in the prevention, treatment and/or biomechanics of ACL injuries. Invited clinicians (n=18) included physical therapists (n=3), certified athletic therapists (n=3) and orthopaedic surgeons (n=12) (i.e. three types of health care providers governed by professional bodies in Canada most commonly involved in rehabilitation after ACL reconstruction) who currently treat patients with ACL injuries on a regular basis. Invited researchers (n=10) included those who publish frequently on topics related to ACL rehabilitation, with particular focus on risk factors for ACL tears, the DVJ and/or outcome

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measure (scale) development. Additionally, we invited combined clinician-researchers (n=3) who were both physical therapists and researchers. We also sought expert representation from different geographical locations, including Canada (n=18), The United States of America (n=11), Europe (n=2), the United Kingdom (n=1) and Australia (n=1). Delphi panel sizes can vary in sizes (i.e. 10 – 1685[42,45,51]), however a panel size of 15 – 30 for a heterogenous group and 5 – 10 for a homogenous group is generally appropriate[9]. We invited 31 experts with the aim of recruiting at least 20 participants[9], with an approximately equal number of researchers and clinicians, and approximately equal number of physical/athletic therapists and surgeons. Specific inclusion criteria required: a minimum of five years of experience working in the field of ACL injuries and rehabilitation; self-declared expertise in mechanisms of ACL injury, risks, and rehabilitation; and availability to review three-to-five versions of a questionnaire and provide feedback on multiple occasions.

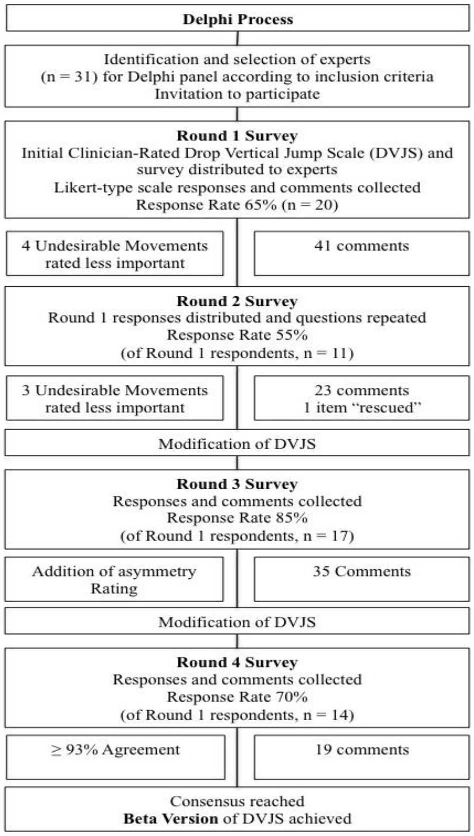

Figure 2.1: Delphi process and study flow.

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2.3.3 Round 1

The pilot DVJS was developed with the intention to help clinicians identify and quantify specific movement patterns during performance of a DVJ that are related to ACL injury risk. The scale was designed to be administered by physical and athletic therapists during ACL rehabilitation. Check boxes and explanations for varying degrees of dynamic knee valgus collapse and identification of relevant undesirable movements, along with a quantitative scoring scale were included on the DVJS. An area to include additional descriptive information on DVJ performance was also provided.

Delphi participants were provided with the pilot version of the DVJS and asked to rate the importance of its proposed items. The DVJS included seven undesirable movements (i.e. joint positions or compensatory movements that were deemed important to observe during the DVJ (Table 2.1). The level of importance of each movement was rated using four-point Likert-type scales (more important, agree, less important, should not be included). Participants were also asked to select the most important movement to observe during landing. The percentage agreement in ratings between experts for each undesirable movement was determined. Participants were also invited to provide suggestions for other undesirable movements they felt should be included in the DVJS, and to provide any comments that would aid in the development of the DVJS.

2.3.4 Round 2

Participants who responded to the initial Delphi survey were provided with his/her individual response to each question from Round 1, as well as the distribution of all responses rated by the panel. Participants were asked to re-evaluate their initial response and either keep their original response, or change it based on the collective results of Round 1. In this way, undesirable movements that did not reach agreement in Round 1 could be "rescued" if they reached consensus after re-evaluation in Round 2. Participants were again encouraged to provide explanations and any additional comments. A summary of the comments received in Round 1 that would be considered in the modification of the DVJS

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was provided to the Delphi panel participants, with further opportunity to comment or provide feedback.

Table 2.1: Preliminary items included in the initial Clinician-Rated Drop Vertical Jump Scale (DVJS) survey for Round 1.

Item	Detail to be Evaluated by Experts
Introduction	Description of Intended use of DVJS
Drop Vertical Jump Protocol	Description of Protocol
Knee Valgus Rating Categories	Safe to None Some: a little 'wiggle' with correction* Moderate: obvious valgus with correction Extreme: obvious valgus, no correction
Undesirable Movements (UM)	Excessive Lateral Trunk Lean Excessive Trunk Flexion Pelvic Rotation (Anterior or Posterior) Insufficient Knee Flexion Tibial Internal Rotation Foot Over Pronation
Vertical Scale that combines Valgus and UM Rating	No Knee Valgus, 0 UMs No Knee Valgus, 1 UM No Knee Valgus, ≥ 2 UMs Some Knee Valgus, 0 UMs Some Knee Valgus, 1 UM Some Knee Valgus, ≥ 2 UMs Moderate Knee Valgus, 0 UMs Moderate Knee Valgus, 1 UM Moderate Knee Valgus, ≥ 2 UMs Extreme Knee Valgus

Abbreviations: UM, undesirable movement; DVJS, Clinician-Rated Drop Vertical Jump Scale.

** Correction: patient goes into some degree of valgus collapse upon landing but is able to 'correct' themselves into a neutral alignment.*

2.3.5 Round 3

Participants were provided with a revised DVJS that only included the undesirable movements reaching the desired level of agreement, and amendments based on comments received from Rounds 1 and 2. Participants were asked to evaluate each component of the revised DVJS by completing new five-point Likert scales (agree, somewhat agree, neutral, somewhat disagree, disagree). Comment boxes were also added to evaluate whether we

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addressed the concerns brought forth in Round 2, and whether the revised DVJS was concise and representative of what it was supposed to measure.

2.3.6 Round 4

Participants were provided with a revised DVJS that incorporated the results and feedback from Round 3. This included the development of an instruction booklet to accompany the scale. This final round included a short set of three questions and additional comments to confirm that the opinions of the participants in the expert Delphi panel were captured, whether or not the DVJS likely measures what it is intended to measure, and whether it can be implemented and tested as a clinical tool.

2.4 Results

The study flow, responses and scale modifications are summarized in Figure 2.1. Table 2.2 shows the number of experts invited and the response rate for each round. Participants were from Canada (13), The United States (6) and Australia (1). Table 2.3 describes the participants' characteristics.

Table 2.2: Response rate by Delphi round stratified by category of expert.

Experts	**Experts invited**	**Round 1**		**Round 2**		**Round 3**		**Round 4**	
		No	**(%)**	**No**	**(%)**	**No**	**(%)**	**No**	**(%)**
Clinicians	18	**9**	50	6	67	9	100	6	67
PT/AT	6	4	67	3	75	4	100	4	100
Orthopædist†	12	5	42	3	60	5	100	2	40
Researchers†	10	**9**	90	4	44	6	67	6	67
Combined †‡	3	**2**	67	1	50	2	100	2	100
Total	*31*	***20***	*65*	*11*	*55*	*17*	*85*	*14*	*70*

Abbreviations: PT, Physical Therapist; AT, Athletic Therapist; No, Number; (%), Response Rate in percentage.

† *Includes participants with expertise in scale development.*

‡ *Participants who described themselves as both Clinician and Researcher.*

2.4.1 Round 1

In Round 1, the experts agreed on the inclusion of three of the seven undesirable movements on the initial DVJS, three other undesirable movements were suggested to be included or replaced, and 41 comments were received to improve the DVJS. The comments were summarized into common categories that included: other important undesirable

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movements, other suggestions necessary for safe return-to-sport after ACL reconstruction, and other considerations to include within the DVJS.

Table 2.3: Delphi expert panel characteristics.

Experts (n = 20)	**Median (Range)**
Years of experience	15 years - 20 years (5 years - 10 years, > 20 years)
Confidence in ability to evaluate DVJ	Very Confident (Somewhat Confident, Extremely Confident)
Skills compared to peers	Above Average (Average, Superior)
Clinicians (n = 11 †)	
Frequency working with patients after ACL reconstruction	Daily (Yearly 2x - 3x per year, Daily)
Familiarity with current ACL rehab protocols	Extremely Familiar (Mostly Familiar, Extremely Familiar)
Researchers (n = 11 †)	
Proportion of research ACL work	61% - 80% (< 20%, > 81%)
Familiarity with ACL risk factors	Extremely Familiar (Mostly Familiar, Extremely Familiar)

Abbreviations: DVJ, drop vertical jump; ACL, anterior cruciate ligament.
Expert characteristic data were collected using 5-point Likert scales. Possible responses were as follows: Years of experience: > 20 years, 15 years - 20 years, 10 years - 15 years, 5 years - 10 years, < 5 years; Level of confidence: Extremely confident, Very confident, Confident, Somewhat confident, Not confident; Skills compared to peers: Superior, Above average, Average, Below average, Inferior; Frequency working with ACL patients: Daily, Weekly (2x - 3x per week), Monthly (2x - 3x per month), Yearly (2x - 3x per year), Never; Proportion of research: > 81%, 61% - 80%, 41% - 60%, 21% - 40%, < 20%; Familiarity with ACL rehab/risk factors: Extremely familiar, Mostly familiar, Moderately familiar, Kind of familiar, Not familiar.
† Two participants self-declared themselves as both Clinician and Researcher.

2.4.2 Round 2

Consensus from the participants resulted in four undesirable movements being retained and three removed (see Table 2.4). One of the undesirable movements, tibial internal rotation, did not meet agreement in Round 1. However, it was "rescued" after Round 2. In addition to the Likert scale results, an additional 23 comments were returned in Round 2. Based on this input, we made the following major revisions to the DVJS: a brief rationale and instructions for use were added; "knee valgus" was replaced with "knee valgus collapse movement pattern" with an operational definition included; a scoring system for each limb was added to address concerns of limb-to-limb asymmetry; and, the list of undesirable movements was limited to only those with agreement ≥ 66%. The undesirable movement "tibial internal rotation" was modified to "excessive tibial rotation" to reflect the opinion of the participants and concerns with the ability to observe tibial internal rotation appropriately.

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Table 2.4: Percent agreement for undesirable movements after Rounds 1 and 2. Those carried forward to Round 3 of the Delphi had ≥ 66.7% of experts respond that the undesirable movement was "as important or more important" than exhibited on the initial DVJS, after Round 2.

	Agreement (%)		
Undesirable Movement	**Round 1**	**Round 2**	**Keep/Remove**
Excessive Lateral Trunk Lean	73.7	78.9	Keep
Excessive Trunk Flexion	52.6*	47.4*	Remove
Pelvic Rotation (Anterior or Posterior)	36.8*	31.6*	Remove
Insufficient Knee Flexion	88.9	89.5	Keep
Knee Valgus	94.4	94.4	Keep
Tibial Internal Rotation †	63.2*	68.4	Keep
Foot Over Pronation	47.4*	47.4*	Remove

* *Did not meet 66.7% agreement inclusion criteria.*

† *The term for tibial internal rotation was changed to "excessive tibial rotation" for following rounds to reflect the concerns brought forth from the Delphi panel regarding the ability of a clinician to adequately observe this undesirable movement pattern.*

2.4.3 Round 3

Agreement (≥ 75%) was achieved on all components of the scale, with the exception of whether the DVJS had an appropriate rating of undesirable movements (68.8% agreement). There was a lack of consensus about whether or not to add an additional quantitative measure of asymmetry; 43.8% agreed, 18.8% were neutral, and 37.5% did not believe an additional quantitative measure of asymmetry was required. In Round 3, 35 comments were received. Based on the agreement results and comments received in Round 3, we made the following adjustments to the DVJS: limb-to-limb asymmetry was incorporated as one of the undesirable movements with an operational definition on how it should be evaluated; insufficient trunk flexion was added as an undesirable movement; and, an instruction booklet describing the DVJ and how to use the scale, was developed to accompany the DVJS. The booklet also includes brief rationale and interpretation of movements observed, and supporting references. We hoped that this added information would aid the clinician in using the scale and improve reliability and validity. Another common suggestion from Round 3 was to include pictures. Images of good mechanics as well as various degrees of dynamic knee valgus collapse and undesirable movements were incorporated into the booklet.

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2.4.4 Round 4

In the final round of the Delphi, the number and nature of comments decreased to 19, of which half were positive suggesting the scale "looks good" and was "ready to go". The overall consensus was that the scale was adequate to be implemented as a clinical tool (≥ 92.9% Agree). 100% of experts agreed that the scale adequately evaluates other undesirable movements including lateral trunk lean, insufficient trunk flexion, insufficient knee flexion, and asymmetry. Agreement was 92.9% for the addition of the accompanying instruction booklet. Furthermore, written feedback indicated that the addition of the instruction booklet was beneficial, and provided further details on the undesirable movements evaluated by the DVJS. Round 4 resulted in a Beta version of the DVJS for preliminary clinical use to test its measurement properties (see Chapter 2 Supplement, Figure 2.10).

2.5 Discussion

Through a four-round consensus building process involving clinicians and researchers who are experts in ACL injury and rehabilitation, we established consensus on the content and scoring on a DVJS for use during rehabilitation after ACL reconstruction. This Beta version of the DVJS consists of a rating for the extent of knee valgus collapse and the presence of other undesirable movements, including evidence of lateral trunk lean, insufficient trunk flexion, insufficient knee flexion, and limb-to-limb asymmetry. A scale from 0 (No knee valgus collapse and no undesirable movements) to 9 (Extreme knee valgus collapse ± undesirable movements) is included for rating each leg during the performance of the DVJ. Its intended use is to quantify performance of the DVJ, facilitating clinicians to focus on landing biomechanics, correct movement patterns when possible, and therefore inform rehabilitation after ACL reconstruction. The scale and its instruction booklet are included in Chapter 2 Supplement (Figure 1.10).

Previous researchers have identified the need for methods to evaluate jump landing performance[11,30,35,36]. The majority of studies have focused on primary ACL injury risk screening. Of these, one[35] used a scale that does not require video recording and showed

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promising results for the reliability of the landing error scoring system-real time (LESS-RT) in young, healthy military cadets. To the best of our knowledge, there have been no previous studies conducted to establish consensus on the content and scoring of a clinician-rated drop landing scale with intended clinical use during rehabilitation.

Throughout all Delphi rounds, the knee valgus collapse movement pattern was consistently identified by participants to be the most important item. This clearly reflects the translation of knowledge that has accumulated from biomechanical studies completed over the past decade. The following movements are involved when dynamic knee valgus collapse occurs: hip adduction and internal rotation, knee abduction, and ankle eversion[28,39]. These movements have a resultant external knee abduction moment directing the distal tibia away from the midline and collectively contribute to increased strain on the ACL, as has been evidenced in a cadaveric model[12,24]. The dynamic knee valgus collapse pattern can indicate a ligament dominant (rather than a muscular dominant) landing technique that produces a large external knee abduction moment about the knee and a large load on the ACL[28,32]. Accordingly, recent findings for risk factors of ACL tears[19,29] and a second ACL injury[39] make it essential to include dynamic knee valgus collapse on the DVJS. All (100%) of our Delphi expert panel agreed that the DVJS denoted knee valgus collapse as the most important factor in jump landing performance for ACL injury risk.

While dynamic knee valgus collapse is of primary concern during the DVJ, other undesirable movements are also important[11,36,48]. The participants in the Delphi expert panel agreed that the following undesirable movements should be included on the DVJS: excessive lateral trunk lean, insufficient forward trunk flexion, insufficient knee flexion, and asymmetry. These movements have all been shown to contribute to dynamic knee valgus collapse and ACL injury. These other undesirable movements included in the DVJS are intended to help identify contributing injurious motions, which can identify hip weakness, sagittal plane knee movement discrepancies and limb-to-limb asymmetries, all of which are reported to be modifiable risk factors for subsequent ACL injury[39].

The panel agreed (78.9%) that excessive lateral trunk lean should be included on the DVJS. Evidence of excessive lateral trunk lean may be an indicator of hip abductor weakness[43], and possibly weak core proprioception[18], both modifiable risk factors that have been associated with subsequent ACL injury[39]. Furthermore, a lateral shift of the trunk over a weaker limb could result in an increase in dynamic knee valgus collapse ipsilaterally.

The panel also recommended including insufficient trunk flexion in the DVJS. This was consistent with the suggestion that insufficient forward trunk flexion can be an indicator of moments acting at the hip and knee[43]. Greater loads at the knee[5,6,43,47] are observed when landing in a more erect position, while trunk flexion during landing can reduce the loads at the knee, promoting hip and knee flexion[5,6,47], and potentially reducing strain on the ACL.

Frequently, the knee is reported to be in a position close to full extension[7] at the time of ACL injury (i.e. insufficient knee flexion). Within a range of 0°-45° of knee flexion, contraction of the quadriceps increases strain on the ACL[2,37]. Meanwhile, the hamstrings, which can assist in reducing anterior tibial translation and therefore strain on the ACL, cannot adequately protect the ACL in a low knee flexion range[27,28,37]. A flat-footed straight-leg landing, often accompanied by loud contact noise[32], can indicate a landing technique with insufficient knee flexion and suggests quadriceps dominance, or poor hamstring strength and recruitment[28,32]. This can be addressed within rehabilitation and promote safer landing techniques. Substantial agreement (89.5%) by the panel demonstrated insufficient knee flexion as an important component on the DVJS.

An imbalance between limbs in landing and jumping forces (i.e. asymmetry) have been observed for as long as 2 years after ACL reconstructive surgery and can remain after return to sport[38]. Paterno et al[39] reported limb-to-limb asymmetries in transverse plane net moment hip impulse and sagittal plane knee moment at initial contact to be modifiable risk factors strongly associated to subsequent ACL injury. Hewett et al[19] also reported asymmetries in lower extremity biomechanics to be risk factors for primary ACL injury. Any lingering asymmetries can put an individual at risk for ipsi- and contralateral ACL (re)injury[38,48]. The panel considered how to incorporate asymmetry into the DVJS over all four Delphi rounds, eventually agreeing to incorporate it into undesirable movements. The panel suggested that asymmetry can present itself in various forms and that any observed asymmetry should be recorded and described on the DVJS.

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Limitations in the present study include those inherent in Delphi studies and must be acknowledged[9,42,51]. Although the response rate following round 2 was 55%, we suspect that this was because the round requested participants to re-evaluate the exact same survey from Round 1, with the opportunity to alter prior responses after viewing the full panel's responses. Nonresponders may have simply felt their original response was adequate and did not feel it was necessary to respond. Importantly, the secondary round did result in an item being "rescued' and the response rates for rounds 3 and 4 returned to 85% and 70%, respectively. Additionally, although the number of experts on the present panel was consistent with suggestions for Delphi studies[9], the experts were primarily from North America. The number of experts in this topic is large internationally and it is unclear if additional participants or additional representation from other geographic regions would alter the present results. It is also important to emphasize that the DVJS is intended to measure landing mechanics to guide rehabilitation efforts, and it is not intended to replace criteria used to determine risk of injury or readiness to return-to-sport. The preliminary nature of the DVJS must also be emphasized. Future research is required to validate this Beta version of the scale for clinical use on patients undergoing ACL rehabilitation. Further testing of its measurement properties are especially required.

2.6 Conclusions

This Delphi process assisted in the development and refinement of a DVJS intended to quantify and monitor change in jump landing performance throughout rehabilitation after ACL reconstruction. A Beta version of this scale has been developed based on expert feedback. It requires further research before implementation into clinical practice.

2.7 Key Points

2.7.1 Findings

Expert consensus was achieved on content and scoring for the development of a Beta version of the Clinician-Rated Drop Vertical Jump Scale to evaluate and quantify landing performance during rehabilitation after ACL reconstruction.

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2.7.2 Implications

Further development of the DVJS may assist clinicians to identify desirable and undesirable landing mechanics to guide rehabilitation efforts, monitor change in landing performance, and participate in clinical research studies on the topic.

2.7.3 Caution

The scale requires further research before widespread clinical implementation outside of research studies can be recommended. The scale is not intended to be used to determine return-to-sport.

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2.9 Chapter 2 Supplement: Clinician-Rated Drop Vertical Jump Scale Instruction Booklet

2.10 Supplement Summary

The purpose of this booklet is to provide instructions for how to use the Clinician-Rated Drop Vertical Jump Scale (see Figure 2.10, end of Supplement Chapter for the scale). A summary of the instructions also appears on the back of the scale. This booklet includes examples of what to observe when using the scale, and provides *instructions*, a brief *rationale* and potential *interpretation* for each component.

2.11 Supplement Introduction

The drop vertical jump (DVJ) is a functional task relevant to anterior cruciate ligament (ACL) injury and rehabilitation. The DVJ is similar to rebounding a basketball, blocking in volleyball or jumping in soccer, among other sporting movements. When quantified in a biomechanics lab with motion analysis equipment, it is an indicator of ACL injury risk, especially in young females when greater dynamic knee valgus motion, knee abduction loads and limb-to-limb asymmetry are observed[7]. The present scale is intended to help clinicians quantify performance on the DVJ, without requiring motion analysis equipment, and evaluate change following therapy.

2.12 Overall Instructions

The clinician should observe at least *three* (more if required) repeated DVJ's while standing in different positions so as to observe movements in all three planes (frontal, sagittal and transverse), looking for joint positions and possible compensatory movements. Based on the repeated jumps, the clinician should check the appropriate boxes on the scale for i) *Knee Valgus Collapse,* and ii) *Other Undesirable Movements*, for both the left and right limbs, then circle the corresponding scale numbers to determine the overall performance for each limb. Even if a joint position or compensatory movement is observed only once, it should be recorded.

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2.13 Drop Vertical Jump Protocol

The patient is instructed to stand on a box of approximately 30 cm in height (e.g. a small plyo-box), with feet shoulder-width apart (~35 cm), with the ball of each foot on the edge of the box (e.g. toes overhanging edge). The patient then drops off the box with both feet at the same time, lands on both feet, and then performs a maximum vertical jump as quickly as possible (similar to jumping for a basketball), landing in the same approximate spot as the initial landing[5]. *The extent of dynamic knee valgus collapse and other undesirable movements should be evaluated from initial contact through to the deepest point during the initial landing, prior to the maximal jump.* An illustration of the sequence of phases in the DVJ is presented in Figure 2.2.

Figure 2.2: Example DVJ. Sequences include: (A) Start position; (B) Drop; (C) Deepest point during initial landing; (D) Maximal jump; and (E) Second landing and completion of jump.

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2.14 Knee Valgus Collapse

2.14.1 Instruction

The dynamic knee valgus collapse pattern includes the following movements: hip adduction and internal rotation, knee abduction, and ankle eversion[11,14]. These movements have a resultant external knee abduction moment directing the distal tibia away from the midline (Figure 2.3).

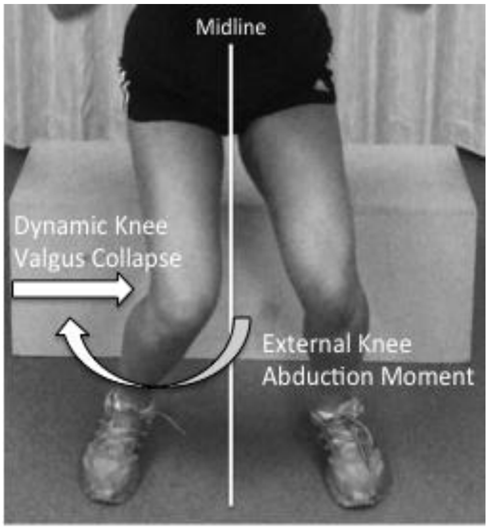

Figure 2.3: Example of the dynamic knee valgus collapse pattern including hip adduction and internal rotation, knee abduction, and ankle eversion. This pattern produces an external knee abduction moment.

The Clinician Rated DVJ Scale has clinicians distinguish between four levels of dynamic knee valgus collapse. These include: NO (none); SOME (slight valgus collapse ("wiggle") with correction); MODERATE (obvious valgus collapse with correction); and EXTREME (obvious valgus collapse with NO correction). The term "correction" refers to a knee valgus collapse pattern that returns to neutral alignment. Figure 2.4 illustrates these four categories of valgus collapse.

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2.14.2 Rationale

The dynamic knee valgus collapse pattern is suggested to indicate a ligament dominant (rather than a muscular dominant) landing technique that produces a large external knee abduction moment about the knee and a large load on the ACL[10,11].

2.14.3 Interpretation

When this pattern is observed, a suggested rehabilitation goal is to decrease medial knee motion to promote a muscle dominant landing technique and decrease risk for ACL (re)injury[11].

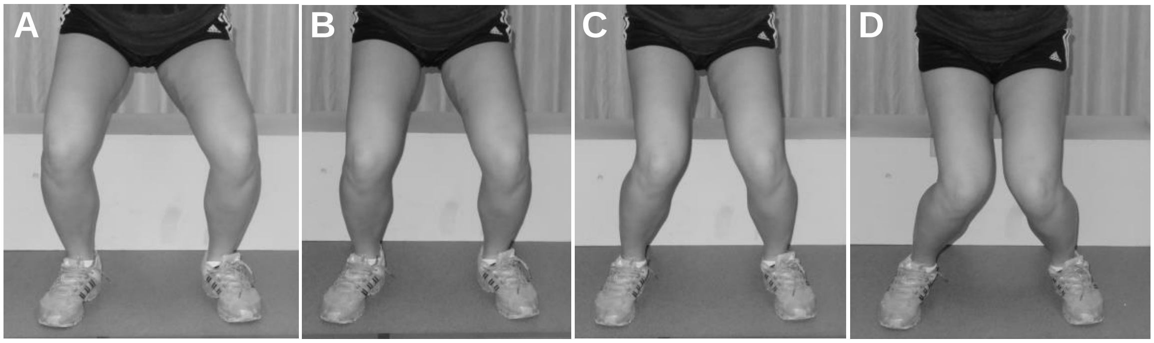

Figure 2.4: Example images of the categories of knee valgus collapse included in the scale. (A) NO (none); (B) SOME; (C) MODERATE; and (D) EXTREME knee valgus collapse.

2.15 Undesirable Movements

While dynamic knee valgus collapse is of primary concern during the DVJ, other undesirable movements are suggested to be important[17]. Therefore, the clinician should also evaluate excessive lateral trunk lean, insufficient forward trunk flexion, insufficient knee flexion and asymmetry using the Clinician Rated DVJ Scale.

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2.15.1 Lateral Trunk Lean

2.15.1.1 Instruction

When evaluating whether a patient exhibits lateral trunk lean, the clinician should observe performance in the frontal plane and whether the patient is in a neutral alignment (Figure 2.5A) or is shifting the trunk over one limb (Figure 2.5B).

2.15.1.2 Rationale

Studies suggest that at the time of ACL injury, the trunk is frequently erect[4,6,15] and displaced laterally[15], which results in less flexion in the lower extremity (esp. hip and knee)[2,3,16]. The consequences are increased load on the ACL and increased risk for injury.

2.15.1.3 Interpretation

Lateral trunk lean is more easily observed with single leg performance; however, it is important to consider in any landing, as it can be an indicator of hip abductor weakness[15] and possibly weak core proprioception[8]. These should therefore be considered as targets of rehabilitation intervention. Note that shifting the trunk over a weaker limb could result in an increase in dynamic knee valgus collapse ipsilaterally.

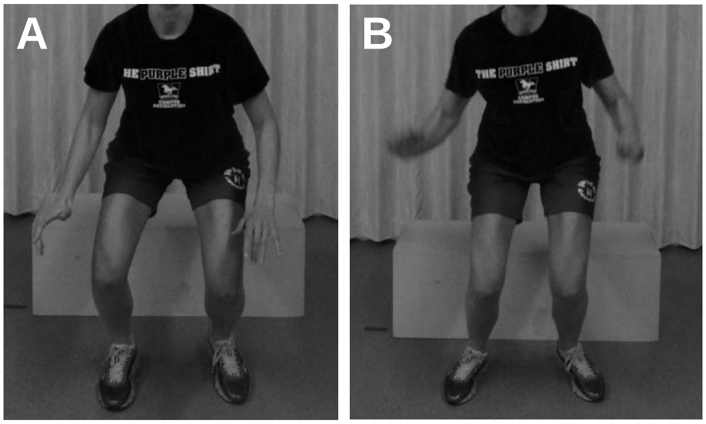

Figure 2.5: Example of (A) neutral trunk and (B) lateral trunk lean to the patients' right side during the DVJ. Note that in image (B) the participant is shifting weight over the right hip (right shoulder and hip dropped) and is also demonstrating a dynamic valgus collapse.

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2.15.2 Insufficient Trunk Flexion

2.15.2.1 Instruction

The clinician should evaluate performance for insufficient trunk flexion in the sagittal plane. When observing decreased trunk flexion during the DVJ, the clinician should also check for accompanying decreased knee and hip flexion, as often when landing with an erect trunk (Figure 2.6A), the patient will also exhibit less knee and hip flexion, in comparison to a more flexed trunk[2,3,16] (Figure 2.6B).

2.15.2.2 Rationale

Hip and knee moments are influenced by sagittal plane trunk motion[15]. A more erect position (Figure 3.5A) results in greater loads at the knee[2,3,15,16], while landing with the trunk in a more flexed position (Figure 3.5B) reduces loads at the knee and potentially ACL strain, while increasing hip and knee flexion angles during landing[2,3,16].

2.15.2.3 Interpretation

If a patient is landing in a trunk erect position, technique training to increase trunk flexion is recommended.

Figure 2.6: Examples of sagittal plane trunk positions during the DVJ: (A) erect trunk position with hip and knee joints demonstrating only slight flexion; and (B) greater trunk flexion accompanied by greater hip and knee flexion.

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2.15.3 Insufficient Knee Flexion

2.15.3.1 Instruction

The clinician should evaluate performance for insufficient knee flexion in the sagittal plane. Cues to look for when observing insufficient knee flexion are a flat-footed straight-leg landing, usually with an associated loud contact noise[11]. Figure 2.7 portrays an example of straight-leg landing (A) and a more flexed landing (B).

2.15.3.2 Rationale

At the time of ACL injury, the knee is frequently reported to be in a position close to full extension[4], a position at which contraction of the quadriceps increases strain on the ACL[1] and the hamstrings cannot adequately protect the ACL[9,11,12].

2.15.3.3 Interpretation

Insufficient knee flexion may suggest quadriceps dominance or poor hamstring strength and recruitment[10,11], which should therefore be a focus of rehabilitation.

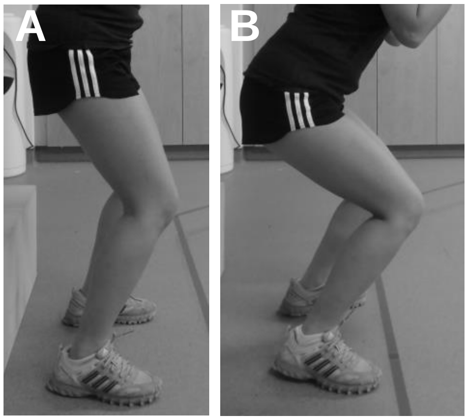

Figure 2.7: Example images of knee flexion observed in the sagittal plane, (A) flat-footed, straight-leg landing depicting insufficient knee flexion; and (B) a more flexed position allowing the hamstrings to activate and reduce anterior tibial translation and strain on the ACL.

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2.15.4 Asymmetry

2.15.4.1 Instruction

When observing performance of the DVJ for asymmetry, the clinician should be watchful for patients leaving the box with one limb prior to the other and/or landing with one limb prior to the other (Figure 2.8). Another cue is a foot placement with one foot posterior to the other (the posterior limb is suggested to be the stronger limb)[11] (Figure 2.9).

2.15.4.2 Rationale

Limb-to-limb asymmetries are also risk factors for ACL injury[7]. Asymmetries in landing and jumping forces following return to sport after ACL reconstruction exist as long as 2 years after surgery[13]. Lingering asymmetries can increase the risk for re-injury of the reconstructed ACL and to the contralateral limb[13,17].

2.15.4.3 Interpretation

Lower limb asymmetry is suggested to indicate that the patient is exhibiting leg dominance, or residual injury deficits[10], and a focus of rehabilitation should therefore be on correcting the observed imbalance between limbs.

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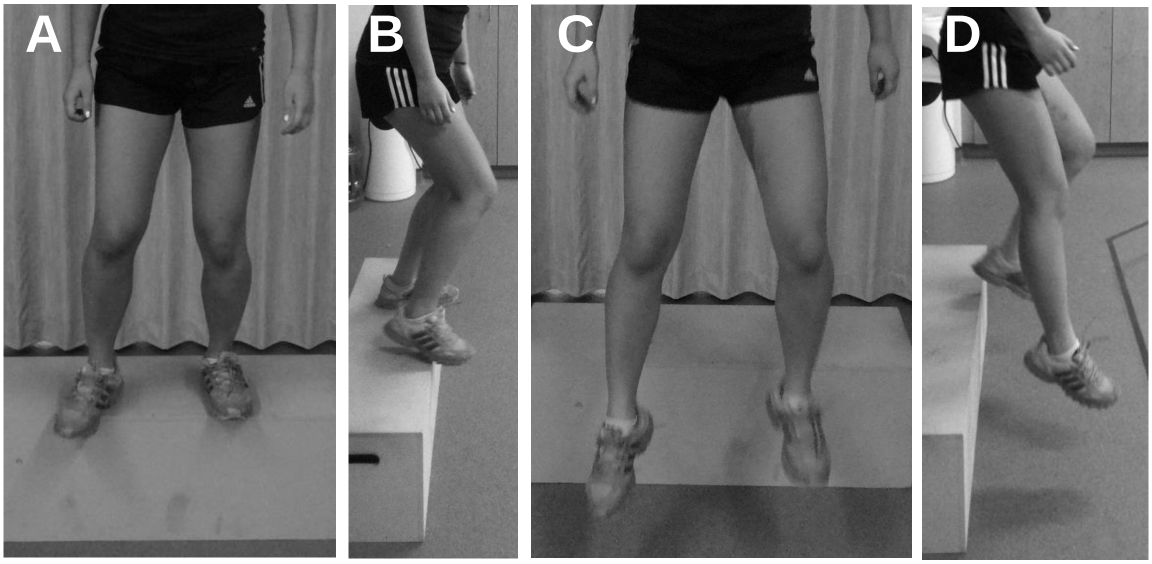

Figure 2.8: Example images of asymmetry: The subject is leading the jump with the right foot by unweighting it first as seen in (A) frontal, and (B) sagittal views; Subject will likely land, or make initial contact with the right foot first as seen in (C) frontal, and (D) sagittal views.

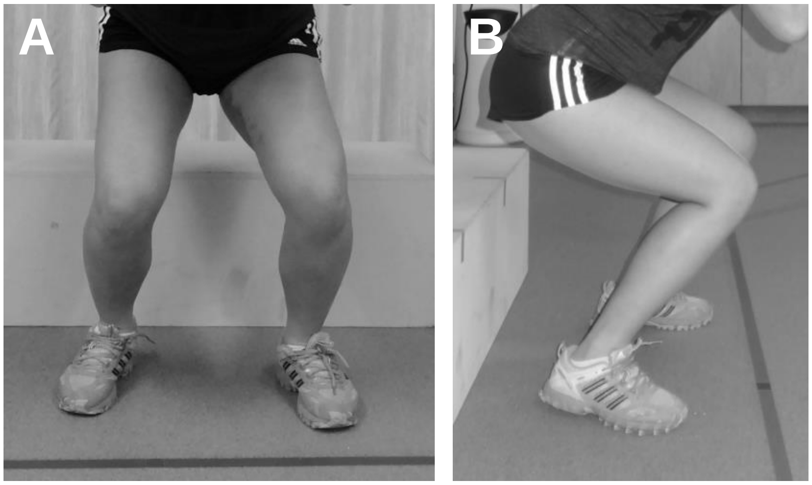

Figure 2.9: Example images of asymmetry demonstrated by staggered foot placement, with the right foot placed posteriorly to the left, suggesting a weaker left limb. (A) Frontal plane and, (B) sagittal plane views. Staggered foot placement is more easily observed from the sagittal view.

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2.16 Supplement Conclusion

This instruction booklet provides guidance to clinicians using the Clinician Rated DVJS for the evaluation of dynamic knee valgus collapse and other undesirable movements including lateral trunk lean, insufficient trunk flexion, insufficient knee flexion and asymmetry between limbs during the performance of a DVJ. Its' intended purpose is to assist the clinician to consistently and quantitatively evaluate potentially risky maneuvers that put the ACL at risk for injury. It would typically be used at various time points throughout the rehabilitation process following ACL injury and/or reconstruction and allow the clinician to assess patient progress and readiness for return-to-sport.

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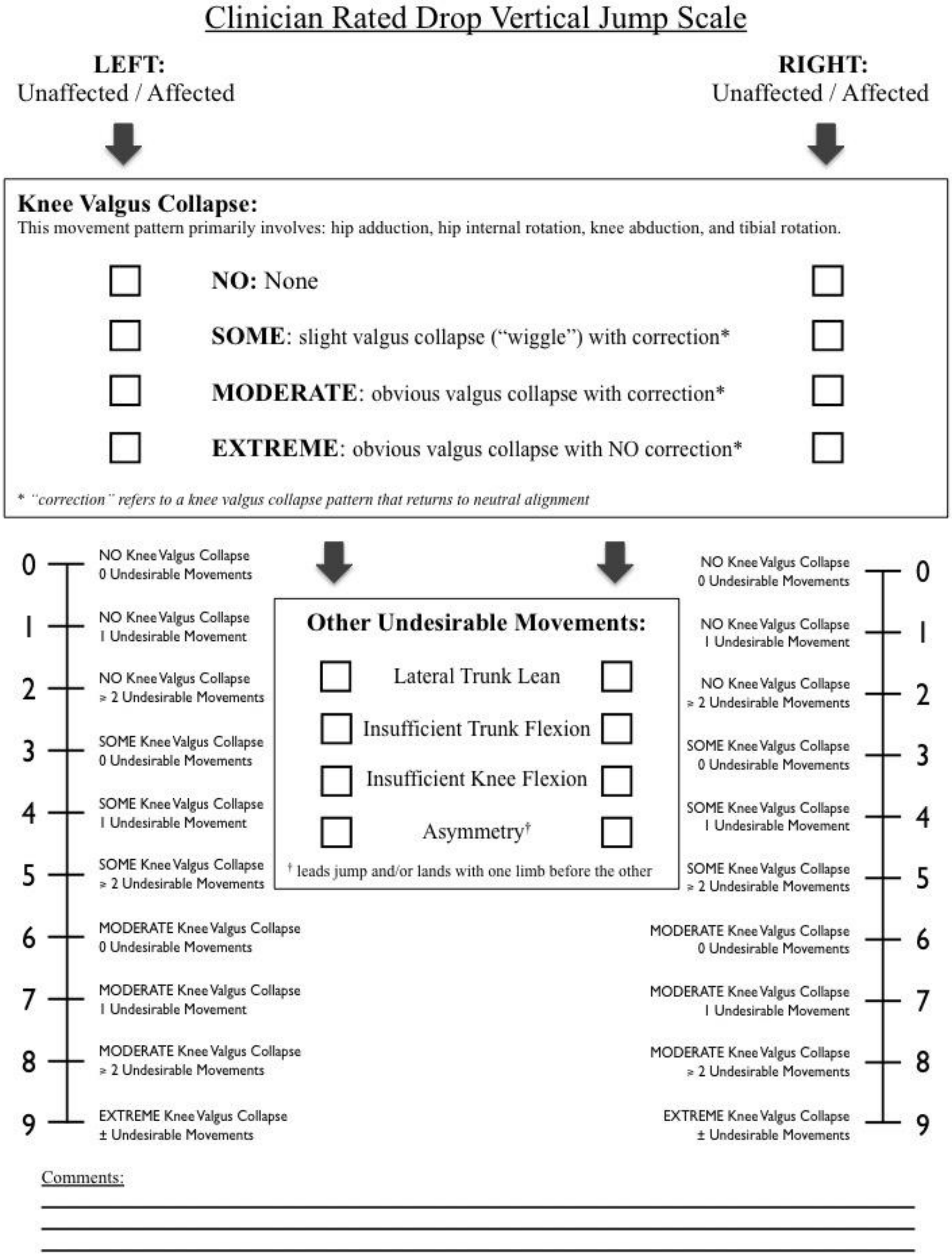
2.17 Clinician-Rated Drop Vertical Jump Scale



Clinician Rated Drop Vertical Jump Scale

LEFT:
Unaffected / Affected

RIGHT:
Unaffected / Affected

Knee Valgus Collapse:
This movement pattern primarily involves: hip adduction, hip internal rotation, knee abduction, and tibial rotation.

☐	**NO:** None	☐
☐	**SOME**: slight valgus collapse (“wiggle”) with correction*	☐
☐	**MODERATE**: obvious valgus collapse with correction*	☐
☐	**EXTREME**: obvious valgus collapse with NO correction*	☐

* *“correction” refers to a knee valgus collapse pattern that returns to neutral alignment*

Other Undesirable Movements:

☐	Lateral Trunk Lean	☐
☐	Insufficient Trunk Flexion	☐
☐	Insufficient Knee Flexion	☐
☐	Asymmetry†	☐

† leads jump and/or lands with one limb before the other

0	NO Knee Valgus Collapse 0 Undesirable Movements	NO Knee Valgus Collapse 0 Undesirable Movements	0
1	NO Knee Valgus Collapse 1 Undesirable Movement	NO Knee Valgus Collapse 1 Undesirable Movement	1
2	NO Knee Valgus Collapse ≥ 2 Undesirable Movements	NO Knee Valgus Collapse ≥ 2 Undesirable Movements	2
3	SOME Knee Valgus Collapse 0 Undesirable Movements	SOME Knee Valgus Collapse 0 Undesirable Movements	3
4	SOME Knee Valgus Collapse 1 Undesirable Movement	SOME Knee Valgus Collapse 1 Undesirable Movement	4
5	SOME Knee Valgus Collapse ≥ 2 Undesirable Movements	SOME Knee Valgus Collapse ≥ 2 Undesirable Movements	5
6	MODERATE Knee Valgus Collapse 0 Undesirable Movements	MODERATE Knee Valgus Collapse 0 Undesirable Movements	6
7	MODERATE Knee Valgus Collapse 1 Undesirable Movement	MODERATE Knee Valgus Collapse 1 Undesirable Movement	7
8	MODERATE Knee Valgus Collapse ≥ 2 Undesirable Movements	MODERATE Knee Valgus Collapse ≥ 2 Undesirable Movements	8
9	EXTREME Knee Valgus Collapse ± Undesirable Movements	EXTREME Knee Valgus Collapse ± Undesirable Movements	9

Comments:

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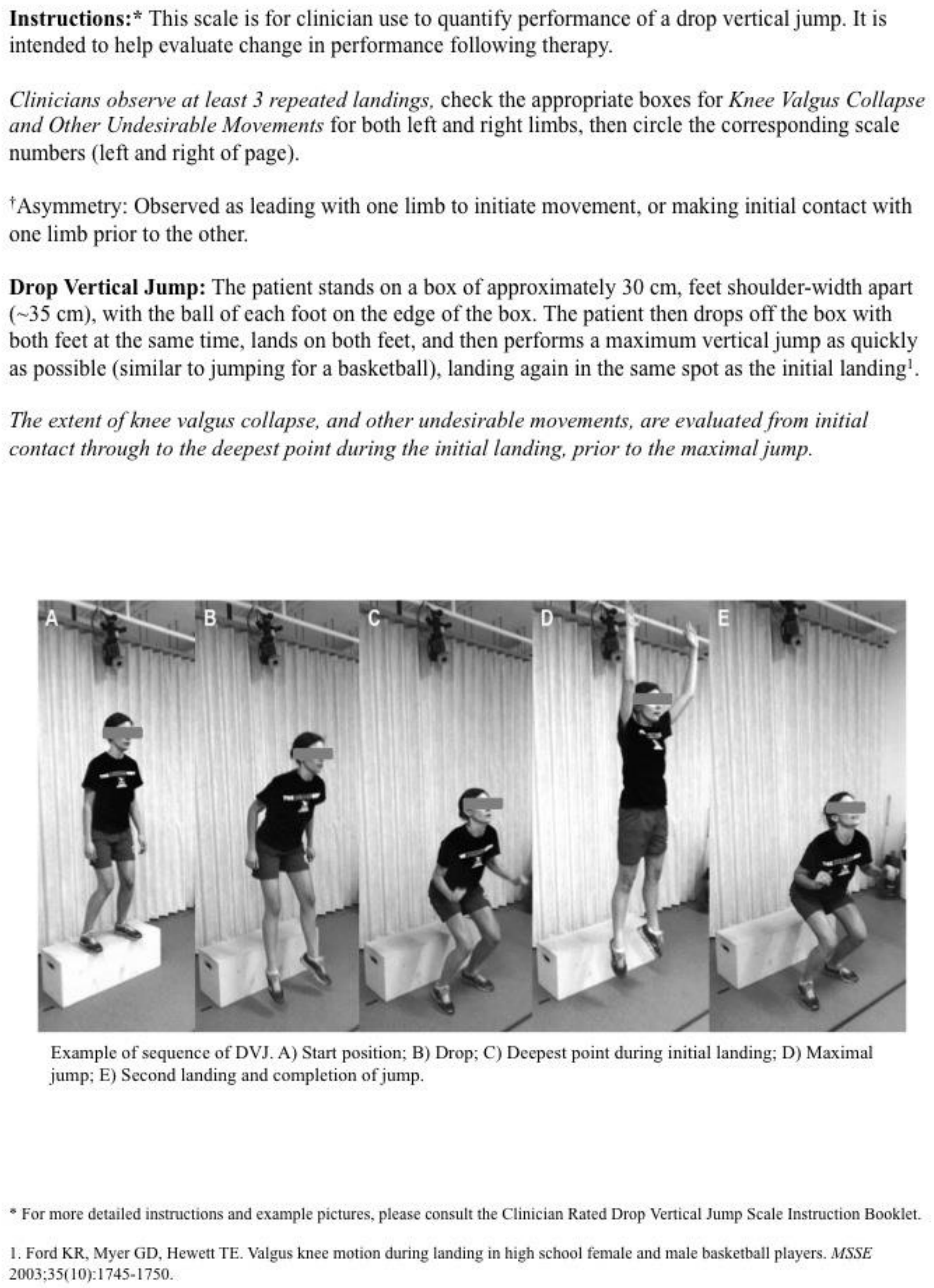

Instructions:* This scale is for clinician use to quantify performance of a drop vertical jump. It is intended to help evaluate change in performance following therapy.

Clinicians observe at least 3 repeated landings, check the appropriate boxes for *Knee Valgus Collapse and Other Undesirable Movements* for both left and right limbs, then circle the corresponding scale numbers (left and right of page).

†Asymmetry: Observed as leading with one limb to initiate movement, or making initial contact with one limb prior to the other.

Drop Vertical Jump: The patient stands on a box of approximately 30 cm, feet shoulder-width apart (~35 cm), with the ball of each foot on the edge of the box. The patient then drops off the box with both feet at the same time, lands on both feet, and then performs a maximum vertical jump as quickly as possible (similar to jumping for a basketball), landing again in the same spot as the initial landing[1].

The extent of knee valgus collapse, and other undesirable movements, are evaluated from initial contact through to the deepest point during the initial landing, prior to the maximal jump.

Example of sequence of DVJ. A) Start position; B) Drop; C) Deepest point during initial landing; D) Maximal jump; E) Second landing and completion of jump.

* For more detailed instructions and example pictures, please consult the Clinician Rated Drop Vertical Jump Scale Instruction Booklet.

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Figure 2.10: Clinician-Rated Drop Vertical Jump Scale: Beta Version

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Chapter 3

3 Test-retest reliability and longitudinal validity of drop vertical jump biomechanics during rehabilitation after ACL reconstruction

3.1 Summary

The objective of this study was to estimate the test-retest reliability and explore the longitudinal validity of selected lower limb biomechanics assessed during a drop vertical jump (DVJ) completed by patients undergoing rehabilitation after ACL reconstruction. Joint biomechanics at the hip and knee measured during a DVJ are used to help assess patients undergoing rehabilitation after ACL reconstruction. If used as an outcome measure to evaluate the effectiveness of treatments and measure change in an individual patient's performance, further information about test-retest reliability and longitudinal validity is required. Forty-six patients (age: 21.7±5.2y) were tested on two separate days within 1 week at approximately 6 months after primary ACL reconstruction surgery, and again at 12 months after surgery (n=36). Isokinetic knee extension and flexion strength and patient-reported global ratings of change (GRC) were also assessed at 6 and 12 months. Knee angles and moments, hip impulse, and vertical ground reaction forces (VGRF) in the operative (19 left, 27 right) and nonoperative limbs, were calculated. Values at initial contact (IC) and peak (highest) were analyzed. An asymmetry index was calculated for peak knee abduction moment, knee flexion moment at IC and VGRF. We evaluated reliability using intraclass correlation coefficients (2,1) (95% confidence intervals) ($ICC_{2,1}$), standard errors of measurement (SEM) and minimum detectable change (90% confidence level) (MDC_{90}). We evaluated longitudinal validity using standardized response means (SRM) and Pearson correlations between changes in landing biomechanics and changes in knee extension and flexion strength and with GRC values. Intraclass correlation coefficients ranged from 0.58 to 0.90 for peak knee flexion and abduction moments, from 0.45 to 0.85 for knee flexion and abduction angles, from 0.61 to 0.93 for VGRFs and loading rate, and from 0.42 to 0.61 for hip impulse in the operative and nonoperative limbs. The SRM for knee flexion angles were 0.38 (peak) and 0.35

(displacement), while other biomechanical measures on the drop vertical jump were ≤0.27. The SRM for strength measures in the operative limb were 0.48 (knee extension) and 0.42 (knee flexion). Knee moments at IC were less reliable, with ICC<0.48. Peak knee flexion moments, knee flexion angles, and VGRFs had the highest reliability (ICC > 0.80). SRMs ranged from 0.00 to 0.48. Correlations with strength (0.00 to 0.48) and GRC (0.03 to 0.43) were also low to moderate. The present results provide data to assist the interpretation of various landing biomechanics assessed during rehabilitation after ACL reconstruction.

3.2 Introduction

Evaluation of landing biomechanics during a drop vertical jump (DVJ) has become an important aspect of assessing patients with or at risk for anterior cruciate ligament (ACL) injury[1,2,6,12,17,20,21]. To complete the DVJ, the patient stands on a 31 cm box, drops off the box, and upon landing, performs a maximal vertical jump similar to the action of rebounding a basketball or blocking in volleyball[8,12]. When quantified in 3D motion capture labs, landing biomechanics during the DVJ can help predict patients at risk for ACL injury[1,2,6,12,17] and detect deficiencies following ACL reconstruction and after return-to-sport[20,21]. The DVJ is also suggested as an objective task to be implemented in the later phase of ACL reconstruction rehabilitation to help evaluate progress and determine readiness for safe return-to-sport[18,20].

Greater dynamic valgus and higher abduction loads in the knee during the DVJ task are risk factors for initial ACL injury[12,16]. The DVJ can also identify modifiable risk factors associated with a second ACL injury, including dynamic knee valgus collapse, contralateral transverse plane hip net moment impulse, asymmetry in sagittal plane knee moment at initial contact[21], and side-to-side asymmetries in vertical ground reaction force (VGRF) during both the landing and takeoff phase of the DVJ[20], including loading rate and VGRFs in the uninvolved limb.

There are encouraging data from healthy participants indicating landing biomechanics during the DVJ are reliable within and between test sessions[8]. Ford et al[8] reported intraclass correlation coefficients of 0.616 and 0.855 for knee flexion and abduction angles (measured in degrees), 0.843 and 0.870 for knee flexion and abduction moments (measured in $Nm \cdot kg^{-1}$), and 0.655 for hip internal rotation moment ($Nm \cdot kg^{-1}$), respectively. However, to our knowledge there is no published research investigating the measurement properties of DVJ landing biomechanics in patients after ACL reconstruction. This is particularly important to help interpret DVJ measures used to evaluate change in patients during rehabilitation. Therefore, the objectives of this study were to 1) estimate the test-retest reliability, and 2) explore longitudinal validity of selected lower limb biomechanics assessed during a DVJ completed by patients undergoing rehabilitation after ACL reconstruction.

3.3 Methods

3.3.1 Participants

We recruited patients undergoing rehabilitation at a sport medicine clinic after primary unilateral ACL reconstruction. The institution's Research Ethics Board for Health Sciences Research Involving Human Participants provided approval for the study. Participants provided informed written consent. Forty-six patients between the ages of 15 and 39 participated (Table 3.1).

Table 3.1: Baseline characteristics (mean ± standard deviation is reported unless stated otherwise).

	Total
Sample size (n)	46
Sex (female/male)	15 / 31
Operative limb (left/right)	19 / 27
Age (y)	21.7 ± 5.2
Height (cm)	175.97 ± 8.19
Mass (kg)	78.0 ± 16.2
Body Mass Index ($kg{\cdot}m^{-2}$)	24.5 ± 5.5
Isokinetic Strength (Nm)	
Operative knee extension peak torque	133.25 ± 47.80
Nonoperative knee extension peak torque	168.70 ± 43.43
Operative knee flexion peak torque	65.37 ± 23.76
Nonoperative knee flexion peak torque	84.71 ± 22.71

3.3.2 Study Design

The DVJ was performed in a biomechanics lab on two separate days at least 24 hours apart and within 1 week at approximately 6 months after surgery, and again 12 months after surgery (Figure 3.1). Testing sessions at 6 months were used to estimate test-retest reliability (*n*=46). Isokinetic knee extension and flexion strength and patient-reported global ratings of change (GRC) (Figure 3.2) were also assessed at 6 and 12 months and used to help evaluate longitudinal validity (*n*=36). Sample size was based on objective 1 and the ability to estimate an ICC of approximately >0.80 with 95% confidence interval (CI) width of 0.2 [5].

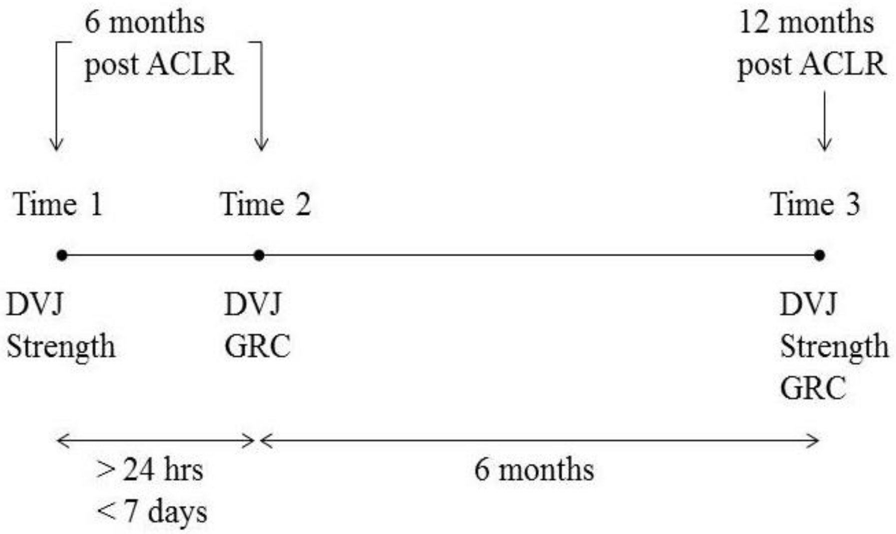
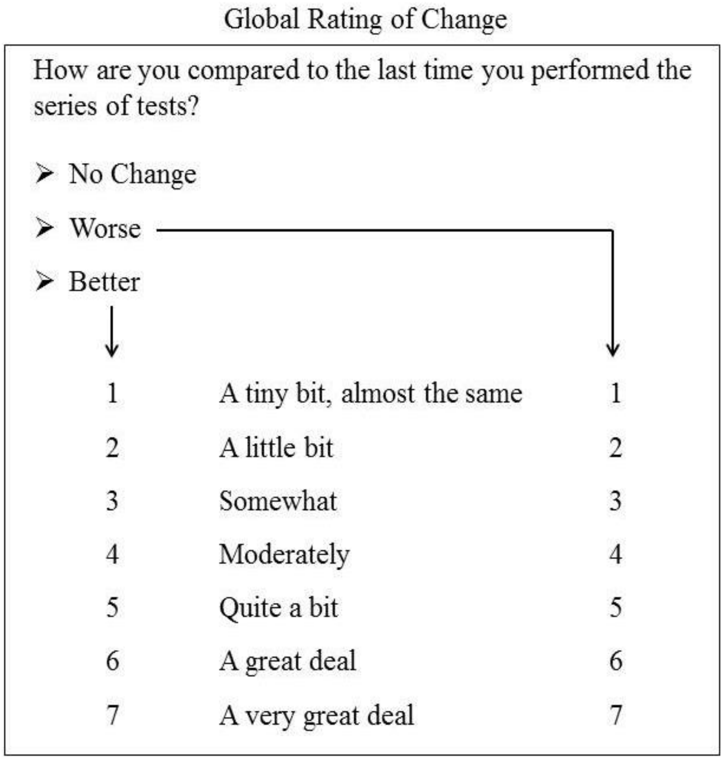


Figure 3.1: Measurement timeline and tasks required. Abbreviations: ACLR, Anterior cruciate ligament reconstruction; DVJ, Drop vertical jump; GRC, Global rating of change; hrs, hours.



Global Rating of Change

How are you compared to the last time you performed the series of tests?

- No Change
- Worse
- Better

Better		Worse
1	A tiny bit, almost the same	1
2	A little bit	2
3	Somewhat	3
4	Moderately	4
5	Quite a bit	5
6	A great deal	6
7	A very great deal	7

Figure 3.2: Global rating of change scale.

3.3.3 DVJ Landing Biomechanics

We used a modified Helen Hayes marker set[13], with extra markers placed bilaterally over the medial knee joint line and medial malleolus for an initial standing static trial to determine positions of joint centers of rotation for the knee and ankle. Medial markers were removed for subsequent dynamic trials (22 passive-reflective markers for the DVJ). Each participant performed four DVJ trials. The DVJ task had the participant stand on a box 31 cm in height with the feet ~ 35 cm apart and toes slightly overhanging the edge. Participants were instructed to drop off of the box with both feet at the same time, and immediately perform a maximum vertical jump, consistent with instructions described in previous studies[8,9,12]. An overhead target was used to help align subjects to jump vertically and motivate them to jump maximally. The initial landing on the force plates was used for analysis in three successful trials.

Three-dimensional marker and force plate data were collected using commercially available software (Cortex-64 2.6.5, Motion Analysis Corporation, Santa Rosa, CA) and ten high-speed digital cameras (8 Eagle Cameras, 2 Hawk Cameras, Motion Analysis Corporation, Santa Rosa, CA) at a sampling frequency of 200 Hz, synchronized with two force plates (Advanced Mechanical Technology Inc., Watertown, MA) positioned 8 cm apart and sampled at 1200 Hz. The system was calibrated using a static calibration frame to orient the cameras to the laboratory coordinate system, followed by a dynamic wand calibration, prior to data collection.

Data reduction of the DVJ was completed using the motion analysis software, and exported to Microsoft Excel, where data were filtered using a low-pass fourth-order Butterworth filter. A residual analysis of data was completed resulting in marker data filtered at 14 Hz and force plate data at 50 Hz. The marker and force data from each trial were combined and used to calculate knee abduction, knee flexion and hip rotation moments using inverse dynamics (Cortex-64 4.0.0, Motion Analysis Corporation, Santa Rosa, CA). Joint angles (kinematics) were determined using the XYZ Euler Rotation Sequence with Z as the bone axis, and net external moments relative to the tibial anatomical frame of reference are described (Cortex-64 4.0.0, Motion Analysis Corporation, Santa Rosa, CA).

Vertical ground reaction forces were used to determine initial contact (IC) and takeoff during the DVJ. Initial contact was defined as a VGRF > 10 N, while takeoff was the instant VGRF was < 10 N (stance phase)[1,2,8,21]. The landing phase was defined as IC to the lowest point of the participants' center of mass (CoM)[1,2,21]. The takeoff phase was from the lowest point of the participants' CoM to takeoff (VGRF <10 N). The following variables for both the operative and nonoperative limbs (*n = 92 limbs*) for knee frontal and sagittal plane and hip transverse plane angles and moments were evaluated during the landing phase: knee abduction angle (KAA) (degrees) at IC and peak, frontal plane displacement (KAA disp), knee flexion angle (KFA) (degrees) at peak and sagittal plane displacement (KFA disp), knee abduction moment (KAM) (Nm, Nm·kg^{-1}) at peak and asymmetry at peak, knee flexion moment (KFM) (Nm, Nm·kg^{-1}) at peak and asymmetry at IC, and transverse plane net hip moment impulse in the first 10% of the landing phase. By convention, knee adduction, knee flexion and hip internal rotation were represented as positive. Maximum VGRF (xBW) during the landing (LP) and takeoff (TO) phases and loading rate (xBW·s^{-1}) during the landing phase were measured. Loading rate was calculated as peak VGRF over time to peak (e.g. time from IC to peak VGRF). Angular displacements were calculated as the difference between values at peak and IC. The peak of the CoM during the flight phase of the maximal vertical jump was used as an indicator of peak height of the jump. Asymmetry was calculated using the Symmetry Angle (SA)[28] (Equation 3.1).

$$SA = (45^\circ - \arctan(X_{affected}/X_{unaffected}))/90^\circ * 100\% \qquad (3.1)$$

3.3.4 Strength Testing

Strength testing was completed using an isokinetic dynamometer (Biodex System3, Biodex Medical Systems, NY) with participants seated with the hips and knees at 90° and the lower limb affixed to the dynamometer arm. Testing of the nonoperative limb occurred prior to that of the operative limb. The participants completed 1 set of 3 maximal effort repetitions of knee extension and flexion at 90°/s. They were instructed to "kick and pull" the leg as fast and forcefully as possible. For familiarization of the task, the participants performed 3 submaximal (50 – 60%) repetitions prior to the maximal effort repetitions for each limb. Testers provided encouragement of maximal effort verbally, in addition to visual feedback of the torque output. If the error in between repetitions was greater than 10%, the set was repeated to ensure maximal effort. The sampling frequency of the Biodex was 1000 Hz, and peak torque (Nm) for each trial was determined from the highest value of each repetition. The mean of three repetitions for knee extension peak torque and knee flexion peak torque were recorded for each limb.

3.3.5 Reliability

For each participant, the mean of three trials in the operative (27 right, 19 left, $N = 46$) and nonoperative limbs on each test session were used to examine between-session test-retest reliability at 6 months. Differences between test and retest were evaluated using paired t-tests. Intraclass correlation coefficients ($ICC_{2,1}$) with 95% CI were calculated. The standard errors of measurement (SEM) were calculated and reported in the variables' original units[26]. The point estimate of the SEM was used to calculate minimal detectable change at the 90% confidence level (MDC_{90})[25].

3.3.6 Longitudinal Validity

Change scores were calculated as the difference between scores obtained at 12mo and the mean of 6mo and 6mo2 (n=36). Changes were compared using paired t-tests. The correlations between changes in biomechanics variables and the GRC and change in strength (PT quad, PT hams) were determined using Pearson correlation coefficients (r) with 95% CI. The standardized response mean (SRM) was calculated as mean change from 6 months to 12 months over the standard deviation of the change (mean Δ / SD_{change}). Statistical analyses were completed using SPSS (IBM SPSS Statistics 25, Chicago, IL) for Windows.

3.4 Results

3.4.1 Reliability

Test-retest reliability statistics are reported in Table 3.2. The mean (SD) time between tests was 3.9 ± 2.1 days. There were no statistically significant differences between test-retest sessions at 6 months, with the exception of KFM and KFA at IC. The peak of the CoM during the flight phase of the maximal vertical jump had excellent reliability with an ICC of 0.94. For knee moments, the ICC for peak KAM ranged from 0.58 to 0.75 and can be described as moderate-to-good (Koo & Li 2016). The ICC for peak KFM ranged from 0.73 to 0.90 (moderate-to-excellent); however, asymmetry measures for knee moments were poor (ICC <0.50). For knee angles, the ICC for KAA ranged from 0.45 to 0.78 (poor-to-good), while KFAs were between 0.83 and 0.85 (good). Reliability for VGRFs at LP and TO were from 0.82 to 0.93 (good-to-excellent). Reliability for asymmetry in VGRFs at LP and TO were moderate-to-good. Loading rate of VGRFs was lower with ICC of 0.71, 0.61, and 0.41 (poor-to-moderate) for operative, nonoperative, and asymmetry, respectively. Transverse net hip moment impulse in the nonoperative limb was moderate at 0.61. The SEM for absolute reliability and MDC at the 90% confidence level are presented in Table 3.2.

3.4.2 Longitudinal Validity

Longitudinal validity statistics are reported in Tables 3.3 and 3.4. Statistically significant changes from 6 to 12 months were observed for KFA measures of peak and displacement, and in strength measures. The SRMs were very low-to-moderate. The SRM of the knee extension and flexion strength in the operative limb were 0.48 and 0.42, respectively. The SRM of all other variables were < 0.39. The GRC was most highly correlated to change in the operative limb's KAM at IC ($r = 0.37$, $p = 0.045$, and $r = 0.43$, $p = 0.019$, for $\mathrm{Nm{\cdot}kg^{-1}}$ and Nm, respectively). The change in the operative limb's knee extension strength was most highly correlated with change in the operative limb's peak KAM ($r = 0.38$). Change in knee flexion strength was most highly correlated with KAMs ($r = 0.48$, 0.45, 0.38 for KAM at IC in $\mathrm{Nm{\cdot}kg^{-1}}$, Nm, and peak KAM in Nm, respectively).

Table 3.2: Descriptive statistics (mean ±SD) and test-retest reliability statistics for Drop Vertical Jump biomechanics (*n*=46). Intraclass correlation coefficients (ICC) with 95% confidence intervals (CI) in parentheses, standard errors of measurement (SEM) and minimal detectable changes (MDC) estimated using the z value for 90% confidence (1.64) are shown.

Test		Time 1 (±SD)	Time 2 (±SD)	Diff T_2-T_1 (±SD)	ICC	SEM	MDC$_{90}$
Peak CoM height (m)		1.742±0.119	1.738±0.115	-0.004±0.040	0.94 (0.90, 0.97)	±28.37	±65.81
Knee Abduction Moment							
IC	Op (Nm/kg)	-0.10±0.11	-0.05±0.11	0.05±0.13	0.31 (0.03, 0.54)	±0.09	±0.22
	NoOp (Nm/kg)	-0.04±0.08	-0.06±0.11	-0.03±0.11	0.29 (0.01, 0.52)	±0.08	±0.18
	Op (Nm)	-7.47±8.21	-3.99±8.25	3.48±8.90	0.33 (0.06, 0.56)	±7.11	±16.50
	NoOp (Nm/kg)	-2.84±6.07	-4.39±7.82	-1.55±7.71	0.28 (0.01, 0.52)	±6.08	±14.10
PEAK	Op (Nm/kg)	-0.37±0.23	-0.32±0.26	0.04±0.17	0.75 (0.59, 0.86)	±0.12	±0.28
	NoOp (Nm/kg)	-0.30±0.25	-0.31±0.25	-0.01±0.23	0.58 (0.35, 0.75)	±0.16	±0.38
	Op (Nm)	-27.90±16. 14	-25.32±21.08	2.58±13.48	0.71 (0.54, 0.83)	±9.54	±22.11
	NoOp (Nm)	-22.78±20.44	-24.33±21.08	-1.56±18.55	0.61 (0.38, 0.76)	±13.05	±30.26
	Asymm (%)	-3.7±31.0	9.6±45.9	13.3±52.9	0.08 (-0.20, 0.36)	±36.79	±85.32
Knee Flexion Moment							
IC	Op (Nm/kg)	-0.15±0.18	-0.11±0.17	-0.13±0.14	0.48 (0.23, 0.68)	±0.14	±0.34
	NoOp (Nm/kg)	-0.10±0.17	-0.15±0.15	-0.12±0.14*	0.33 (0.05, 0.56)	±0.11	±0.26
	Op (Nm)	-11.53±14.96	-7.89±13.00	-9.7±11.29	0.45 (0.19, 0.65)	±11.75	±27.26
	NoOp (Nm)	-6.97±13.37	-11.19±11.29	-9.08±10.60*	0.29 (0.01, 0.53)	±9.17	±21.27
	Asymm (%)	25.6±56.1	30.0±53.4	4.5±72.6	0.12 (-0.18, 0.40)	±51.28	±118.93
PEAK	Op (Nm/kg)	-0.99±0.34	-0.98±0.34	0.01±0.25	0.73 (0.56, 0.84)	±0.18	±0.41
	NoOp (Nm/kg)	-1.22±0.38	-1.26±0.42	-0.04±0.25	0.81 (0.68, 0.89)	±0.18	±0.41
	Op (Nm)	-77.40±29.59	-76.19±29.44	1.22±18.93	0.80 (0.66, 0.88)	±13.30	±30.85
	NoOp (Nm)	-94.83±36.79	-98.18±40.41	-3.34±17.52	0.90 (0.82, 0.94)	±12.45	±28.87
Knee Abduction Angle (degrees)							
IC	Op	-4.83±4.96	-5.29±5.31	-0.45±4.55	0.61 (0.39, 0.76)	±3.20	±7.42
	NoOp	-4.23±4.23	-4.08±4.87	0.16±3.04	0.78 (0.64, 0.87)	±2.12	±4.93
PEAK	Op	-17.92±9.29	-16.62±8.02	1.29±9.08	0.45 (0.19, 0.65)	±6.40	±14.85
	NoOp	-17.53±6.36	-16.78±7.15	0.75±6.39	0.56 (0.32, 0.73)	±4.50	±10.44
DISPL	Op	-13.08±7.22	-11.34±6.03	1.75±6.32	0.54 (0.30, 0.71)	±451	±10.46
	NoOp	-13.30±4.50	-12.71±5.70	0.59±4.54	0.61 (0.39, 0.76)	±3.18	±7.38

Knee Flexion Angle (degrees)							
IC	Op	16.73±7.27	17.38±6.88	0.65±5.75	0.67 (0.48, 0.80)	±4.06	±9.41
	NoOp	13.56±5.88	15.76±7.71	2.20±5.87*	0.61 (0.38, 0.76)	±4.26	±9.89
PEAK	Op	77.44±13.97	78.44±16.50	1.00±8.87	0.84 (0.73, 0.91)	±6.23	±14.45
	NoOp	78.83±13.97	80.08±15.22	1.25±8.37	0.84 (0.72, 0.91)	±5.91	±13.71
DISPL	Op	60.72±14.25	61.06±14.88	0.35±8.58	0.83 (0.71, 0.90)	±6.01	±13.93
	NoOp	65.27±14.68	64.32±14.78	-0.95±8.18	0.85 (0.74, 0.91)	±5.76	±13.36
Peak Vertical Ground Reaction Force (xBW)							
LP	Op	1.41±0.32	1.42±0.30	0.01±0.15	0.89 (0.81, 0.94)	±0.10	±0.24
	NoOp	1.59±0.31	1.62±0.30	0.03±0.18	0.82 (0.70, 0.90)	±0.13	±0.30
	Asymm (%)	3.8±5.9	4.2±4.9	0.4±3.9	0.74 (0.57, 0.85)	±2.76	±6.41
TO	Op	1.12±0.22	1.13±0.22	0.01±0.10	0.90 (0.83, 0.95)	±0.07	±0.16
	NoOp	1.23±0.28	1.22±0.26	-0.00±0.10	0.93 (0.87, 0.96)	±0.07	±0.17
	Asymm (%)	2.8±3.1	2.4±3.1	-0.4±2.0	0.78 (0.63, 0.87)	±1.44	±3.35
Loading Rate (xBW/s)							
	Op	16.32±6.50	16.79±5.20	0.47±4.50	0.71 (0.53, 0.83)	±3.16	±7.32
	NoOp	18.57±5.40	19.94±6.47	1.38±5.21	0.61 (0.39, 0.76)	±3.72	±8.64
	Asymm (%)	5.1±12.3	5.0±8.9	-0.0±11.7	0.41 (0.13, 0.63)	±8.16	±18.92
Transverse Plane Net Hip Moment Impulse (Nms/kg)							
	Op	-0.1x10^{-3}±0.001	-0.3x10^{-3}±0.001	-0.2x10^{-3}±0.001	0.42 (0.15, 0.63)	±0.001	±0.002
	NoOp	0.2x10^{-3}±0.001	-0.2x10^{-3}±0.002	-0.4x10^{-3}±0.001	0.61 (0.39, 0.76)	±0.001	±0.002

** $p < 0.05$*

Abbreviations: Time 1, first testing session at 6 months postoperatively; Time 2, second testing session at 6 months postoperatively +1 – 7 days from Time 1; Diff T_2-T_1, Difference between Time 2 and Time 1; ICC, Intraclass correlation coefficient; SEM, Standard error of measurement; MDC_{90}, Minimal detectable change with 90% confidence; Peak CoM height, peak height of the center of mass during the maximal vertical jump flight phase; Op, Operative limb; NoOp, Nonoperative limb; Asymm, Asymmetry index; IC, initial contact; DISPL, displacement; LP, Landing phase; TO, Toe off.

Table 3.3: Changes in drop vertical jump measures (*n*=36). Mean ± standard deviation (SD), isokinetic strength measures, global rating of change (GRC), and standardized response mean (SRM).

Test		**6mo (±SD)**	**12mo (±SD)**	**Change (±SD)**	**SRM**
GRC				3.1±2.0	
Peak CoM height (m)		1.731±0.113	1.702±0.173	-0.030±0.155	-0.19
Knee Abduction Moment					
IC	Op (Nm/kg)	-0.08±0.09	-0.05±0.13	0.03±0.12	0.27
	Op (Nm)	-5.89±7.13	-3.44±10.93	2.45±9.99	0.25
PEAK	Op (Nm/kg)	-0.37±0.23	-0.31±0.21	0.06±0.27	0.22
	Op (Nm)	-27.83±15.82	-25.03±23.22	2.80±20.71	0.14
Knee Flexion Moment					
IC	Op (Nm/kg)	-0.14±0.15	-0.14±0.20	0.01±0.24	0.02
	Op (Nm)	-10.57±12.15	-10.57±16.12	0.00±18.02	0.00
PEAK	Op (Nm/kg)	-1.03±0.30	-1.15±0.40	-0.13±0.47	-0.27
	Op (Nm)	-79.54±28.61	-87.40±33.63	-7.85±36.49	-0.22
Knee Abduction Angle (degrees)					
IC	Op	-4.95±4.65	-4.21±4.43	0.74±4.27	0.17
PEAK	Op	-16.92±7.74	-15.59±7.49	1.33±7.71	0.17
DISPL	Op	-11.98±6.27	-11.39±5.80	0.59±5.47	0.11
Knee Flexion Angle (degrees)					
IC	Op	17.62±7.04	18.26±7.95	0.64±8.13	0.08
PEAK	Op	78.60±14.86	83.70±15.10	5.10±13.38*	0.38
DISPL	Op	60.98±13.22	65.44±15.33	4.46±12.86*	0.35
Peak Vertical Ground Reaction Force (xBW)					
LP	Op	1.40±0.26	1.38±0.29	-0.01±0.22	-0.06
TO	Op	1.11±0.18	1.16±0.22	0.04±0.19	0.22
Loading Rate (xBW/s)					
	Op	15.99±5.33	15.20±5.27	-0.79±4.01	-0.20
Transverse Plane Net Hip Moment Impulse (Nms/kg)					
	NoOp	-0.1x10^{-3}±0.0014	-0.1x10^{-3}±0.0016	0.0x10^{-3}±0.0015	-0.02
Strength (Nm)					
Extension	Op	135.47±50.98	148.04±41.74	12.58±26.47*	0.48
Flexion	Op	66.15±25.29	71.46±21.92	5.31±12.81*	0.42

** p<0.05*

*** p<0.001*

Abbreviations: 6mo, mean of testing sessions 1 and 2 at 6 months postoperatively; 12mo, testing session 3 at 12 months postoperatively; SRM, Standardized response mean; GRC, Global rating of change; Peak CoM height, peak height of the center of mass during the maximal vertical jump flight phase; Op, Operative limb; NoOp, Nonoperative limb; IC, initial contact; DISPL, displacement; LP, Landing phase; TO, Toe off; Extension, knee extension; Flexion, knee flexion.

Table 3.4: Pearson correlations (*r*) between change in drop vertical jump measures (scores from time 3 *vs*. the mean score from times 1 and 2), the global rating of change (GRC), and change in strength.

Δ Variable		GRC (n=30)	Δ Strength (n=36) Knee Extension	 Knee Flexion
Peak CoM height (m)		-0.20	0.06	0.17
Knee Abduction Moment				
IC	Op (Nm/kg)	0.37*	0.29	0.48**
	Op (Nm)	0.43*	0.26	0.45**
PEAK	Op (Nm/kg)	-0.04	0.27	0.26
	Op (Nm)	0.05	0.38*	0.38*
Knee Flexion Moment				
IC	Op (Nm/kg)	0.33	0.13	0.41*
	Op (Nm)	0.35	0.21	0.45*
PEAK	Op (Nm/kg)	0.29	-0.02	0.22
	Op (Nm)	0.29	-0.07	0.17
Knee Abduction Angle (degrees)				
IC	Op	0.05	-0.05	-0.17
PEAK	Op	0.06	-0.04	-0.14
DISPL	Op	0.05	-0.01	-0.06
Knee Flexion Angle (degrees)				
IC	Op	0.03	-0.20	-0.35*
PEAK	Op	-0.11	0.06	-0.01
DISPL	Op	-0.15	0.19	0.21
Peak Vertical Ground Reaction Force (xBW)				
LP	Op	0.27	0.21	0.13
TO	Op	0.18	0.05	-0.05
Loading Rate (xBW/s)				
	Op	0.06	0.16	-0.00
Transverse Plane Net Hip Moment Impulse (Nms/kg)				
	NoOp	0.20	0.18	0.32

* $p < 0.05$

** $p < 0.01$

Abbreviations: Δ, Change; GRC, Global rating of change; Peak CoM height, peak height of the center of mass during the maximal vertical jump flight phase; IC, initial contact; DISPL, displacement; LP, Landing phase; TO, Toe off; Op, operative limb; NoOp, nonoperative limb.

3.5 Discussion

This study provides reliability and longitudinal validity data for key biomechanical variables (movement patterns) evaluated during a DVJ that are risk factors for ACL injury and targets of rehabilitation after ACL reconstruction. The study was completed at a time postoperatively where ACL reconstruction patients typically aim to return-to-sport[27] and exercises to improve dynamic knee stability are a focus of rehabilation[18]. Reliability coefficients ranged from poor-to-excellent. Knee moments at IC had the lowest reliability (< 0.48), while VGRFs and peak KFM had the highest reliability (0.73 - 0.93). Longitudinal validity, as indicated by the SRM, suggest small to moderate changes for the majority of the variables analyzed. Improved strength measures over time were associated with a reduction in peak KAM and greater KFM at IC showing improved landing biomechanics.

Previous investigators have evaluated the reliability of the DVJ performed by young healthy participants. Ford et al[8] reported good-to-excellent reliability of kinematic and kinetic variables during the DVJ in a sample (n=11) of healthy young basketball and soccer athletes. Mok et al[15] also reported also reported good-to-excellent reliabilty in a sample (n=41) of healthy elite female handball and soccer athletes. To our knowledge, the present study is the first to evaluate the reliability of DVJ parameters in patients undergoing rehabilitation after ACL reconstruction.

The present ICCs for KAM and KFM variables ranged from 0.58 to 0.80 (Table 3.2) and were slightly lower than those reported by Ford et al[8] (0.87 and 0.84 for peak KAM and KFM, respectively) and Mok et al[15] (0.69 and 0.85 for KAM and KFM, respectively). The present KAAs were also generally lower (ranged from 0.45 - 0.78) than those reported by Ford et al[8] (0.80 - 0.86) and Mok et al[15] (0.75 - 0.81), whereas KFAs were generally higher (KFA at IC 0.67 and 0.61, and 0.83 - 0.85 for peak and displacement) than those reported by Ford et al[8] (0.40 - 0.62) and Mok et al[15] (0.74 - 0.79). Greater variability in DVJ biomechanics in patients 6 months after ACL reconstruction versus healthy participants is not surprising and this finding should be considered when evaluating the DVJ in patients undergoing postoperative rehabilitation. Also, there are a number of factors that may affect the reliability of optical motion capture data, including marker placement[7,14], skin artefacts[3,8,22], single *vs.* multiple trial averages[8], and filtering frequency[8,22]. It is possible that differences in these testing methods also contributed to differences between the present and previously published studies.

Although an increased knee abduction moment during a DVJ is a predictor of initial ACL injury[12,21], less is known about its association with subsequent ACL injuries. Paterno et al[21] evaluated the association of modifiable risk factors for subsequent ACL injuries and identified the transverse plane net hip moment impulse as the strongest predictor. Specifically, participants who went on to retear had a net hip internal rotator moment in the uninvolved limb, while those who did not retear had an external rotator moment. In the present study, there was considerable variability between test sessions for the transverse plane net hip moment impulse and it did not change significantly from 6 to 12 months. This finding may suggest that strategies to more directly target weakened hip musculature with rehabilitation are required. As the gluteus maximus is the most powerful hip extensor and hip external rotator[19], exercises such as lunges, tuck jumps, lateral jumps and single limb exercises[21,24] that target the gluteals and other hip external rotators should be incorporated into the ACL rehabilitation process. Weaker gluteus maximus and medius strength has been found in individuals with patellar femoral pain[23]. These same individuals also had a net internal rotation moment of the hip during a drop jump task.

Asymmetry in landing mechanics during the DVJ is also associated with future ACL (re)injury[21] and is a focus during rehabilitation after ACL reconstruction[10]. We calculated the Symmetry Angle (see Equation 3.1) because it is suggested to be a robust indicator of inter-limb asymmetry percentage that is immune to inflated scores and the necessity to identify a reference limb[4,11,28]. Although the ICCs for asymmetry in force data including VGRFs at LP and TO were good (0.74 and 0.78, respectively), and loading rate was 0.41, asymmetry in knee moments were poor (peak KAM = 0.08 and KFM at IC = 0.12). As the ICC measured for asymmetry in peak KAM and KFM at IC were so poor, the reliability of the Symmetry Angle measure on motion analysis data is uncertain and should likely be reconsidered.

As the ICC provides a measure of relative reliability, an indication of how well a variable can distinguish between patients, the present ICCs suggest many of the tested variables are suitable when comparing groups of ACL reconstructed patients in research studies (Table 3.2). Alternatively, the SEM is a measure of absolute reliability, which can be used to estimate the measurement error in an individual patient’s performance. For example, the SEM of 9.54 Nm for the operative limb’s KAM at peak suggests considerable measurement error exists and should be considered when evaluating an individual patient’s DVJ KAM value. The large MDC (±22.11 Nm) also suggests this parameter is less useful for assessing potential change in a patients DVJ KAM with rehabilitation.

KFA peak and displacement values, and knee extension and flexion strength changed significantly from 6 to 12 months, and SRMs were mostly small-to-moderate (Table 3.3). An increase in KFA for peak and displacement is promising as increased KFA in landing reduces risk for ACL injury. Concurrent increases in knee extension and flexion strength may have contributed to the increased KFA.

The KAM at IC was moderately positively correlated to the GRC and to isokinetic knee flexion peak torque (i.e. strength). The peak KAM was also moderately positively correlated to knee flexion and extension (Table 3.4). Thus, larger increases in strength were associated with smaller KAMs, thereby demonstrating greater control in landing. A perceived and self-reported improved performance (GRC) was also correlated with a reduction in KAM at IC. Furthermore, increased knee flexion strength was moderately positively correlated with KFM at IC. This increased hamstring strength is likely associated with improved landing biomechanics (i.e. greater flexion moment). The negative correlation of knee flexion strength with KFA at IC shows that patients who landed in a more extended knee position (i.e. less knee flexion) also had reduced knee flexion (hamstring) strength.

There are limitations in this study. We evaluated the DVJ at 6 and 12 months after ACL reconstruction as the timing coincides with rehabilitation that focuses on jumping and sport-specific exercises. However, some participants may still have been hesitant to provide their maximal efforts during the DVJ at these time points. We encouraged maximal effort and included an overhead target during testing to standardize performance, and the repeatability of peak height of the CoM (i.e. maximal jump height) was the same between testing days 1 and 2 (ICC = 0.94), so we can safely assume that patients jumped in a similar manner on both days. Although the same testers completed the assessments during the test and re-test within 1 week at the 6-months postoperative visits, different testers may have run the testing at 12 months post-operative. That may have introduced measurement error that contributed to the relatively small changes observed and the generally low-to-moderate associations between change scores. Other measures such as knee-specific patient-reported outcomes and kinesiophobia may influence the reliability and longitudinal validity of the DVJ measures and were not assessed in this study.

3.6 Conclusion

The present ICCs observed in patients undergoing rehabilitation after ACL reconstruction suggest test-retest reliability of knee flexion and abduction angles and moments, asymmetries and VGRFs during the DVJ test vary from poor-to-excellent depending on the point of landing assessed. The measures with greatest reliability (ICC> 0.75) were the peak KAM in the operative limb, peak KFMs, KFAs, and VGRFs in both operative and nonoperative limbs. The present SEMs and MDCs suggest caution is required when evaluating change in an individual patient's specific DVJ parameters during rehabilitation after ACL reconstruction. Increased knee flexion and extension strength shows an improvement in landing mechanics as peak KAM is reduced and KFM and KFA at IC is increased.

3.7 Key Points

3.7.1 Findings

In patients undergoing rehabilitation after ACL reconstruction, reliability of biomechanical variables assessed during a DVJ ranged from poor to excellent. Changes in DVJ variables from 6 to 12 months postoperatively were associated with changes in strength.

3.7.2 Implications

Vertical ground reaction forces, peak knee abduction and flexion moments, and knee flexion angles can be evaluated with good reliability in patients as early as 6 months after ACL reconstruction. Changes in strength affects landing mechanics, particularly an improvement in strength increases knee flexion and reduces the knee abduction moment during the DVJ.

3.7.3 Caution

Measurement error should be considered when evaluating change in an individual patient’s DVJ parameters during rehabilitation after ACL reconstruction.

3.8 References

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3.9 Chapter 3 Supplement: Technical Note

Determination of filtering frequency for jumping analysis: Implications for anterior cruciate ligament rehabilitation injury prevention.

3.10 Supplement Summary

Biomechanical motion analysis of movement properties during jumping performance can provide valuable information when evaluating injury risk and readiness for return-to-sport in patients rehabilitating from anterior cruciate ligament (ACL) reconstruction. Motion analysis data has inherent error included in the collected raw data that must be filtered. Residual analysis is an objective means to determine filtering cut-off frequency. A digital filter is then applied to the raw data using the filtering cut-off frequency as determined using residual analysis. In biomechanics, a common filtering technique is the Butterworth filter. The process does however require trial-and-error and subjective judgement on the part of the researcher. For jumping analysis in ACL reconstructed patients, it was determined that a filtering cut-off frequency of 14 Hz for movement and 50 Hz for forces was acceptable to ensure physiological data is kept in the filtered signal for this cohort. A separate residual analysis is recommended for each cohort prior to analysis of motion analysis data.

3.11 Supplement Introduction

Anterior cruciate ligament injuries are devasting, and highly prevalent among athletes. Accompanying ACL injury is the financial burden of the injury through rehabilitation and often reconstructive surgery. The rate of return to activity after injury is less than desired, and the long-term effects, including osteoarthritis, are not favourable. Biomechanical analysis of human movement can provide important information with regards to human movement properties. Three-dimensional motion analysis techniques and force production allow the evaluation of kinematics and kinetics. Kinematics describe movement, irrespective of the forces that cause the movement, while kinetics describes the forces that cause the movement. Motion analysis has been used to evaluate landing mechanics to assess differences between healthy individuals and those who have suffered an ACL injury and reconstruction[4,6,7,9,23]. A useful and popular measure to analyze landing mechanics is the drop vertical jump (DVJ), which has been used in predicting risk for primary[2,14,21] and secondary[24] ACL injury. This provides researchers and practitioners information such as who may be predisposed to ACL injury, how patients recover after ACL reconstruction, or help identify those more likely to re-injure their ACL.

Collecting motion analysis data involves transformation from an analog to a digital signal. Unfortunately, this process introduces *noise* to the *true* signal, and therefore the *raw* data (noise + true signal) must be filtered before it can be analyzed and subsequently interpreted. Sources of noise, which is considered additional signal that was not attributed to the actual process itself (e.g. walking or jumping), can include electronic noise, spatial processing and human error[28]. Furthermore, marker placement[10,15], skin artefacts[3,11,26], vibrations in foot-to-ground contact[26], single *vs.* multiple trial averages[11], and filtering frequency[11,26] can all individually, or collectively, affect the final signal. Even with careful experimental procedures to minimize sources of noise, some will remain[5]. Therefore, raw kinetics and kinematics data need to be filtered to remove these artefacts so we can evaluate the movement signal.

3.12 Butterworth Filter

A widely used filtering technique in the field of biomechanics for kinetic and kinematic analyses is the zero-lag low-pass fourth-order Butterworth digital filter[29,30]. It was introduced for use in gait analysis by Winter et al[29], and later Pezzack et al[25] confirmed it was the best choice of several methods to attenuate noise in kinematic signals. While some methods such as finite difference differentiation left obvious artefacts in the signal, polynomial curve fitting tended to smooth the signal too much[25]. In a perfect world, we would filter out all the noise or artefacts from the raw data and keep only the true signal. This, however, is not possible. Filtering to ensure removal of all noise may result in a smooth signal that would look more visually appealing; however, we would lose important physiological data for the sake of removing all artefacts[28]. Over-filtering is therefore not appropriate.

Digital filtering using a Butterworth filter attenuates noise in kinematic and kinetic signals in biomechanics. It is based on frequency differences between signal and noise[28]. Frequency of human movement tends to be low-frequency or band-limited[5]. Noise is assumed to be primarily white noise with a flat power spectrum[5], which is largely high-frequency signal. Low-pass filtering will improve the signal-to-noise ratio by removing high-frequencies from the signal. The Butterworth filter can be defined by the following equation [see Equation 3.2][8], which is a second-order, recursive filter:

$$y_n = a_0(x_n + 2x_{n-1} + x_{n-2}) + b_1 y_{n-1} + b_2 y_{n-2} \qquad (3.2)$$

where y_n is the filtered signal, x_n is the raw data, a and b are coefficient constants of the filter determined by cut-off frequency and the number of passes[1,8]. Sample rate and cut-off frequency define the constants[1,5]. This recursive equation involves dependence on previous outputs to determine current output[5] and running the filter to smooth data therefore results in a phase lag or phase distortion[28]. To rectify this phase shift, the filter is run a second time, this time in the reverse direction[1,5,8,28,29], returning the filtered signal to be back in phase with the original data. This doubles the order of the filter and the result is a dual-pass (e.g. filtered in both forward and backward directions) fourth-order zero-lag digital filter. This low-pass filter is allowing low-frequency movement data to pass through within the defined band limit (i.e. below the cut-off frequency) and removing most of the high-frequency noise from the filtered signal. However, determining the optimal cut-off frequency remains challenging and an ongoing debate in the literature.

3.13 Optimal Cut-Off Filtering Frequency

An optimal cut-off frequency will provide us with the best approximation of our true movement signal, with the smallest amount of noise remaining. With walking or gait analysis, it has been well established that a cut-off frequency of 6 Hz[28,29] is typically appropriate to attenuate noise using a low-pass filter, while maintaining the mostly true signal. However, there is no established ideal filtering frequency of more dynamic, fast and high-load movements such as jumping or cutting, often seen in sports. This poses a problem when evaluating jumping or cutting performance with motion analysis. Moreover, it is often during one of these dynamic movements during a sporting session that ACL injuries occur. It is therefore imperative that we be able to accurately evaluate the loads that occur at the knee, and on the ACL itself.

Jumping frequency occurs at a frequency of 1 to 4 hz[17]. There is fast acceleration of limb segments and large impact ground reaction forces[26]. Typically, marker data from motion analysis are filtered at < 20Hz[26]. Meanwhile, with ground reaction forces (GRF), especially in jumping and cutting maneuvers, there is a high-impact peak that is observed. This involves large forces that are transmitted through the foot that need to be attenuated by the body, including muscles, bones, ligaments and tendons[26]. There is some debate regarding the appropriate cut-off frequency of GRFs and whether it should be the same as marker filtering frequency (e.g. Kristanslund et al[16]), or if this would result in inappropriate loss of important physiological information[26]. Roewer et al[26] therefore suggest different filtering frequencies should be applied to marker and GRF signals in jumping analysis, especially when injury prediction or prevention is involved. In fact, Hewett et al[14] demonstrated that applying different filtering cut-off frequencies for marker (9 Hz) and GRF (50 HZ) in the analysis of peak knee abduction moment (KAM) during the DVJ maneuver predicted ACL injury in female athletes with high sensitivity and specificity. Regardless, determination of optimal filtering cut-off frequency for the movement in question should be determined via residual analysis[28]. This can be done for both marker and GRF data separately.

3.14 Residual Analysis

Residual analysis is a means to assist in the decision-making process for optimal filtering cut-off frequency. It evaluates the differences between the *raw* and *filtered* signals over a range of cut-off frequencies[22,27,28]. The *residual* is the signal that remains after the *filtered* signal is removed from the *raw* signal[27]. The *residual* is determined using the following equation [see Equation 3.3][28]:

$$R(f_c) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\mathrm{X}_i - \hat{X}_i)^2} \qquad (3.3)$$

where R is the residual, f_c is the cut-off frequency of the dual-pass fourth-order zero-lag Butterworth filter, N is the sample points of the signal in time, X_i is *raw* data at the *i*th sample, and $\hat{X}_i$ is the filtered data at the *i*th sample using the aforementioned filter[28] (*p*.70). These residuals can then be plot as a function of the range of filtering frequencies chosen (see Figure 3.3). A sharp rise in the residual at lower frequencies is signal distortion that is taking place[28]. It is at this inflection point that the *optimal* frequency (*a*) for displacement data occurs[28]. *Optimal* frequency is at a point where the signal distortion is equal to residual noise[28].

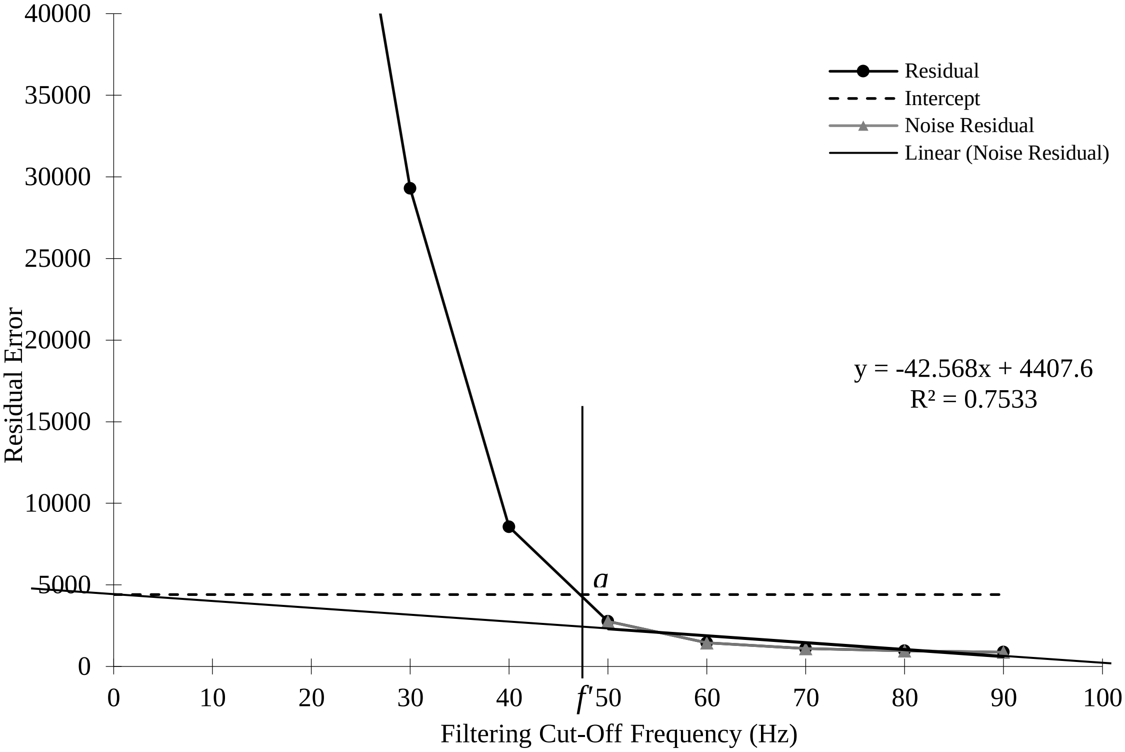

Figure 3.3: Plot of the residual analysis of ground reaction forces during the landing phase of the drop vertical jump for a selected subject (Subject A). The sum of squares of the residual (*y*-axis) are plot over a range of filtering cut-off frequencies (*x*-axis). A line is drawn through the flat part of the curve (*Noise Residual*) through to the *y*-intercept. A horizontal line (*Intercept*) is drawn from the *y*-intercept. The intersection of the *Residual* curve and the horizontal line (*a*) identifies the ideal cut-off frequency (*f'*).

The plot of residual *vs* frequency gives us an objective tool to assist in the determination of the desired cut-off frequency. In Figure 3.3, is an example of a plot of the residual. The sum of squares of the residual are plot over a wide range of cut-off frequencies ("*Residual*"). The curve will drop and then flatten. It is at this abrupt change that the *optimal* cut-off frequency (*f'*) occurs. The process nonetheless requires trial-and-error to come to a decision where the filtered curve passes reasonably through the "middle" of the raw data[25]. For example, in Figure 3.4 we have the residual analysis of frontal plane knee kinematics during the landing phase of a DVJ. The *f'* is slightly greater than 11 Hz. Figure 3.5 shows the curves of *raw* data *filtered* data at a variety of cut-off frequencies for this same trial. This provides a visual representation of which cut-off frequency should be considered for analysis, and trial-and-error or best judgement is applied.

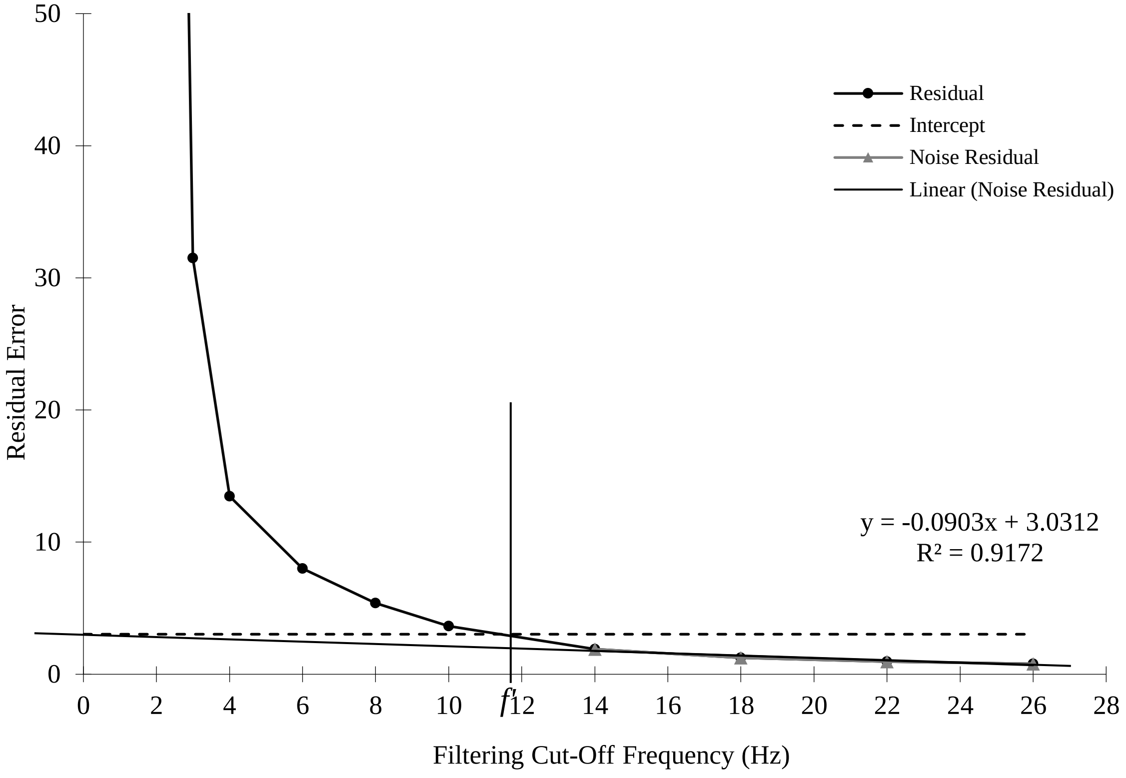

Figure 3.4: Residual analysis of frontal plane knee kinematics during the landing phase of a drop vertical jump for a representative subject (Subject A). Based on this analysis, the *optimal* cut-off frequency (*f'*) was determined to be almost 12 Hz for this trial.

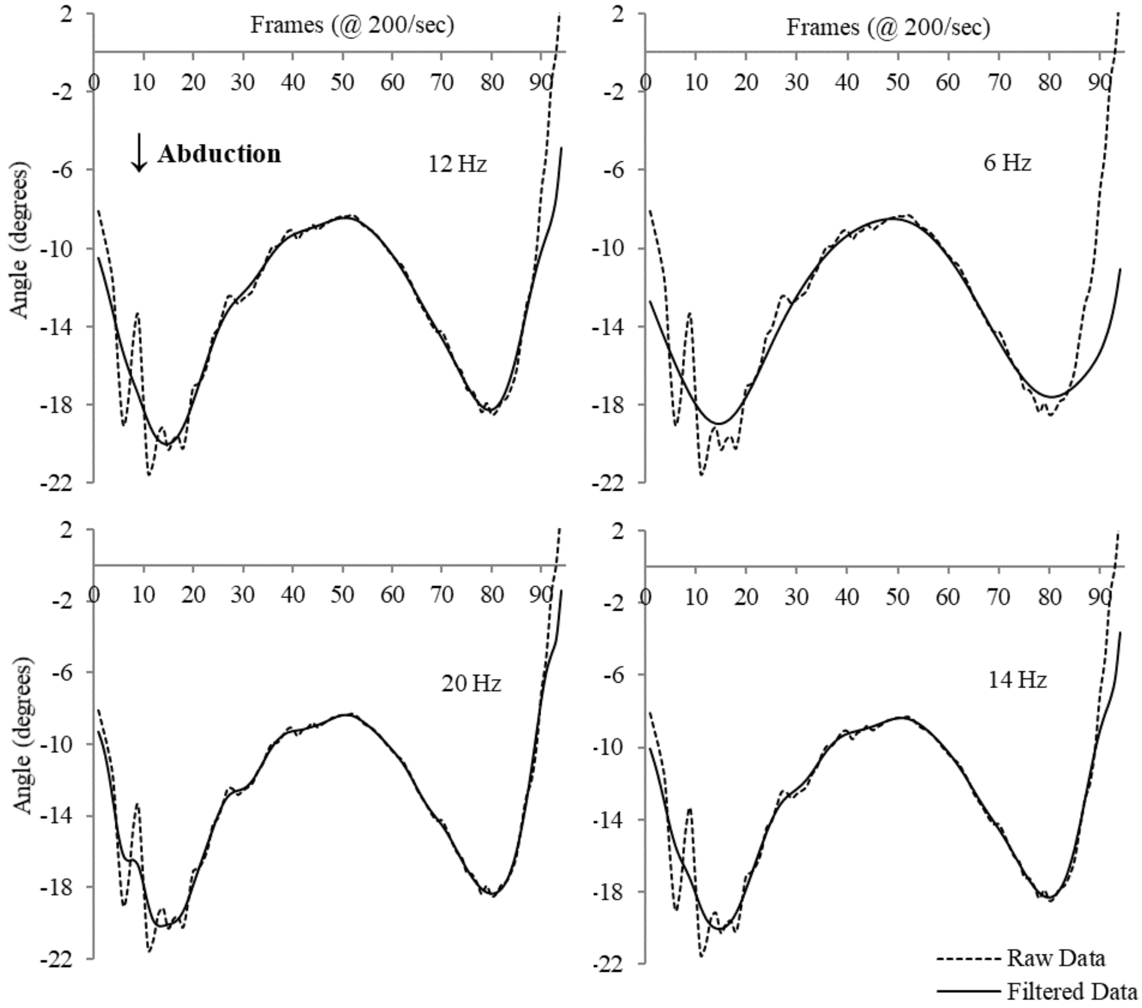

Figure 3.5: Filtered and raw data for frontal plane knee kinematics during the landing phase of the drop vertical jump of a representative subject (Subject A). Sampling rate was 200 Hz. The *optimal* filtering frequency (*f'*) was determined via residual analysis to be 12 Hz (see Figure 2). The curve in the upper left quadrant is filtered at 12 Hz. Top right used a filtering cut-off of 6 Hz, and it is evident that the filtered curve does not follow a trajectory "through the middle" of the raw data and some physiological information is lost. In the bottom left quadrant, data was filtered at 20 Hz. The filtered data here tends to follow the raw data too closely. In the bottom right quadrant, a filtering cut-off of 14 Hz was implemented, which is similar to the 12 Hz cut-off.

The representative data portrayed in Figures 3.3 and 3.4 is representative of DVJ performance for one variable, during one trial, on one limb, for a single subject. It is a tedious, time consuming process. If we look at the performance of a different subject, for the same variable, the results will differ, as illustrated in the residual analysis graph in Figure 3.6. Completing this process for each trial, for each limb, for each subject, for each time point in a larger scale study, is very time consuming. An alternative approach is to complete a residual analysis on a subject within the cohort that has demonstrated good performance on the DVJ, along with a residual analysis on a subject that demonstrates obvious undesirable movement in the landing of their DVJ performance. Undesirable movement identified in the DVJ can include a dynamic knee valgus collapse, and other movements such as lateral trunk lean, insufficient trunk flexion, insufficient knee flexion, and limb-to-limb asymmetry[12]. From this process, it is the judgement call of the respected researcher to determine the appropriate cut-off frequency to implement in their analyses for their respective subject cohort.

3.15 Decision of Filtering Cut-Off Frequency

This process, while objective, is nonetheless subjective to the judgement of the researcher. Residual analysis provides an objective starting point in determining appropriate cut-off frequency. Additionally, the researcher should reflect on the literature and the cut-off frequencies implemented by previous researchers in similar settings. With the DVJ, a variety of cut-off frequencies have been applied by various research groups. Hewett et al[14] filtered their kinematics and kinetics at 9 Hz and forces at 50 Hz. Paterno et al[24], Ford et al[11], and Myer et al[20] all filtered their motion and force data at 12 Hz. Myer et al[21] reported a filtering frequency of 12 Hz for kinematics but did not report the filtering frequency for forces. Bates et al[2] filtered their kinematics and kinetics at 12 Hz, and their forces at 100 Hz. Finally, a reliability study on drop jump landing in elite athletes filtered marker trajectories and forces at 15 Hz[19], while another reliability study on stop jump landings[18] filtered their kinematics at 6 Hz and ground reaction forces at 60 Hz. Meanwhile, some studies do not report the filtering cut-off frequency they applied[4,6,7,23]. Evidently, there is no clearly defined optimal filtering frequency that can be applied for jump landing analysis across laboratories and populations.

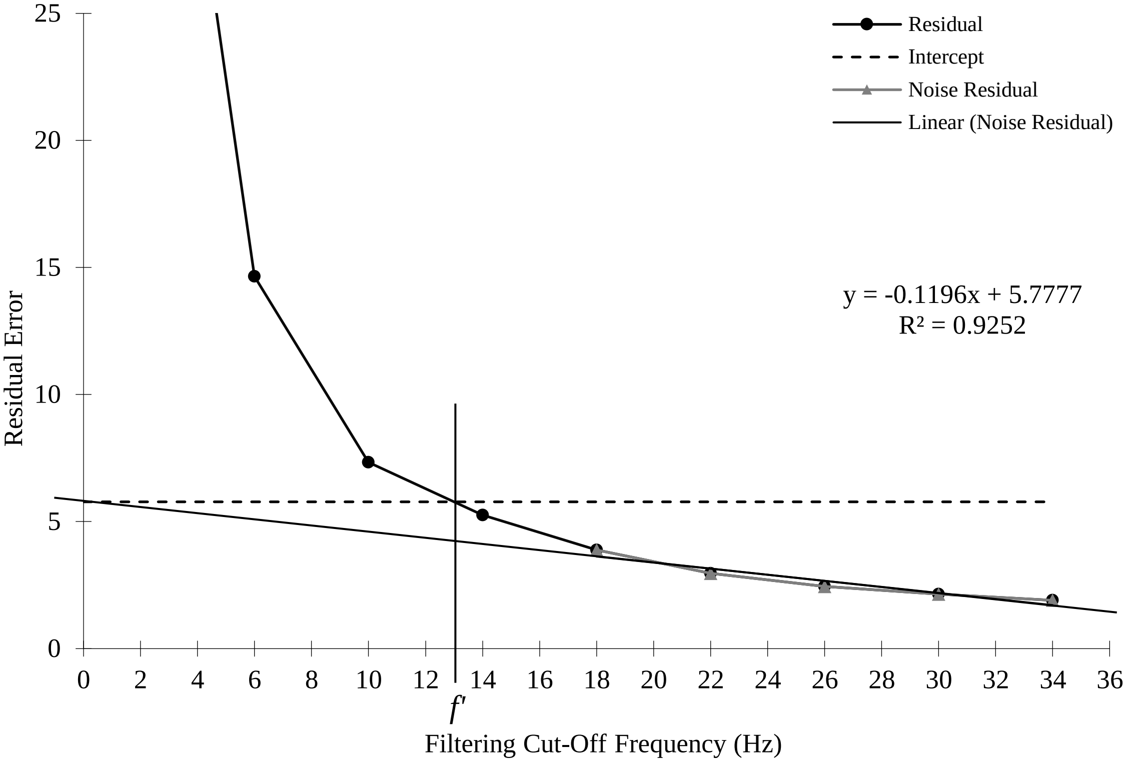

Figure 3.6: Residual analysis of frontal plane knee kinematics in a different subject during the landing phase of the drop vertical jump of a representative subject (Subject B). *Optimal* cut-off filtering frequency (*f'*) is 13 Hz for this trial.

To further complicate the issue, a few studies have attempted to address the filtering cut-off frequencies for movement and force data, particularly for injury prevention. Kristianslund et al[16] completed motion analysis evaluation of a side-step cutting movement in elite handball players using same and different filtering cut-off frequencies for movement and force: 10-10, 15-15, 10-50, and 15-50 for movement and forces, respectively. They reported that force and movement data should be processed with the same low filtering frequency, and even recommended that previously reported jump landing studies with different filtering frequencies should be interpreted with caution. However, a study by Roewer et al[26] specifically evaluating the DVJ, responded to the study suggesting Kristianslund et al[16] may have "over-extended" their results by comparing filtering frequencies of side-stop movement to jump landing. Roewer et al[26] evaluated the DVJ at a variety of same (10, 12, and 15 Hz) and different (10-50, 12-50, and 15-50 Hz for movement and forces, respectively) filtering frequencies. In particular, Roewer et al[26] evaluated the difference in peak knee abduction moment (KAM) as a result of changes in filtering frequency. Peak KAM has been identified as an important predictor of primary ACL injury[14]. A peak KAM that exceeds a threshold of 25.25 Nm[21] indicates ‘high risk’ for ACL injury. In their analyses, Roewer et al[26] identified 17 of 22 subjects of being at risk for ACL injury when different filtering frequencies were applied to movement (10 Hz) and forces (50 Hz), yet three of these subjects were no longer considered ‘at risk’ when data was filtered using same low cut-off filtering frequencies. Applying same low cut-off filtering frequency may therefore prove too aggressive, filtering out vital physiological information. When an increased injury risk is identified, appropriate prevention strategies such as neuromuscular training specifically developed to reduce ACL injury risk[13] can be initiated to reduce this risk. Arguably, it is more ethical to intervene and work to reduce injury risk, than filter more aggressively and potentially miss patients that may be at high risk for ACL injury.

Further to the debate on using low cut-off filtering frequencies in biomechanics, computer simulation of the countermovement jump (CMJ) has been implemented to evaluate whether completing residual analysis to determine optimal cut-off frequency is appropriate[22]. A noise-free kinematic computer simulation of a CMJ was created. Random white noise was then added to distort the signal and add typical error that is seen with *in vivo* biomechanical analyses. A residual analysis was then performed to determine the optimal filtering frequency (*f’*) and a fourth-order zero-lag Butterworth digital filter was thereafter applied to filter the computer simulated CMJ data. It was found that through residual analysis the *f’* was underestimated, potentially resulting in information loss from the kinematic signal. Nagano et al[22] concluded that when possible, the *f’* should be determined by analyzing error-free kinematics. While this process may not be feasible for all situations, an alternative approach could be to determine an approximate *f’* for the subject population, and applying a conservative approach, choose a filtering frequency that is slightly greater than that identified with the residual analysis. This would inherently reduce the possibility of over-filtering and information loss.

For the purposes of determining the *f'* for a large-scale research project evaluating the effectiveness of two different rehabilitation strategies in a subject population with patients completing rehabilitation following ACL reconstruction, a residual analysis was carried out. Two subjects were chosen, one that was identified as having 'good' performance on the DVJ, and one that demonstrated 'risky movement patterns', three trials were evaluated on each limb, per subject for frontal plane knee motion (12 residual plots analyzed) and for ground reaction forces (12 residual plots analyzed). Frontal plane knee motion was used for the residual analysis as it has been shown to be highly relevant in identifying ACL injury risk[14,24]. An example of residual analysis results for *f'* for movement data are shown in Table 3.5. Figures 3.3, 3.5 and 3.6 show an example of the plot of the residual analysis for representative Subject A for forces (Figure 3.3) and frontal plane movement (Figure 3.4), and for Subject B frontal plane movement (Figure 3.6). Based on the residual analyses and visual inspection, a conservative approach was adopted to minimize information loss, and an *f'* was selected at a cut-off filtering frequency of 14 Hz for movement and 50 Hz for forces.

Table 3.5: Example of residual analysis for frontal plane movement for two representative subjects completing the drop vertical jump. Three trials were evaluated for each subject, in each limb. The right limb was the ACL reconstructed limb for both subjects. The optimal filtering frequency (*f'*) is displayed. Visual inspection for each trial was also completed for each trial at varying frequencies around the identified *f'*. Results of the researchers' visual inspection for ideal smoothing is reported. An example of the visual inspection of curves through raw data can be seen in Figure 3.5.

Subject	Trial	Limb	*f'*	Visual
A	1	R	11-12	12-14
		L	9	14
	2	R	7	12-14
		L	11-12	14-16
	3	R	10	12
		L	14-15	14
B	1	R	13	14-16
		L	12-13	14-16
	2	R	14-15	16
		L	12	14-16
	3	R	13	12
		L	11-12	14-16

3.16 Supplement Conclusion

A decision process guided by residual analysis provides an objective means to decide on filtering cut-off frequency in biomechanics research. The process should be completed for each subject cohort prior to evaluating movement properties of biomechanical data. Residual analysis tends to underestimate the cut-off frequency. It is important to consider the risks of removing more noise at the sake of losing physiological data, especially when predicting or evaluating injury risk. The residual analysis process implemented for analyzing movement properties during a DVJ for this cohort of subjects that have undergone recent ACL reconstruction resulted in a filtering cut-off frequency of 14 Hz for kinematics and kinetics, and 50 Hz for GRFs. This may differ from other subject cohorts, and in other research settings. A separate residual analysis should be performed prior to analysis of biomechanical movement properties for each study.

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Chapter 4

4 A randomized trial of a staged home-based and in-clinic rehabilitation programs after anterior cruciate ligament reconstruction: biomechanical and functional outcomes

4.1 Summary

The objective of this study was to compare biomechanical and functional outcome measures in patients undergoing staged (home-based and in-clinic) rehabilitation after anterior cruciate ligament (ACL) reconstruction versus usual care. Rehabilitation after ACL reconstruction lasts several months and includes a focus on neuromuscular exercises and sport-specific training to achieve optimal biomechanical and functional outcomes. There can be substantial barriers to attending in-clinic rehabilitation for prolonged periods. We randomized patients undergoing ACL reconstruction to staged postoperative rehabilitation (n = 62) or usual care (n = 63). Staged rehabilitation included remote, home-based physical therapy for the first 12 postoperative weeks followed by in-clinic supervised physical therapy for the following 12 weeks. Usual care consisted of typical in-clinic supervised physical therapy for 24 weeks. Landing biomechanics during a drop vertical jump (DVJ), forward hop for distance and isokinetic knee extension and flexion strength were compared 6 and 12 months postoperatively. No group differences for primary and secondary functional outcomes measures were observed between rehabilitation groups at 6 months. The staged group had significantly greater operative limb peak knee abduction moment (-20.70 Nm ± 12.39 for usual care *vs.* -26.89 Nm ± 19.21 for staged; p = 0.03) and limb-to-limb symmetry for peak knee abduction moment (2.38 Nm ± 17.10 for usual care *vs.* -7.55 ± 18.91 for staged; p = 0.00) at the 12 month follow-up. Both groups had significant within-group limb asymmetry at both 6- and 12-months for vertical ground reaction forces, loading rate and knee flexion moments. No differences in hop nor strength testing were observed between groups. Completing home-based physiotherapy in the early-stages of rehabilitation can be an effective measure for patients who have the motivation and resources to complete their rehabilitation exercises at home, when detailed instruction by a qualified therapist is provided beforehand. Future consideration of neuromuscular

function and the long-term success of rehabilitation programs is an ongoing problem that is necessary to investigate.

4.2 Introduction

Rehabilitation after anterior cruciate ligament (ACL) reconstruction focuses on enabling patients to pursue an active lifestyle after surgery, including return to high risk activities such as jumping and cutting. ACL rehabilitation typically lasts several months and is generally divided into early and later postoperative phases[22,30]. The early phase focuses primarily on managing pain and swelling and recovering range of motion and strength in the operative limb. The later phase focuses on dynamic stability of the limb, aiming to prepare the patient for return to high level functioning, including pre-injury level of sport[22,30]. The possibility for failure of ACL graft, and an increased chance for injury to the contralateral limb[20] are greatly elevated during return-to-sport[30,31]. Modern ACL rehabilitation protocols progressively place increased demands on the operative limb during the later phase, with the goal of attaining optimal dynamic stability of the limb and safely returning the patient to pre-injury levels of function and performance.

Unfortunately, there are substantial barriers to attending in-clinic rehabilitation for prolonged periods of time. Although current safety concerns related to COVID-19 highlight the importance of being able to deliver care remotely, there are other important barriers that can hinder attendance to in-clinic ACL rehabilitation. Many insurance companies cover only a portion of the costs associated with physiotherapy. If these funds are depleted in the early postoperative rehabilitation phase, patients may be unable to continue with the late-phase, sport-specific rehabilitation that is thought to be crucial for neuromuscular training and injury prevention. An alternative approach to ACL rehabilitation to facilitate patient adherence to late-stage in-clinic physiotherapy is therefore warranted. Home-based rehabilitation programs following ACL reconstruction may be promising, however, evidence-based approaches evaluating functional outcomes of known predictors of secondary ACL injury has yet to be conducted. Moreover, to date, only one published study investigating effectiveness of a home-based ACL rehabilitation program presented adequate statistical power[19]. The study reported that the home-based group had significantly greater knee flexion and extension ROM, but no differences in any other measures (ROM during walking, knee laxity, and strength) at 3 months postoperatively. Furthermore, the evaluation of functional outcomes, such as the drop vertical jump, has yet to be examined, and provide critical insight on patient rehabilitation success.

Previous studies[12,18,19,23,37] have investigated alternative ACL rehabilitation strategies, and suggest that with the right type of patient (i.e. motivated, adequate resources and support at home) and sufficiently detailed instruction, completing home-based ACL rehabilitation can be accomplished. However, although promising, the ability of alternative rehabilitation to achieve the same biomechanical and functional outcomes that are the focus of later-stage physiotherapy remains unknown. Importantly approximately 65-75% of patients return to their pre-injury level of sport after ACL reconstruction[5], and of those that return, as many as one in four sustain a second knee injury[22]. Risk factors for ACL injury include aberrant landing biomechanics observed during a drop vertical jump (DVJ), such as greater knee abduction moment[21,35]. Moreover, risk factors for secondary ACL injuries have been identified and include side-to-side asymmetries and the hip rotation impulse of the uninvolved limb in the early phase of the DVJ[22,35]. These are modifiable motor function and neuromuscular patterns that can be addressed with preventative rehabilitation protocols. Such prevention programs have shown promise for prevention of primary ACL injury[10,31]. A shift of focus from early-guided physiotherapy to a later-stage, sport-specific guided physiotherapy may prove beneficial for patients in preventing secondary knee injuries.

The objective of this study was to evaluate whether a staged physiotherapy program (e.g. home-based rehabilitation followed by late supervised physiotherapy) leads to similar functional measures, including biomechanical measures of drop vertical jump, hop testing, and strength, as usual care physiotherapy (early supervised) in patients following primary unilateral autograft ACL reconstruction.

4.3 Methods

4.3.1 Trial Design

This study was completed at the Wolf Orthopaedic Biomechanics Lab, Fowler Kennedy Sport Medicine Clinic, University of Western Ontario, Canada. The study was a randomized trial with two parallel groups and a primary endpoint of 12 months after ACL reconstruction. Primary biomechanical DVJ measures were assessed at 6- and 12-months, secondary functional measures of hop and strength testing were assessed at baseline (pre-surgery) and at 6- and 12-months, and secondary descriptive measures of range of motion and IKDC were assessed at baseline. Sixty patients per group were recruited based on 80% power to detect a moderate effect size with alpha set at 0.05[8].

4.3.2 Participants

Patients were randomized to either a Usual Care physiotherapy or a Staged Physiotherapy intervention following primary unilateral ACL reconstructive surgery. Eligibility requirements are listed in Table 4.1. Patients were recruited at the Fowler Kennedy Sport Medicine Clinic where they were seeing an orthopaedic surgeon for their injury. Five orthopaedic surgeons were involved in the study. All participants underwent unilateral hamstring autograft ACL reconstruction, which eliminated the influence of graft choice on the rehabilitation intervention.

4.3.3 Randomization

Patients were randomized on a 1:1 basis to one of two groups, 1) Usual Care (UC), and 2) Staged Physiotherapy (SP). Randomization occurred after surgery assuming the patient still met eligibility criteria. Randomization was in permuted mixed block sizes and stratified by surgeon, presence or absence of meniscal repair, and whether they attend the Fowler Kennedy Clinic for their physiotherapy.

Two researchers recruited patients to the study. One researcher was responsible for randomization of patients after their surgery. This was completed in EmPower (empower health research inc. 2009). The researcher then informed subjects of their group allocation and provided direction on their intervention and rehabilitation process.

Table 4.1: Study inclusion and exclusion criteria.

Inclusion:	
(1)	Between 15 and 40 years of age
(2)	Unilateral ACLR
(3)	Hamstring autograft ACLR
(4)	Available for post-operative rehabilitation at specified time periods: before surgery, 2-weeks, 6-weeks, 12-weeks, 6-months, 12-months, and 24-months
Exclusion:	
(1)	Previous or concomitant ACLR on either knee
(2)	Requires repair or reconstruction of posterior cruciate or medial cruciate ligament
(3)	Past/present history of metabolic bone, collagen, crystalline, degenerative joint or neoplastic disease
(4)	Chondral defect requiring treatment
(5)	Femoral, tibial or patellar fracture (other than Segond fractures)
(6)	Patient does not speak/understand English language
(7)	Patient has cognitive impairment or psychiatric illness that precludes informed consent or renders the patient unable to complete questionnaires
(8)	Patient has no fixed address and no means of contact
(9)	Patient has a major medical illness where life expectancy is less than two years

4.3.4 Blinding

The researcher who was primarily responsible for collecting and analyzing the DVJ and strength measures was blinded to subject group allocation throughout the study. Treating orthopaedic surgeons were blinded to group allocation throughout the study.

4.3.5 Interventions

Patients randomized to UC group attended their first consultation with a physiotherapist of their choice (Fowler Kennedy or Community clinics) at approximately 2 weeks post-surgery and continued with in-clinic physical therapy as per the usual practice of their respective therapist. The physiotherapist was provided the ACL Protocol (currently provided to all patients who have undergone an ACL reconstruction). The ACL Protocol is included in Appendix G. Both physiotherapy programs (UC, SP) were designed by physiotherapists at the Fowler Kennedy clinic who have more than 10 years of experience with providing therapy for patients who have undergone an ACL reconstruction.

Patients randomized to the SP group attended one appointment with a physiotherapist at 2 weeks post-surgery, and their second appointment at 6 weeks. The patients allocated to SP completed the first 12 weeks of their protocol at home with the guidance one of two physiotherapists from the Fowler Kennedy Clinic. These two physiotherapists oversaw SP patients for their home-based rehabilitation program. Patients received a copy of the home-based program and reviewed the first half of the program with the physiotherapist. The home-based program of the SP group is included in Appendix F. The home-based portion of the SP program was 12-weeks in duration. At six weeks, SP patients returned to the clinic to meet with their respective physiotherapist to review the second half of the home-based SP program. Patients then returned at 12 weeks post-surgery and received a copy of the ACL Protocol (same as UC group). Patients attended in-clinic physiotherapy regularly from 12 – 24 weeks with a physiotherapist of their choice. The surgeon's instructions to the physiotherapist was to start sport-specific rehabilitation under supervision according to the provided ACL Protocol.

4.3.6 Both Groups

Both groups were seen by their orthopaedic surgeon at 6- and 12-weeks post-surgery. At 6 weeks, the surgeon evaluated patient progress by answering yes or no to the following questions: Does the patient demonstrate; 1) an inability to bend their knee at least 80° (knee flexion), 2) an inability to straighten their knee by greater than 10° (knee extension), 3) an inability to contract and hold their quadriceps muscle, 4) an inability to perform a straight leg raise, and 5) a quads avoidance gait pattern? If the surgeon answered 'yes' to any of these questions the patient was instructed to increase their visits to a physiotherapist until all required criteria were met, after which, they continued treatment according to their respective groups.

At 12 weeks, the treating orthopaedic surgeon evaluated patient progress by answering yes or no to the following questions: Does the patient demonstrate; 1) an inability to bend their knee at least 90° (knee flexion), 2) an inability to fully straighten their own knee (active and passive knee extension), and 3) a quads avoidance gait pattern? If the surgeon answers 'yes' to any of these questions the patient was asked to increase their visits to a physiotherapist.

4.3.7 Outcome Measures

We selected two primary outcome measures assessed during a DVJ at 12-months post ACL reconstruction: the peak knee abduction moment (peak KAM); and the transverse plane net hip moment impulse. The DVJ has previously been shown to identify primary[21] and secondary[35] risk factors for ACL injury in females. Peak knee abduction moment during landing has been identified as a key predictor of primary ACL injury[21]. Paterno et al[35] reported that transverse plane net hip moment impulse in the uninvolved limb was the strongest predictive risk factor for secondary ACL injury. The DVJ was assessed at 6- and 12-months post-operatively.

Secondary outcome measures of functional performance in the DVJ were also collected, including side-to-side differences in lower extremity biomechanics, and vertical ground reaction forces (VGRF). Additionally, hop testing and strength measures were evaluated. Secondary measures of hop testing and strength were assessed at baseline, 6-months and 12-months post-operatively. These have previously been reported to provide valuable information on the rehabilitation of the ACL reconstructed limb, and on safety in returning to sport. Range of motion (ROM) of the knee joint and the International Knee Documentation Committee (IKDC) Subjective questionnaire were administered at baseline to help describe the patient population.

4.3.8 Drop Vertical Jump

The DVJ protocol has been described in detail previously[13,15,16,21]. Briefly, subjects were instrumented with 22 passive-reflective markers for the DVJ using a modified Helen Hayes marker set. Each subject performed four successful DVJ trials. The DVJ task had the subject stand on a box 31 cm in height with the feet ~ 35 cm apart and toes slightly overhanging the edge. Subjects were instructed to drop off the box with both feet at the same time, and immediately perform a maximum vertical jump, consistent with instructions described in previous studies[13,15,21]. The initial landing on the force plates was used for analysis in three successful trials.

Three-dimensional marker and force plate data were collected using commercially available software (Cortex-64 2.6.5, Motion Analysis Corporation, Santa Rosa, CA) and ten high-speed digital cameras (Motion Analysis Corporation, Santa Rosa, CA) at a sampling frequency of 200 Hz, synchronized with two force plates (Advanced Mechanical Technology Inc., Watertown, MA) positioned 8 cm apart and sampled at 1200 Hz. The system was calibrated using a static calibration frame to orient the cameras to the laboratory coordinate system, followed by a dynamic wand calibration, prior to data collection.

4.3.9 Drop Vertical Jump Data Analysis

These data analysis techniques have been previously described in detail by Gagnon et al[16]. Data reduction of the DVJ was completed using Cortex, and exported to Microsoft Excel, where data were filtered using a low-pass fourth-order Butterworth filter. Joint angles (kinematics) were determined using the XYZ Euler Rotation Sequence with Z as the bone axis (Cortex-64 4.0.0, Motion Analysis Corporation, Santa Rosa, CA). The marker and force data from each trial were combined and used to calculate knee abduction, knee flexion and hip rotation moments using principles of inverse dynamics, and net external moments relative to the tibial anatomical frame of reference are described (Cortex-64 4.0.0, Motion Analysis Corporation, Santa Rosa, CA).

Vertical ground reaction forces were used to determine initial contact (IC) and takeoff of the initial landing in the DVJ. Discrete variables of kinematics and kinetics for both the operative and nonoperative limbs (*n = 250 limbs*) for knee frontal and sagittal plane at initial contact (IC), peak values, and displacement were evaluated during the landing phase of the DVJ. Transverse plane hip net moment impulse in the first 10% of landing phase[16,35] was calculated. Maximum VGRF (xBW) during the landing and takeoff phases and loading rate ($xBW \cdot s^{-1}$) during the landing phase were measured. Angular displacement of the knee in the frontal and sagittal planes was calculated as the difference between peak and IC abduction and flexion angles, respectively. By convention, knee adduction, knee flexion and hip internal rotation were represented as positive values. On each test occasion, all DVJ discrete variables were recorded in their respective units and calculated as the mean of three trials.

4.3.10 Hop Testing

Four hop tests (single leg hop for distance, timed 6-m hop, triple hop and crossover triple hop) were administered, and the resulting limb symmetry index (LSI)[32] was calculated. A thorough explanation of these hop tests are described by Reid et al[36] and Noyes et al[32].

Overall LSI was calculated as the average LSI of the four hop tests. This instrument has demonstrated validity and excellent test-retest reliability[36].

4.3.11 Strength Assessment

Strength testing was completed using an isokinetic dynamometer (Biodex System3, Biodex Medical Systems, NY) and has been described elsewhere[16]. Testing of the nonoperative limb occurred prior to that of the operative limb. Participants completed 1 set of 3 maximal effort repetitions of knee extension and flexion at 90˚/s. Peak knee extension and knee flexion torques (Nm) were recorded for each limb.

4.3.12 Range of Motion

Passive knee extension and active-assisted knee flexion were measured using a universal goniometer, as described by Clarkson and Gilewich[9]. Measurements were taken for both the unaffected and affected knee.

4.3.13 Statistical Methods

As not all subjects were available for both testing sessions for a variety of reasons including but not limited to, re-injury, lost to follow-up, and inability to attend, we carried out a multiple imputation. Multiple imputation is the preferred method to account for missing data[17]. After evaluation of patterns of missing data, it was determined that we had data missing completely at random (MCAR). Missing data at 12 months was correlated using Pearson r to baseline data and functional performance at 6 months. We used 15 passes for multiple imputations as there was 14.4% missing data at 12 months for jump variables. Pooled results are reported.

Means, standard deviations and proportions were analyzed to provide descriptive tables of the characteristics of each group. Independent *t-tests* were used to evaluate group differences for primary and secondary outcomes measures at 6 and 12 months. Dependent *t-tests* were used to evaluate limb differences in primary and secondary DVJ outcome measures. Group differences are presented as mean difference with 95% confidence intervals. *Chi-Square* was used to evaluate group distribution differences above and below a pre-determined cut-off for primary outcomes. For transverse plane net hip moment impulse, the cut-off was defined as 0 or whether a subject had a net internal *vs* external moment[35]. We used a cut-off of -25.25 Nm for peak KAM[21,26,28]. This cut-off for peak KAM has been shown to provide maximal sensitivity and specificity in the prediction of primary ACL injury risk during a DVJ[21,26,28] and has previously been used to classify individuals as 'high-risk' or 'low risk'[26,28]. *Chi-Square* was also used to evaluate the percentage of patients unable to complete hop testing at each time point. Finally, a repeated measures multivariate ANOVA was used to see if a trajectory of change over time existed for hop and strength testing.

4.4 Results

Flow of participants through the trial is presented in Figure 4.1. One-hundred and twenty-five of the 162 randomized patients were available for biomechanics laboratory assessment. Two patients randomized to the SP group were crossovers, they were still included in the analyses. Loss to follow-up at 12 months was 13% and 8% for the UC and SP groups, respectively. Four patients in the UC group re-tore their ACL after the intervention but before the 12-month follow-up. One patient in the SP group re-tore their ACL during the intervention period (i.e. before the 6-month time point). One participant in the SP group moved to another province after the 6-month intervention and was unavailable for the 12-month follow-up. The UC group had 3 patients that we were unable to contact, and 1 patient that was unable or unwilling to return for the 12-month follow-up measurements. The SP group had 1 patient that we were unable to contact, and 2 patients that were unable or unwilling to return for the 12-month follow-up measurements. Fifty-seven and 58 participants were analyzed at the end of the intervention at 6-months post ACL reconstruction in the UC and SP groups, respectively. Fifty-three and 55 participants were analyzed at 12-months post ACL reconstruction follow-up in the UC and SP groups, respectively.

There were no significant differences between groups pre-surgery for age, height, body mass, BMI, ROM, strength or hop testing (Table 4.2). Missing data at 12 months was weakly correlated to baseline measures of body mass and BMI (r = -0.245 and -0.251, respectively, $p < 0.01$), peak knee extension torque in both unaffected and affected limbs, and the affected peak knee flexion torque (r = -0.204, -0.189, and -0.222, respectively, p <

0.05), active flexion ROM in the unaffected limb ($r = 0.212$, $p < 0.05$), affected limb single hop for distance and triple hop for distance ($r = -0.229$ and -0.221, $p < 0.05$ and to baseline IKDC ($r = 0.244$, $p < 0.05$). In the UC group, 11 of 63 subjects (17%) and 7 of 62 subjects (11%) in the SP group, were missing data at 12 months. While loss to follow-up accounted for 13% and 8% of missing data at 12 months for UC and SP, respectively, the other 4% and 3% are attributed to data collection or technical issues.

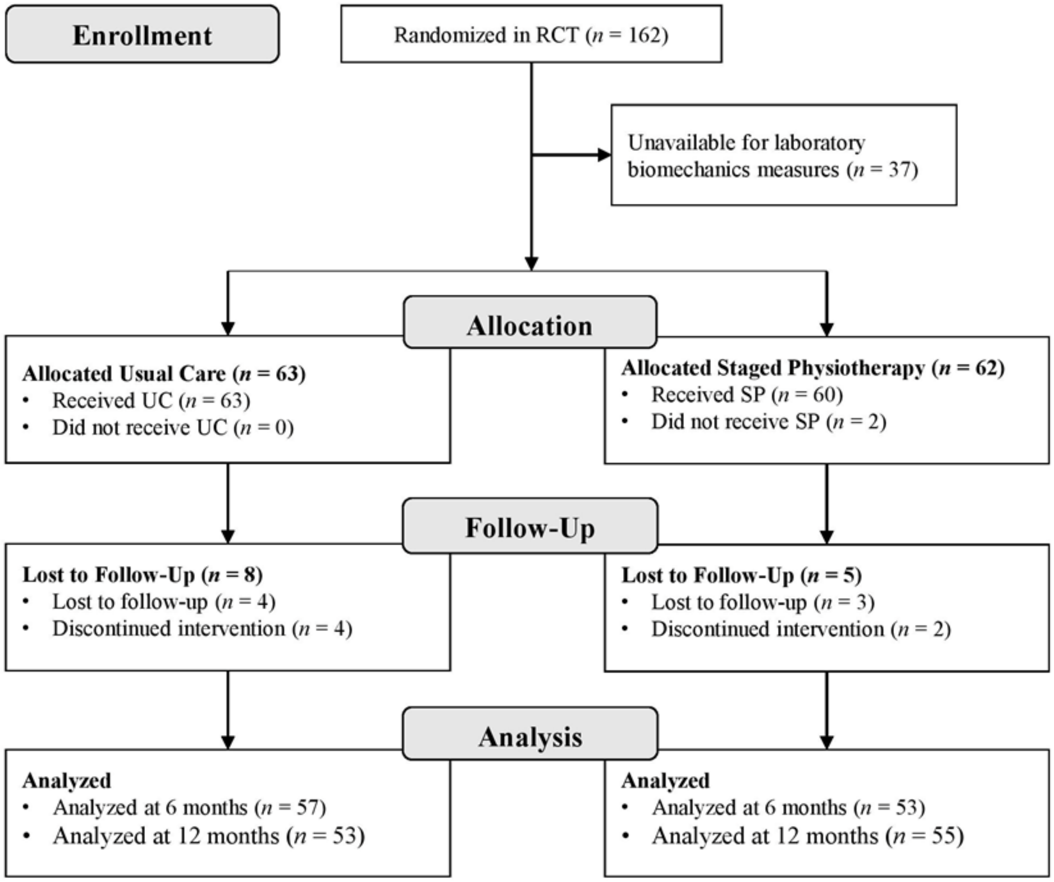

Figure 4.1: Flow diagram of subjects in the study.

Primary DVJ outcome measure group differences are presented in Table 4.3 (6 months) and Table 4.4 (12 months). No differences between groups were seen at 6 months. Scatterplots of primary DVJ outcome measures at 6 months are shown in Figures 4.2 to 4.5 that portray the number of patients above and below risk factor cut-offs for each respective measure. No significant group differences were observed. At 12 months, there were no group differences in transverse plane net hip moment impulse, however peak KAM in the operative limb was significantly different between groups (p = 0.03), as was limb difference in peak KAM ($p < 0.01$).

Table 4.2: Baseline (before surgery) characteristics (mean ± standard deviation are reported unless stated otherwise).

Variable	**Usual Care N = 63**		**Staged Physiotherapy N = 62**	
Sex (female/male)	32 / 31		23 / 39	
Operative limb (left/right)	34 / 29		24 / 38	
Age (y)	22.5 ± 6.0		23.2 ± 6.8	
Height (cm)	172.4 ± 9.1		174.3 ± 8.4	
Mass (kg)	77.3 ± 20.9		80.9 ± 20.2	
BMI ($kg \cdot m^{-2}$)	25.9 ± 6.0		26.4 ± 5.0	
IKDC	62 ± 20		57 ± 16	
Range of Motion (deg)				
Op Extension	-3 ± 3		-3 ± 3	
NoOp Extension	-4 ± 3		-4 ± 3	
Op Flexion	137 ± 10		137 ± 10	
NoOp Flexion	141 ± 9		142 ± 8	
Strength (Nm)				
Op Quadriceps	120.81 ± 45.73		126.61 ± 43.76	
NoOp Quadriceps	157.53 ± 56.40		161.49 ± 50.96	
Op Hamstrings	63.59 ± 24.59		67.84 ± 24.73	
NoOp Hamstrings	75.22 ± 27.76		78.77 ± 29.96	
Op HQ Ratio (%)	54 ± 13		54 ± 10	
NoOp HQ Ratio (%)	48 ± 7		49 ± 9	
Hop Testing: Limb Symmetry Index (%)*		*(N)*		*(N)*
Single leg hop	85.7 ± 18.4	*(54)*	84.0 ± 16.1	*(43)*
Timed hop	87.2 ± 14.7	*(51)*	87.2 ± 17.0	*(40)*
Triple hop	84.0 ± 13.2	*(50)*	85.0 ± 17.5	*(41)*
Crossover hop	84.8 ± 16.1	*(47)*	85.8 ± 15.2	*(41)*
Overall	85.7 ± 14.1	*(47)*	85.5 ± 15.2	*(40)*

** Not all patients were safely able to complete all portions of the hop testing. The N is included for those patients that completed each individual portion of the hop test.*

Abbreviations: BMI, Body mass index; IKDC, International Knee Documentation Committee; Op, Operative limb; NoOp, Nonoperative limb; Extension, passive knee extension; Flexion, active knee flexion; Quadriceps, peak torque of the quadriceps; Hamstrings, peak torque of the hamstrings; HQ Ratio, Ratio of peak torque of the hamstrings to the quadriceps; Single leg hop, Single leg hop for distance; Timed hop, single leg timed 6-m hop; Triple hop, single leg triple hop for distance; Crossover hop, single leg triple crossover hop for distance; Overall, mean of four hop tests.

Table 4.3: Comparison of imputed drop vertical jump primary functional performance outcome measures between groups (means ± SD) at 6 months post-surgery.

Measure	Usual Care (*n*=63)	Staged Physio (*n*=62)	Difference (95% CI)	*p*
Transverse Plane Net Hip Moment Impulse (Nms/kg)				
Operative	-0.23x10^{-3} ± 0.002	-0.29x10^{-3} ± 0.002	0.06x10^{-3} (-0.0007, 0.0008)	.89
Non-operative	-0.27x10^{-3} ± 0.002	-0.02x10^{-3} ± 0.002	-0.25x10^{-3} (-0.0010, 0.0005)	.52
Limb Difference	0.04x10^{-3} ± 0.003	-0.26x10^{-3} ± 0.002	0.30x10^{-3} (-0.0008, 0.0014)	.59
Peak Knee Abduction Moment (Nm)				
Operative	-24.80 ± 15.18	-26.36 ± 16.30	1.56 (-3.98, 7.11)	.58
Non-operative	-21.32 ± 14.98	-24.02 ± 18.94	2.69 (-3.31, 8.70)	.38
Limb Difference	-3.48 ± 20.75	-2.35 ± 20.00	-1.13 (-8.31, 6.05)	.76

Abbreviations: Operative, Operative limb; Non-operative, Nonoperative limb; Limb Difference, limb difference for outcome measure determined as operative – non-operative. Net external hip rotation and knee abduction moments are negative values.

Table 4.4: Comparison of imputed drop vertical jump primary functional performance outcome measures between groups (means ± SD) at 12 months post-surgery.

Measure	Usual Care (*n*=63)	Staged Physio (*n*=62)	Difference (95% CI)	*p*
Transverse Plane Net Hip Moment Impulse (Nms/kg)				
Operative	0.22x10^{-3} ± 0.004	-0.20x10^{-3} ± 0.003	0.43x10^{-3} (-0.0012, 0.0021)	.61
Non-operative	-0.52x10^{-3} ± 0.003	-0.32x10^{-3} ± 0.002	-0.20x10^{-3} (-0.0014, 0.0010)	.73
Limb Difference	0.74x10^{-3} ± 0.005	0.11x10^{-3} ± 0.004	0.63x10^{-3} (-0.0012, 0.0025)	.50
Peak Knee Abduction Moment (Nm)				
Operative	-20.70 ± 12.39	-26.89 ± 19.21	6.19 (0.52, 11.86) [†]	.03
Non-operative	-23.09 ± 13.23	-19.35 ± 14.96	-3.74 (-8.71, 1.23)	.14
Limb Difference	2.38 ± 17.10	-7.55 ± 18.91*	9.93 (3.60, 16.26) [†]	<.01

[†] *Significant difference between rehabilitation groups.*

**Statistically significant difference between limbs within rehabilitation group for peak knee abduction moment, p=0.002, for the staged physiotherapy group.*

Abbreviations: Operative, Operative limb; Non-operative, Nonoperative limb; Limb Difference, limb difference for outcome measure determined as operative – non-operative.

Net external hip rotation and knee abduction moments are negative values.

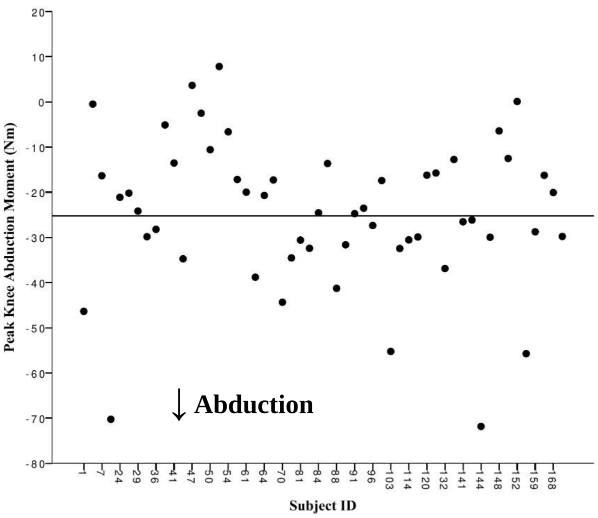

Figure 4.2: Scatterplot of usual care physiotherapy group for operative limb peak knee abduction moment at 6 months post ACL reconstruction. The horizontal line identifies the "high-risk" cut-off of -25.25 Nm. Patients below the line (46.3%) are at greater risk. Original data (*n* = 54) was used for the graph.

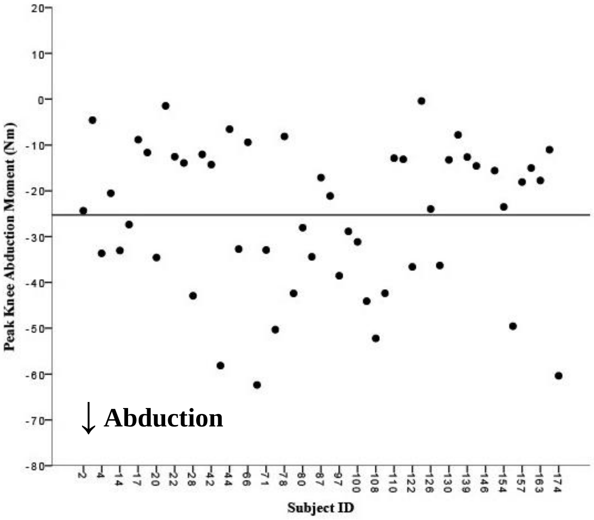

Figure 4.3: Scatterplot of staged physiotherapy group for operative limb peak knee abduction moment at 6 months post ACL reconstruction. The horizontal line identifies the "high-risk" cut-off of -25.25 Nm. Patients below the line (45.3%) are at greater risk. Original data (*n* = 53) was used for the graph.

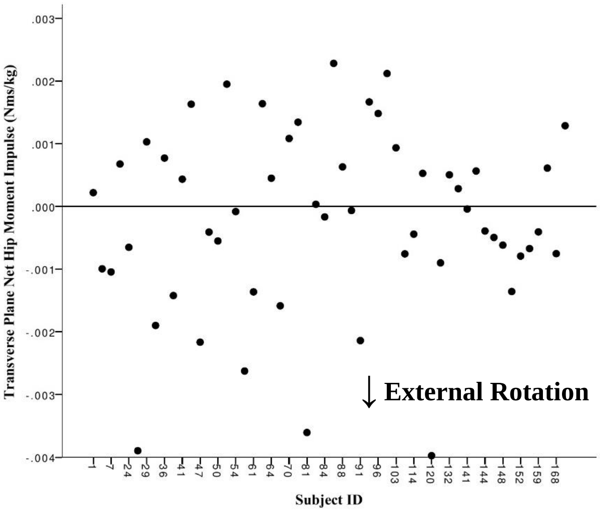

Figure 4.4: Scatterplot of usual care physiotherapy group for non-operative limb transverse plane net hip moment impulse at 6 months post ACL reconstruction. The horizontal line identifies the "high-risk" cut-off of between internal and external moments. Patients above the line (44.4%) have a net internal moment and are at greater risk. Original data (*n* = 54) was used for the graph.

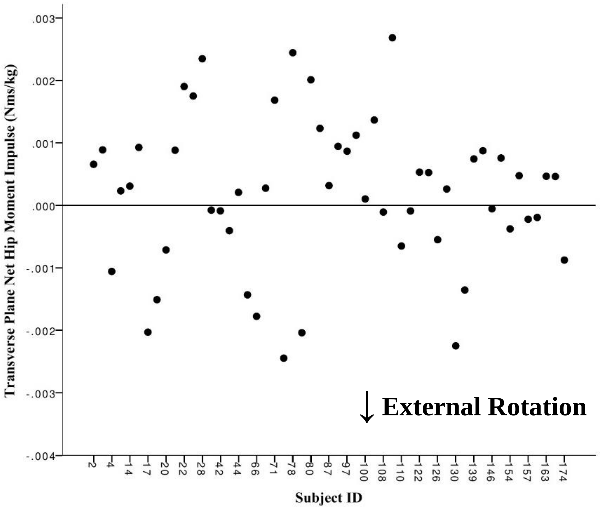

Figure 4.5: Scatterplot of staged physiotherapy group for non-operative limb transverse plane net hip moment impulse at 6 months post ACL reconstruction. The horizontal line identifies the "high-risk" cut-off of between internal and external moments. Patients above the line (58.5%) have a net internal moment and are at greater risk. Original data (*n* = 53) was used for the graph.

There were no between group differences for secondary DVJ outcome measures at 6 and 12 months. This data is presented in Table 4.5 and Table 4.6, for 6- and 12-months, respectively. Within each rehabilitation group, significant differences were observed between operative and non-operative limbs for peak KFM, peak VGRFs, and for loading rate at 6- and 12-months post ACL reconstruction.

Table 4.5: Comparison of imputed drop vertical jump secondary functional performance outcome measures between groups (means ± SD) at 6 months post-surgery.

Measure		**Usual Care (*n*=63)**	**Staged Physio (*n*=62)**	**Difference (95% CI)**	***p***
Peak COM (mm)		1704.4 ± 117.0	1709.1 ± 104.1	-4.8 (-43.6, 34.1)	.81
Knee Abduction Angle (degrees)					
IC	Operative	-4.54 ± 4.69	-4.81 ± 4.83	0.27 (-1.42, 1.97)	.75
	Non-operative	-4.49 ± 4.07	-4.46 ± 3.39	-0.03 (-1.38, 1.32)	.97
	Limb Difference	-0.05 ± 4.07	-0.35 ± 4.71	0.30 (-1.30, 1.91)	.71
PEAK	Operative	-16.03 ± 8.24	-17.00 ± 7.92	0.97 (-1.88, 3.83)	.50
	Non-operative	-17.15 ± 7.32	-16.65 ± 6.06	-0.51 (-2.89, 1.88)	.68
	Limb Difference	1.13 ± 9.61	-0.35 ± 7.17	1.48 (-1.55, 4.51)	.34
DISP	Operative	-11.37 ± 6.32	-12.14 ± 5.83	0.77 (-1.39, 2.93)	.49
	Non-Operative	-12.64 ± 5.79	-12.19 ± 4.24	-0.45 (-2.25, 1.36)	.63
	Limb Difference	1.27 ± 7.37	0.05 ± 5.07	1.22 (-1.06, 3.50)	.30
Knee Flexion Angle (degrees)					
PEAK	Operative	77.85 ± 13.94	77.83 ± 12.50	0.02 (-4.65, 4.69)	.99
	Non-operative	78.74 ± 14.40	79.30 ± 11.79	-0.56 (-5.21, 4.09)	.81
	Limb Difference	-0.89 ± 4.77	-1.47 ± 4.86*	0.58 (-1.33, 2.49)	.55
Knee Flexion Moment (Nm)					
IC	Operative	-9.67 ± 14.60	-11.60 ± 15.41	1.94 (-3.35, 7.22)	.47
	Non-operative	-8.43 ± 15.53	-9.66 ± 13.00	1.23 (-3.82, 6.29)	.63
	Limb Difference	-1.23 ± 15.54	-1.94 ± 14.92	0.70 (-4.69, 6.10)	.80
PEAK	Operative	-74.60 ± 28.60	-76.65 ± 26.66	2.05 (-7.67, 11.77)	.68
	Non-operative	-93.33 ± 28.80	-98.78 ± 44.23	5.45 (-7.64, 18.54)	.41
	Limb Difference	18.73 ± 18.84**	22.13 ± 36.03**	-3.40 (-13.57, 6.76)	.51
Peak Vertical Ground Reaction Force (xBW)					
LP	Operative	1.36 ± 0.30	1.40 ± 0.332	-0.04 (-0.17, 0.09)	.55
	Non-operative	1.62 ± 0.31	1.61 ± 0.34	0.01 (-0.12, 0.13)	.91
	Limb Difference	-0.26 ± 0.35**	-0.21 ± 0.40**	-0.05 (-0.20, 0.11)	.56
TO	Operative	1.11 ± 0.29	1.11 ± 0.25	0.00 (-0.11, 0.12)	.96
	Non-Operative	1.23 ± 0.32	1.21 ± 0.29	0.01 (-0.10, 0.13)	.81
	Limb Difference	-0.12 ± 0.26*	-0.11 ± 0.24*	-0.01 (-0.13, 0.10)	.84
Loading Rate (xBW/s)					
	Operative	15.93 ± 5.67	16.53 ± 5.75	-0.60 (-2.64, 1.43)	.56
	Non-Operative	19.88 ± 5.46	19.37 ± 5.80	0.51 (-1.51, 2.54)	.62
	Limb Difference	-3.95 ± 5.58**	-2.84 ± 6.83*	-1.12 (-3.36, 1.13)	.33

** Significant difference (p<0.05) between operative and non-operative limbs within rehabilitation group.*

*** Significant difference (p<0.001) between operative and non-operative limbs within rehabilitation group.*

For the following variables: peak KAA limb difference, and displacement in KAA for the non-operative limb, Levene's test for homogeneity of variance was significant, and equal variances were not assumed.

Abbreviations: Operative, Operative limb; Non-operative, Nonoperative limb; Limb Difference, limb difference for outcome measure determined as operative – non-operative; Peak COM, peak height of the center of mass during the maximal jump; IC, initial contact; DISP, displacement; LP, landing phase; TO, toe off.

Table 4.6: Comparison of imputed drop vertical jump secondary functional performance outcome measures between groups (means ± SD) at 12 months post-surgery.

Measure		**Usual Care (*n*=63)**	**Staged Physio (*n*=62)**	**Difference (95% CI)**	***p***
Peak COM (mm)		1661.0 ± 162.2	1678.8 ± 159.4	-17.8 (-74.3, 38.6)	.54
Knee Abduction Angle (degrees)					
IC	Operative	-4.34 ± 4.26	-4.63 ± 3.96	0.29 (-1.20, 1.78)	.70
	Non-operative	-5.41 ± 4.92	-4.75 ± 3.86	-0.66 (-2.23, 0.91)	.41
	Limb Difference	1.07 ± 4.23	0.12 ± 3.88	0.95 (-0.54, 2.44)	.21
PEAK	Operative	-16.09 ± 7.30	-16.52 ± 6.97	0.43 (-2.11, 2.97)	.74
	Non-operative	-18.52 ± 7.40	-16.46 ± 7.26	-2.06 (-4.68, 0.55)	.12
	Limb Difference	2.42 ± 9.16*	-0.07 ± 7.51	2.49 (-0.50, 5.48)	.10
DISP	Operative	-11.73 ± 5.84	-11.87 ± 5.92	0.14 (-1.98, 2.25)	.90
	Non-Operative	-13.15 ± 6.11	-11.71 ± 6.23	-1.44 (-3.63, 0.75)	.20
	Limb Difference	1.42 ± 6.69	-0.15 ± 6.26	1.58 (-0.75, 3.90)	.18
Knee Flexion Angle (degrees)					
PEAK	Operative	79.60 ± 14.74	81.15 ± 13.00	-1.56 (-6.46, 3.35)	.53
	Non-operative	79.20 ± 16.08	81.05 ± 12.59	-1.85 (-6.96, 3.25)	.48
	Limb Difference	0.40 ± 5.60	0.11 ± 4.98	0.30 (-1.72, 2.31)	.77
Knee Flexion Moment (Nm)					
IC	Operative	-12.05 ± 16.01	-12.18 ± 12.46	0.13 (-4.95, 5.21)	.96
	Non-operative	-11.52 ± 13.46	-10.19 ± 14.82	-1.33 (-6.33, 3.67)	.60
	Limb Difference	-0.53 ± 14.16	-1.99 ± 13.91	1.46 (-3.57, 6.49)	.57
PEAK	Operative	-79.45 ± 31.52	-79.69 ± 24.89	0.24 (-9.75, 10.23)	.96
	Non-operative	-90.42 ± 29.84	-94.71 ± 34.10	4.28 (-6.98, 15.55)	.46
	Limb Difference	10.97 ± 22.54**	15.02 ± 28.49**	-4.04 (-13.10, 5.01)	.38
Peak Vertical Ground Reaction Force (xBW)					
LP	Operative	1.45 ± 0.36	1.35 ± 0.31	0.10 (-0.04, 0.23)	.15
	Non-operative	1.59 ± 0.34	1.54 ± 0.31	0.05 (-0.08, 0.19)	.46
	Limb Difference	-0.15 ± 0.37*	-0.19 ± 0.35**	0.04 (-0.12, 0.21)	.60
TO	Operative	1.14 ± 0.32	1.10 ± 0.27	0.05 (-0.08, 0.17)	.46
	Non-Operative	1.21 ± 0.34	1.13 ± 0.26	0.08 (-0.04, 0.20)	.20
	Limb Difference	-0.07 ± 0.31	-0.04 ± 0.25	-0.03 (-0.18, 0.11)	.66
Loading Rate (xBW/s)					
	Operative	17.47 ± 5.92	16.38 ± 4.50	1.09 (-0.77, 2.96)	.25
	Non-Operative	20.54 ± 5.97	20.09 ± 5.51	0.45 (-1.59, 2.50)	.66
	Limb Difference	-3.07 ± 5.05**	-3.71 ± 6.15**	0.64 (-1.40, 2.68)	.54

** Significant difference (p<0.05) between operative and non-operative limbs within rehabilitation group.*
*** Significant difference (p<0.001) between operative and non-operative limbs within rehabilitation group.*
Abbreviations: Operative, Operative limb; Non-operative, Nonoperative limb; Limb Difference, limb difference for outcome measure determined as operative – non-operative; Peak COM, peak height of the center of mass during the maximal jump; IC, initial contact; DISP, displacement; LP, landing phase; TO, toe off.

There was a significant within-subjects effect of time ($p < 0.001$), but not time by group ($p = 0.278$), in LSI for overall hop testing, knee extension and flexion strength from baseline to 6 months to follow-up at 12 months. Overall hop testing LSI improved from baseline to 6 months ($p = 0.001$) and again from 6 to 12 months ($p < 0.001$). Knee extension LSI at 12 months was significantly greater than baseline ($p = 0.002$) and 6 months ($p < 0.001$). There was no difference in knee extension LSI from baseline to 6 months ($p = 0.678$). There was no difference in knee flexion LSI between baseline and 12 months (*p* = 0.433), but 6 months was significantly lower than baseline (*p* = 0.045) and 12 months (*p* = 0.012).

There was a significant difference between rehabilitation groups for the percentage of patients unable to safely complete hop testing at pre-surgery for the single (*p* = 0.028) and timed (*p* = 0.039) LSI, but not triple, cross-over or overall LSI. In the UC group, 14% and 19% of patients could not safely complete the single and timed hop tests on both limbs, compared to 31% and 36% of the SP, respectively. After surgery, both rehabilitation groups had similar percentages of patients that could not complete the hop testing protocol safely for all tests. For overall LSI, 34% of all patients could not complete the hop testing protocol safely by 12 months post ACL reconstruction. There were no between group differences for strength and hop testing outcomes at 6- or 12-months post ACL reconstruction, which are presented in Table 4.7 and Table 4.8.

Table 4.7: Comparison of imputed strength and hop testing secondary functional performance outcome measures between groups (means ± SD) at 6 months post-surgery.

Measure	**Usual Care (*n*=63)**	**Staged Physio (*n*=62)**	**Difference (95% CI)**	***p***
Strength (%)				
Op HQ Ratio[a]	52.84 ± 14.28	50.72 ± 10.80	2.12 (-2.33, 6.57)	.35
NoOp HQ Ratio[a]	49.00 ± 6.78	50.11 ± 7.07	-1.11 (-3.56, 1.33)	.37
Extension LSI[b]	78.45 ± 14.85	79.37 ± 16.43	-0.93 (-6.45, 4.59)	.74
Flexion LSI[b]	82.75 ± 16.88	79.00 ± 14.60	3.75 (-1.89, 9.40)	.19
Hop Testing Limb Symmetry Index (%)				
Single[b]	87.37 ± 11.27	90.00 ± 8.86	-2.63 (-6.21, 0.95)	.15
6m Timed[c]	90.55 ± 9.19	90.63 ± 8.73	-0.08 (-3.35, 3.20)	.96
Triple[b]	89.27 ± 8.65	89.93 ± 7.31	-0.67 (-3.55, 2.22)	.65
Cross[b]	93.25 ± 14.36	91.68 ± 8.12	1.57 (-2.64, 5.77)	.47
Overall[d]	90.67 ± 7.63	91.07 ± 6.34	-0.40 (-2.89, 2.09)	.75

[a] *Hamstrings as a percentage of the quadriceps (i.e. hamstrings / quadriceps x 100).*
[b] *Operative limb as a percentage of the non-operative limb (i.e. operative / non-operative x 100).*
[c] *Non-operative limb divided by the non-operative limb (i.e. non-operative / operative x 100)*
[d] *Overall limb symmetry index calculated as the average of the limb symmetry index of the four hop tests.*
Abbreviations: Op, Operative limb; NoOp, Nonoperative limb; HQ Ratio, Hamstrings to quadriceps ratio in same limb; Extension, knee extension torque; Flexion, knee flexion torque; LSI, Limb Symmetry Index.

Table 4.8: Comparison of imputed strength and hop testing secondary functional performance outcome measures between groups (means ± SD) at 12 months post-surgery.

Measure	Usual Care (*n*=63)	Staged Physio (*n*=62)	Difference (95% CI)	*p*
Strength (%)				
Op HQ Ratio[a]	48.74 ± 9.69	49.10 ± 8.15	-0.36 (-3.51, 2.79)	.82
NoOp HQ Ratio[a]	48.89 ± 6.70	51.10 ± 6.86	-2.21 (-4.61, 0.19)	.07
Extension LSI[b]	88.88 ± 11.64	88.13 ± 13.92	0.75 (-3.81, 5.30)	.75
Flexion LSI[b]	88.23 ± 13.52	84.23 ± 11.52	4.00 (-0.47, 8.47)	.08
Hop Testing Limb Symmetry Index (%)				
Single[b]	96.44 ± 6.63	94.49 ± 10.43	1.95 (-1.20, 5.10)	.23
6m Timed[c]	95.94 ± 7.28	94.71 ± 7.37	1.23 (-1.40, 3.86)	.36
Triple[b]	95.37 ± 5.62	94.67 ± 5.94	0.70 (-1.37, 2.77)	.51
Cross[b]	97.35 ± 5.77	96.34 ± 7.87	1.01 (-1.46, 3.49)	.42
Overall[d]	96.67 ± 4.77	95.60 ± 5.87	1.06 (-0.89, 3.02)	.29

[a] *Hamstrings as a percentage of the quadriceps (i.e. hamstrings / quadriceps x 100).*

[b] *Operative limb as a percentage of the non-operative limb (i.e. operative / non-operative x 100).*

[c] *Non-operative limb divided by the non-operative limb (i.e. non-operative / operative x 100)*

[d] *Overall limb symmetry index calculated as the average of the limb symmetry index of the four hop tests.*

Abbreviations: Op, Operative limb; NoOp, Nonoperative limb; HQ Ratio, Hamstrings to quadriceps ratio in same limb; Extension, knee extension torque; Flexion, knee flexion torque; LSI, Limb Symmetry Index.

4.5 Discussion

The main objective of this study was to evaluate whether SP leads to similar functional outcomes as UC in patients following primary unilateral autograft ACL reconstruction via biomechanical measures of DVJ, hop testing and strength. The DVJ is a functional measure of neuromuscular performance and provides an indication of the dynamic status of the knee. It is a predictor of primary and secondary ACL injury, and is therefore essential to assess before return-to-sport after ACL injury. Based on other studies evaluating strength and hop testing in different rehabilitation strategies, we did not see any differences in functional outcomes immediately post-intervention between groups at 6 months post-ACL reconstruction, yet at the 12-month follow-up, group differences in peak KAM were observed.

Several studies have looked at variations in home vs. supervised rehabilitation programs[3,7,12,18,19,23,37]. All these studies have concluded that there are minimal differences in a variety of assessment measures such as ROM, Lysholm, ACL Quality of Life, laxity etc., and at various time points including 3, 6, 12 and 24 months post-operatively. However, Grant et al[19] found their home-based group had improved results for flexion and extension ROM at 3 months, but no differences in any other measures. Their follow-up study at 2 - 4 years post reported improved ACL Quality of Life scores in the home group, but no differences in any other measures. At 6 months post-operatively, Fischer et al[12], Beard and Dodd[3], De Carlo and Sell[7], and Hohmann et al[23], all showed no differences between their rehabilitation groups. This tendency continues to 12 months post-operative where Schenck et al[37], Hohmann et al[23], and De Carlo and Sell[7] all report no differences between rehabilitation groups. Among the variety of measures evaluated in these studies, functional measures included muscular strength[3,7,18,19,23], and some variation of hopping tests[12,23,37].

A more recent measure of functional performance and ACL injury prediction is the DVJ test. Hewett et al[21] and Paterno et al[35] have introduced this measure to screen for ACL injury risk in young athletes as it can predict primary ACL injury with high sensitivity and specificity[21]. The reliability of three-dimensional motion analysis to measure kinetics and kinematics of the DVJ in ACL patients has shown to be moderate-to-excellent depending on the variable measured[16]. To the best of our knowledge, we are the first group to include the DVJ in an RCT evaluating rehabilitation strategies following ACL reconstruction. None of the home vs. supervised ACL studies have examined whether performance on the DVJ differs between rehabilitation protocols. Performance on the DVJ is an indicator of risk for primary and secondary ACL injuries, yet it is not currently considered as part of functional testing for return to sport.

The primary outcome measures of hip impulse and peak KAM were selected, as they are associated with primary and secondary ACL injury risk. No group differences were observed for these measures immediately after the intervention (at 6 months), thus both rehabilitation programs seemed to have demonstrated similar results. Importantly, when we evaluated the distribution of patients in each group that were identified as “higher risk” due to either a net hip internal impulse moment[35], or a peak KAM > 25.25 Nm[26,28], there were no group differences. However, the fact that 51% and 47% of all patients fell in the high-risk group for hip impulse and peak KAM, respectively, was concerning. This translates roughly to 1 in 2 patients at a considerably increased risk for ACL re-injury. It is imperative that the need for revision ACL reconstruction is minimized, as recovery after revision ACL reconstruction is reportedly worse than primary ACL reconstruction[22] and may even be considered a “salvage procedure”[2,22]. At follow-up, the percentage of patients in the high-risk group for hip impulse dropped to 44%, and for peak KAM dropped to 38%, of all patients. However, if we had used a high-risk cut-off of 21.74 Nm for peak KAM, as suggested by Myer et al[27], the percentage of patients in the high-risk category at follow-up would have remained elevated (53%). Yet, hop testing results were considered normal with an Overall LSI > 90 at 6 months and > 95 at 12 months in both groups. Clearly, functional deficits remain, even with normal hop testing outcomes. Typically, an LSI ≥ 90 is recommended for hop and strength testing before return to sport after ACL reconstruction[39]. The LSI for strength at follow-up for knee extension was >88 and for knee flexion was >84 in both groups. Strength deficits of 15% or more at 12 months post ACL reconstruction are not unusual. Hohmann et al[23] had similar strength LSI scores 12 months after ACL reconstruction. Quadriceps strength deficits upwards of 20% have been reported[24] 12 months post-operatively. Even with late-stage, sport specific, and highly supervised neuromuscular rehabilitation intervention, such as the SP approach, functional deficits following ACL reconstruction are still evident soon after surgery. Consequently, there is still an obvious concern for high-risk movement patterns and ACL injury, despite adequate strength and hop testing results.

Previous studies[7,23,37] reported no differences between rehabilitation groups at 12 months post ACL reconstruction. Grant and Mohtadi[18] demonstrated improved ACL QOL at their 2 - 4 year follow-up in their early home-based rehabilitation group, but no differences between groups for strength. While we also had no group differences for strength or hop testing at the 12-month follow-up, we did however find that the SP group had significantly greater peak KAM in their operative limb, and a greater magnitude of difference between limbs for peak KAM. Greater asymmetry and greater peak KAM can predict ACL injury risk[21,35]. Possible explanations could be if SP patients perhaps felt overconfident as they believed they had more sport-specific training in the latter phase of the intervention. However, upon further examination, we found fewer patients in the SP were able to complete the hop testing battery at baseline (*n* = 47 vs 40 for UC vs. SP). This is possibly an indication of previous deficits that contributed to the initial ACL injury. Additionally, the knee flexion LSI of the SP group at 12 months was lower than 85. A minimum strength symmetry of 85% is recommended before resuming sports participation[22,39]. Myer et al[25] found that female athletes who suffered ACL injury had significantly lower hamstrings strength than matched female and male controls. The biceps femoris muscle of the hamstrings muscle group helps prevent internal rotation of the knee in single limb drop landing[14]. The hamstrings muscle group plays an important role in dynamic knee joint stability, and a reduction in hamstrings strength or recruitment would result in a greater dynamic knee valgus collapse, and subsequently increase the KAM. In fact, low hamstrings-to-quadriceps strength ratio is part of a clinical tool to identify high KAM in young females[29]. Finally, it can also be postulated that with a lack of intervention, these patients regressed without adequate physiotherapeutic supervision. Compliance to ACL rehabilitation programs tends to decrease over time[4,39], particularly when recovery does not occur as quickly as expected. Nevertheless, strength and hop testing are not the only functional measures that should be considered when evaluating return to sport after ACL reconstruction.

While performance on hop and strength testing can provide valuable information on patient readiness for return to sport and rehabilitation progress, more stringent assessment tools are warranted. Thomée et al[39] reported that these muscle function tests tend not to be adequately sensitive to differentiate between injured and non-injured limbs. Augustsson et al[1] demonstrated that at 12 months post-operatively, ACL reconstruction subjects who had a hop LSI ≥ 90 in a non-fatigued condition, two-thirds of them had unsatisfactory results (i.e. LSI < 90) after the quadriceps muscle was fatigued. Furthermore, Wordeman and Hewett[41] assert that the current criteria for return to sport is not adequate for prevention of subsequent injury or safe return to sport. The DVJ task may provide additional information regarding faulty movement patterns increasing ACL injury risk that hop testing and strength testing are not sensitive enough to detect. Additionally, the DVJ allows evaluation of bilateral performance, which is imperative to evaluate for a complete profile of movement deficiencies or compensations that are present post-operatively[6,11,22]. Both limbs are at risk for ACL injury after ACL reconstruction, as the uninjured limb has been shown to overcompensate and attenuate greater forces even 2 years post-operatively[34]. In our study, both rehabilitation groups had significant limb asymmetries for secondary biomechanical DVJ outcome measures and force attenuation at 6- and 12-months post ACL reconstruction.

While using a 3D motion-analysis system is not feasible in many physiotherapy clinics, alternative means to evaluate performance, especially for KAM during a DVJ, are possible. For example, Gagnon et al[15] has developed a Clinician-Rated Drop Vertical Jump Scale that can facilitate the assessment of this high-risk functional performance measure. It also allows a clinician to monitor patient progress over the course of their rehabilitation and helps identify undesired / risky movement patterns that require attention. Similar evaluation tools using 2D video analysis have also been proposed, such as the Landing Error Scoring System[33,38] and observational risk screening for dynamic knee valgus[11]. Implementing these tools in return to sport screening could prove beneficial to identify patients with faulty movement patterns and who are at increased risk for ACL re-injury.

There is evidence to support home-based rehabilitation, at least in the early phase such as was the SP, for rehabilitation following ACL reconstruction. Most ACL patients are young, highly motivated and physically active individuals. It can be assumed that they are therefore more likely to be invested in their recovery, as suggested by Hohmann et al[23]. Nevertheless, it is highly recommended to consider the type of patient when considering alternative rehabilitation protocols. While the need for supervised physiotherapy may not be necessary, guided rehabilitation in some form is highly recommended. For example, a study by Treacy et al[40] demonstrated noncompliance (i.e. < 2 visits over 6 months) to have suboptimal outcomes for Lysholm score, patient satisfaction, and return to preoperative activity level, yet a minimally compliant group (12 visits over 6 months) and extensive supervised rehabilitation group (60 visits over 6 months) fared the same in all indices.

There were several strengths to this study. All measurements for the DVJ and strength were collected and analyzed by a blinded examiner, thereby minimizing measurement bias. The implementation of an RCT allowed for a controlled comparison of the treatment and assignment of a cause and effect relationship by reducing the probability of selection bias and balancing prognostic factors between treatment groups. Permutated mixed block randomization eliminated the possibility of unequal numbers of patients by group, stratification based on surgeon balanced any effect of surgeon technique, stratification based on the presence or absence of meniscal tear allowed a balance in the rate of progression in physiotherapy for both treatment groups, and stratification based on physiotherapy clinic (FKSMC versus a Community Clinic) eliminated bias in the intensity of physiotherapy offered at each facility. Finally, as both groups progressed in hop testing and knee extension limb symmetry from baseline to 12 months, we can be confident that both rehabilitation protocols were beneficial.

There are some limitations to the study that warrant mention. The sample size and loss to follow-up is of concern, yet other studies evaluating home vs physiotherapy-supervised programs including some form of functional outcome measure (hop and/or strength testing) after ACL reconstruction have smaller sample sizes (e.g. Hohmann et al[23], Grant & Mohtadi[18], Grant et al[19]) or greater loss to follow-up[18]. The patient physiotherapy visits were not tracked for this study and could have provided supportive data. We also cannot assure fidelity of treatment as we cannot control whether patients were compliant with their assigned group. They may have denied outside intervention if specifically asked. Patient reported outcomes were collected at baseline to help describe the patients and could have also provided supportive data if collected at 6- and 12-months. However, the focus of this study was biomechanical outcome measures, and it is the first of its kind that we are aware of, to evaluate performance on the DVJ following two different rehabilitation programs.

4.6 Conclusion

Completing home-based physiotherapy in the early stages of rehabilitation can be an effective measure for patients who have the motivation and resources to complete their rehabilitation exercises at home, when detailed instruction by a qualified therapist is provided beforehand. Future consideration of neuromuscular function and the long-term success of rehabilitation programs is an ongoing problem that is necessary to continue investigating.

4.7 References

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Chapter 5

5 Summary and General Discussion

The purpose of this chapter is to summarize and discuss the main results of the studies in the thesis. Study findings are discussed, relating the three studies and two reports with regards to landing biomechanics in patients with ACL reconstruction. Study limitations, future research possibilities, and final recommendations are also discussed.

5.1 Summary

The purpose of the present thesis was to develop and evaluate methods of assessing landing mechanics and investigate the effects of different rehabilitation strategies after ACL reconstruction.

5.1.1 Chapter 2: Study 1

This study established consensus on the content and scoring of a Clinician-Rated DVJS using a Delphi process, and developed a Beta version for use during rehabilitation after ACL reconstruction. Biomechanical parameters measured during a DVJ task are risk factors for ACL injury and are targeted during rehabilitation after ACL reconstruction. This clinical tool quantifies observed performance on the DVJ and can help inform treatment efforts. The content and scoring were deliberated upon by a group of experts throughout its development. Using a modified Delphi process, experts (researchers and/or clinicians) on the risk factors, prevention, treatment and/or biomechanics of ACL injury anonymously critiqued versions of a DVJS that were developed iteratively based on the feedback from the panel, using Likert-like scale responses to questions and by providing written comments. Four rounds of the Delphi scale resulted in 92% agreement. Final items on the scale included the rating of knee valgus collapse (No collapse to Extreme collapse) and the presence of the following other undesirable movements: lateral trunk lean, insufficient trunk flexion, insufficient knee flexion and limb-to-limb asymmetry. The Delphi process resulted in a Beta version of a DVJS. Expert consensus was achieved on its content and scoring to support further clinical testing of the scale.

5.1.2 Chapter 2 Supplement: Instruction Booklet and Clinician-Rated DVJS

A booklet was written to accompany the Clinician-Rated DVJS and provide instructions on its’ use. It includes examples of what to observe when using the scale, and provides instructions, a brief rationale and potential interpretation for each component. The scale guides clinicians in the evaluation of the extent of dynamic knee valgus collapse, as well as the following undesirable movements: lateral trunk lean, insufficient trunk flexion, insufficient knee flexion, and asymmetry between limbs. The Clinician-Rated DVJS and accompanying booklet are intended to help clinicians quantify performance on the DVJ, without requiring motion analysis equipment, and evaluate change following therapy.

5.1.3 Chapter 3: Study 2

This study evaluated the test-retest reliability and explored the longitudinal validity of selected lower limb biomechanics assessed during a DVJ completed by patients undergoing rehabilitation after ACL reconstruction. Knee abduction and flexion moments and angles were evaluated, along with hip rotation moment, VGRFs, and loading rate for reliability and longitudinal validity. Intraclass correlation coefficients ranged from 0.58 to 0.90 for peak knee flexion and abduction moments, from 0.45 to 0.85 for knee flexion and abduction angles, from 0.61 to 0.93 for VGRFs and loading rate, and from 0.42 to 0.61 for hip impulse in the operative and nonoperative limbs. Knee moments at IC were less reliable, with ICC<0.48. The most reliable measures (ICC > 0.80) were peak knee flexion moments, knee flexion angles, and VGRFs. Standardized response means ranged from -0.00 to 0.48. Correlations with strength (0.00 to 0.48) and GRC (0.03 to 0.43) were also low to moderate. The present results support the interpretation of various landing biomechanics assessed during repeated measures during rehabilitation after ACL reconstruction.

5.1.4 Chapter 3 Supplement: Technical Report

Biomechanical motion analysis of movement properties during jumping performance can provide valuable information when evaluating injury risk and readiness for return-to-sport in patients rehabilitating from ACL reconstruction. Motion analysis data has inherent error included in the collected raw data that must be filtered. Residual analysis is an objective means to determine filtering cut-off frequency. A digital filter is then applied to the raw data using the filtering cut-off frequency as determined using residual analysis. In biomechanics, a common filtering technique is the Butterworth filter. The process does however require trial-and-error and subjective judgement on the part of the researcher. For jumping analysis in ACL reconstructed patients, it was determined that a filtering cut-off frequency of 14 Hz for movement and 50 Hz for forces was acceptable to ensure physiological data is kept in the filtered signal for this cohort. These filtering cut-off frequencies were applied in studies 2 and 3 to analyze movement properties in patients after ACL reconstruction, during the course of their rehabilitation.

5.1.5 Chapter 4: Study 3

This randomized clinical trial evaluated whether a staged physiotherapy program (e.g. home-based rehabilitation followed by late supervised physiotherapy) led to similar functional measures, including biomechanical measures of DVJ, hop testing, and strength, as a usual care physiotherapy protocol in patients following primary unilateral autograft ACL reconstruction. Joint biomechanics of hip impulse moment and peak knee abduction moment are good predictors of primary and secondary ACL injury. Assessment of functional measures including performance on the DVJ, hop and strength testing after ACL reconstruction are necessary for identification of patients at risk for ACL injury. No group differences for primary and secondary functional outcomes measures were observed between rehabilitation groups at 6 months. The staged group had significantly greater operative limb peak KAM (-20.70 Nm ± 12.39 for usual care *vs.* -26.89 Nm ± 19.21 for staged; $p = 0.03$) and limb-to-limb symmetry for peak KAM (2.38 Nm ± 17.10 for usual care *vs.* -7.55 ± 18.91 for staged; $p < 0.01$) at the 12 month follow-up. Both groups had significant within-group limb asymmetry at both 6- and 12-months for VGRF, loading rate and KFM. No differences in hop nor strength testing were observed between groups. Completing staged physiotherapy can be an effective measure for patients who have the motivation and resources to complete their rehabilitation exercises at home, when detailed instruction by a qualified therapist is provided beforehand.

5.2 Implications

Injury to the ACL results in long term implications on activity and health status, including increased risk for secondary injury and knee OA. Modifiable biomechanics should be addressed to improve outcomes. There is a lack of consensus and a paucity of functional testing tools for ACL rehabilitation and objective assessment prior to return to activity after ACL reconstruction[1]. In two systematic reviews scrutinizing return to activity requirements after ACL reconstruction, they found very few studies reported objective functional criteria as requirements before return to activity[1,2]. The three most common published objective criteria were lower extremity isokinetic muscle strength, lower limb symmetry as evaluated by the single leg hop test, and range of motion and joint effusion[2]. Only one study in their review recommended all three criteria should be evaluated. Additionally, there was a lack of consistency in the requirements to be met before return to activity. For example, when evaluating lower extremity isokinetic muscle strength, recommendations and type of assessment ranged from quadriceps strength requirements of > 80% to > 90% of the contralateral limb, there was no recommended minimum for hamstring to quadriceps ratio, and maximum difference in thigh circumference ranged from < 0.5 cm to < 1.0 cm. Rehabilitation from ACL reconstruction is multifaceted, including recovery of muscular strength, stability, neuromuscular control and lower limb function. Therefore, it stands to reason that prior to return to activity a multifaceted approach should also be required to optimize safe return. The addition of an evaluative tool, such as the Clinician-Rated DVJS developed in Study 1 (Chapter 2), can provide clinicians with a standardized and simple means to identify high-risk movement patterns, such as dynamic knee valgus collapse, and provide rehabilitation exercises to correct such deficits in movement patterns that increase risk for re-injury. Likewise, Barber-Westin & Noyes[1] suggest evaluating the DVJ to evaluate performance prior to return to activity.

5.2.1 Delphi Process

Study 1 (Chapter 2) implemented the use of a Delphi process to develop consensus on the content and scoring of the proposed Clinician-Rated DVJS. The Delphi process is a common method to develop consensus among a panel of experts on the topic in question[25]. Implementation of this process permits anonymity to the responders, resulting in less bias and more honest responses[40]. Furthermore, the process is not restricted to a specific geographical region. Rather, it can expand over several regions, and thus, access to a wide variety of experts is possible. In our study, a heterogeneous group of experts provided a wide variety of personalities and different perspectives on the risk factors of ACL injury and reconstruction.

The Delphi technique has been used in previous literature related to screening tool development (e.g. Eberman et al[11]) and for generating evidence-based guidelines for patients and physicians in OA (e.g. French et al[16]; Roddy et al[43]). Eberman et al[11] developed a preventative screening tool to identify athletes with risk factors associated to exertional heat illness using a Delphi panel. After three rounds, they were able to estimate content validity and agree on items included on their screening tool. Similarly, we were able to agree on the content included in the DVJS after four rounds. A Delphi process is designed to use 3 to 5 rounds of review[25,42]. Typically, 3 rounds are implemented; we achieved > 75% consensus after 4 rounds. While a criterion of 51% can be used to determine consensus in a Delphi[42], a more common criteria for consensus in the Delphi process is a Kappa statistic of > 0.61, or > 61% termed "substantial agreement"[23]. However, to be more conservative in our results, we chose to inflate our criterion to ≥ 66.7% of experts that responded they agreed with the inclusion of the undesirable movement on the scale for the first two rounds. We then inflated this to ≥ 75% agreement for the following rounds.

The findings from Study 1 resulted in a Beta version of the Clinician-Rated DVJS that can be implemented in rehabilitation settings to monitor patient progress, readiness for RTS and guide the rehabilitation process after ACL reconstruction. The scale includes the evaluation dynamic knee valgus collapse, and four undesirable movements that are implicated in risky movement patterns that increase the risk for ACL injury. The undesirable movements included in the scale are insufficient trunk flexion, insufficient knee flexion, lateral trunk lean and asymmetry. Chapter 2 Supplement is an instruction booklet written to accompany the developed Clinician-Rated DVJS.

5.2.2 Dynamic Knee Valgus Collapse

Dynamic knee valgus collapse has been implicated in primary and secondary ACL injury by increasing abduction moments about the knee[20,29,38,39]. Figure 5.1 shows the varying degrees of dynamic knee valgus collapse during landing, as evaluated with the DVJS. This can also be observed using motion analysis. Figure 5.2 shows a motion analysis capture of two separate ACL reconstruction patients performing the DVJ. One patient demonstrates a dynamic knee valgus collapse with a resulting KAM, while the other has safer landing biomechanics. Observing this movement pattern during landing indicates a ligament dominant rather than a muscular dominant landing technique. Landing with dynamic knee valgus collapse produces a large external KAM about the knee and ultimately a large load on the ACL[29,30]. When this landing pattern is observed, a goal for rehabilitation should include promoting muscle dominant landing and decreasing medial knee motion to reduce injury risk[30].

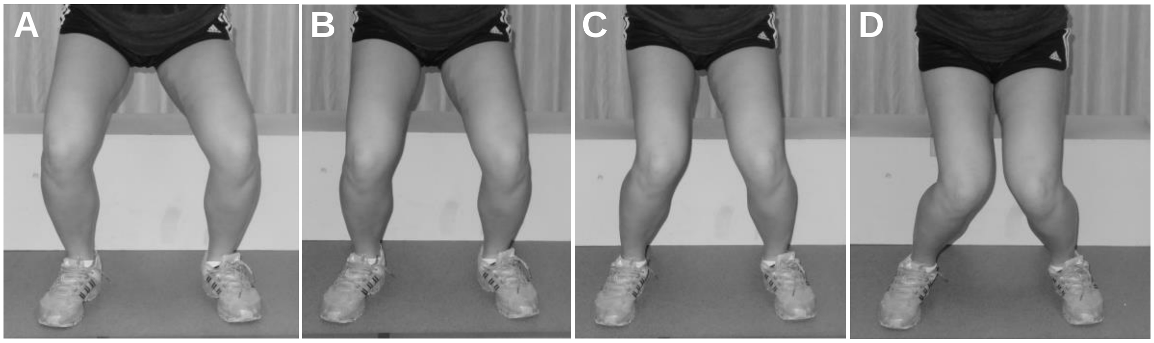

Figure 5.1: Example images of the categories of knee valgus collapse included in the Clinician-Rated DVJS. (A) NO (none); (B) SOME; (C) MODERATE; and (D) EXTREME knee valgus collapse.

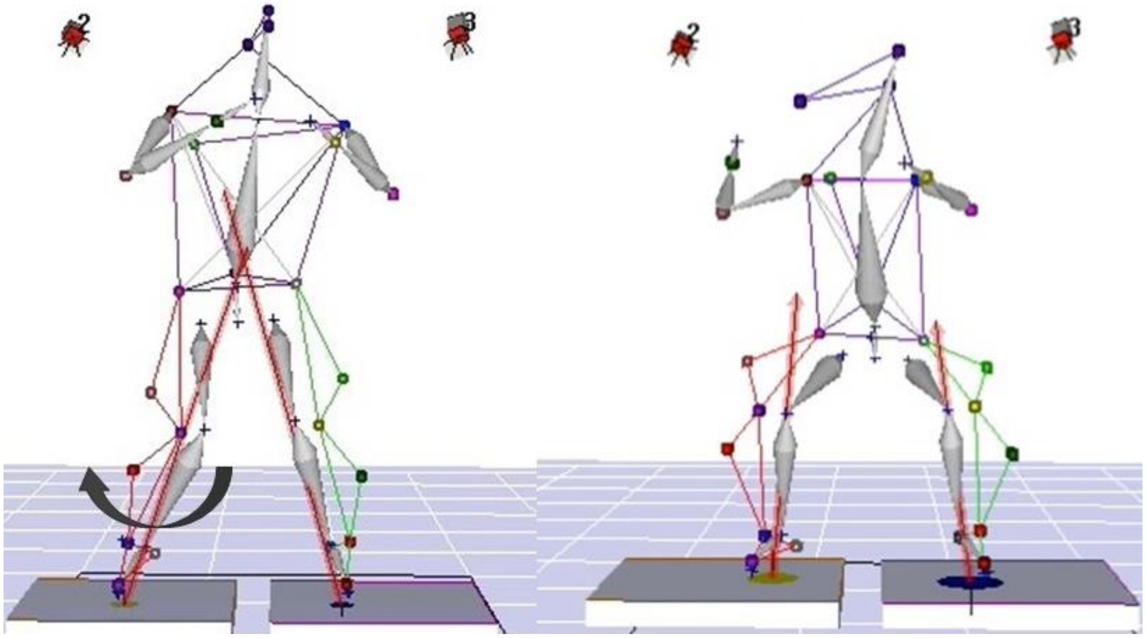

Figure 5.2: Motion analysis of two landing techniques during the DVJ in select patients after ACL reconstruction. The image on the right shows a dynamic knee valgus collapse with a resultant knee abduction moment. The image on the right is a different patient with a safer landing technique.

Observation of undesirable movements such as lateral trunk lean, insufficient trunk flexion, insufficient knee flexion and asymmetry, whether accompany dynamic knee valgus collapse or independently, also are indicators of increased ACL injury risk. At the time of ACL injury, the trunk is frequently in an upright or erect position[8,19,41] and displaced laterally[41]. This results in reduced flexion of the lower extremity, particularly in the hip and knee[6,7,48]. Once again, we have increased load on the ACL and thereby increased risk for injury. Lateral trunk lean can be an indicator of hip abductor weakness[41]. Hip abductor weakness can also contribute to an internal rotation moment at the hip during landing as the gluteals cannot stabilize the joint. Gluteus medius and minimus, piriformis and sartorius are all hip muscles that act in both hip abduction and external rotation[34]. The gluteus maximus is a powerful hip extensor and external rotator[34]. Souza and Powers[49] found that individuals with patellar femoral pain also had weaker gluteus maximus (extensor) and medius (abductor) strength and a net hip internal rotation moment during a drop jump task, when compared to healthy controls. Paterno et al[39] has identified a hip internal rotation moment in the uninvolved limb as the strongest predictor of secondary ACL injury. Delahunt et al[10] also found that during the landing phase of a DVJ protocol, ACL reconstruction patients were in a more hip adducted and internally rotated position, when compared to healthy controls. Hip musculature should therefore be considered as targets of rehabilitation intervention. Note that shifting the trunk over a weaker limb could result in an increase in dynamic knee valgus collapse ipsilaterally.

5.2.3 Secondary Injury Prevention

The rate of secondary ACL injury, whether ipsi- or contralateral, after ACL reconstruction has been reported to be as high as 17 to 25% in young athletes[21,26,39,47], and even as high as 44% in a cohort of young females in a five-year follow-up[21]. Furthermore, in this high-risk group, those that unfortunately sustain a secondary ACL injury have less favorable outcomes[21], including instability, severity of OA, poor functional abilities and likely even lower levels of return-to-play[4], although there is a lack of data on the success of return-to-sport in this population[21]. This in turn, impacts long-term health outcomes and economic burden. There is evidently a need for strategies to prevent revision ACL reconstruction and secondary ACL injury[21,39]. The incidence of secondary ACL injury has been reported to be more dependent on modifiable risk factors than primary ACL injury[21,39].

5.2.4 Biomechanical Analysis

Observational assessment tools, such as the Clinician-Rated DVJS in Study 1, are important for availability and ease of use in clinical settings. However, the content included on such observational tools is based on information collected using biomechanical analysis of performance (e.g. Figure 5.3). Using 3D movement analysis techniques provides insight on ACL injury risk factors. The DVJ is indicative of neuromuscular performance and dynamic stability of the knee and has been implicated in identifying movement properties of modifiable ACL injury risk factors and predicting those at risk for ACL injury[3,12,20,31]. However, to confidently assess ACL reconstructed patients on the DVJ, measurement properties of DVJ biomechanics in this population should be known. Study 2 (Chapter 3) evaluated the reliability and longitudinal validity of movement properties during the DVJ task in such a population. Findings from Study 2 support the interpretation of various landing biomechanics assessed during repeated measures during rehabilitation after ACL reconstruction.

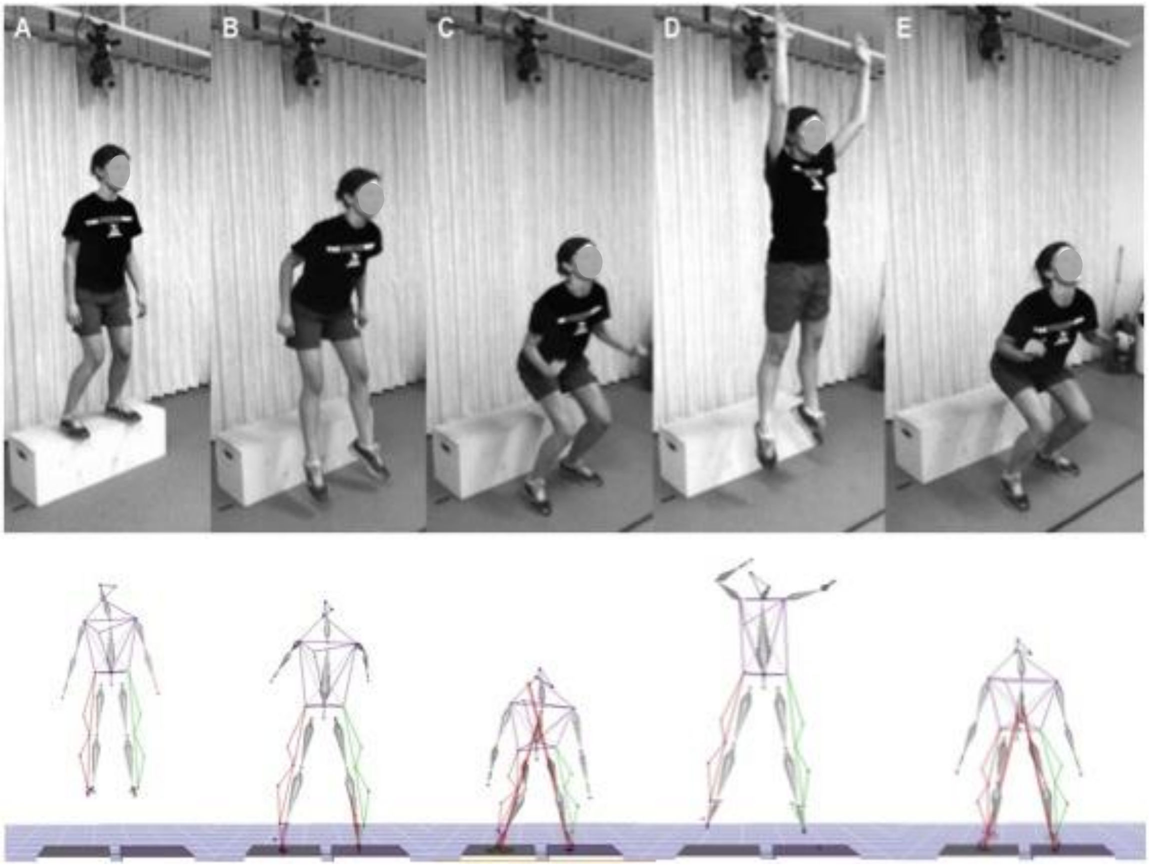

Figure 5.3: Biomechanical analysis of movement properties of the DVJ. Pictures (top) and motion-capture stick figures (bottom) showing (A) Start position; (B) Drop (Initial Contact); (C) Deepest point during landing; (D) Maximal jump; and (E) Second landing and completion of jump.

Filtering frequency for Study 2 was determined using residual analysis, as described in the Technical Report (Chapter 3 Supplement). This resulted in a cut-off of 14 Hz for marker data and 50 Hz for VGRF data. It is important to consider the impact of using too low of a cut-off filter at the risk of artificially removing important physiological information[44,53]. For example, Roewer et al[44] evaluated the effect of using same and different filtering frequencies for marker and GRFs (e.g. 10 and 10 *vs* 10 and 50 Hz) on drop landing data.

They looked specifically at peak KAM as this is a strong predictor of ACL injury. They reported that when using same low-frequency cut-off (i.e. 10 and 10, or 12 and 12, or 15 and 15 Hz for marker and GRF, respectively), the average peak KAM were significantly lower than those using different cut-offs (10, 50 or 12, 50, or 15, 50 Hz). This resulted in 3 participants who were considered ‘at risk’ for ACL injury based on their peak KAM when data was filtered at 10 and 50 Hz, were no longer considered ‘at risk’ when using same low cut-off frequencies for markers and VGRF.

Reliability studies by Ford et al[15] and Mok et al[28] filtered their data at the same low cut-off frequency of 12 and 12 Hz[15], and 15 and 15 Hz[28] for markers and VGRF. Typically, marker data is filtered using a low cut-off frequency less than 20 Hz[44]. The residual analysis completed in the Supplemental Technical Note to Chapter 3 resulted in 14 Hz and 50 Hz to be appropriate cut-off frequencies for markers and VGRFs, respectively. Hewett et al[20], who concluded that peak KAM is the strongest predictor of ACL injury, with high sensitivity (78%) and specificity (73%), filtered their data at 9 and 50 Hz for markers and VGRF. Arguably, identifying individual’s potentially at risk for ACL injury is more important than smooth joint moment curves[44].

The findings from Study 2 (Chapter 3) provide valuable information to researchers and clinicians for the assessment of ACL injury risk using the DVJ. Important risk factors for ACL injury include high KAM[20,31,39,50], contralateral transverse plane hip net moment impulse in the initial 10% of landing, frontal plane knee motion (KAA disp), asymmetry in sagittal plane knee moment at IC[39], and side-to-side asymmetries in VGRF during landing, takeoff and loading rate of the limb[37]. Peak KAM in the ACL reconstructed limb had an ICC of 0.75, hip impulse in the nonoperative limb was 0.61, frontal plane knee displacement (KAA disp) of the ACL reconstructed limb was 0.54, and sagittal plane KFM at IC was 0.48 and 0.33 in the ACL reconstructed and nonoperative limbs, respectively. Peak VGRF had higher ICC with 0.89 and 0.82 during the LP, and 0.90 and 0.93 during TO, in the ACL reconstructed and nonoperative limbs, respectively. Loading rate in the ACL reconstructed limb had an ICC of 0.71.

Loading rate asymmetry in female ACL reconstruction patients 2 years postoperatively has been reported in the literature[37]. While Paterno et al[37] reported an increased loading rate in the uninvolved limb in ACL reconstruction participants 2 years postoperatively, Decker et al[9] reported reduced loading rate in the involved limb when compared to healthy controls during a drop landing task of participants at a time point greater than 1 year postoperatively. Paterno et al[37] attributed this difference to the time postoperatively that testing took place. Note that Decker et al[9] did not report the loading rate of the contralateral limb so asymmetry could not be evaluated in this case. Regardless, asymmetry in loading rate has been reported as a high potential risk factor for ACL injury[8,20,36,39]. Study 2 evaluated reliability in loading rate in both limbs, as well as asymmetry between limbs. ICCs were poor-to-moderate (0.41, 0.61, and 0.71 for asymmetry, nonoperative and operative limbs, respectively). Ultimately, asymmetries between limbs for loading rate, or increased loading rate coupled with increased VGRF of the uninvolved limb (i.e. attenuating greater forces in a shorter period of time) could put individuals at a greater risk for ACL (re)injury.

Overall, reliability measures for peak knee flexion and abduction moments in the ACL reconstructed limb were moderate-to-good. Studies by Ford et al[15] and Mok et al[28] reported similar ICC ranges in their healthy subjects performing the DVJ for these measures. However, reliability for knee abduction angles ranged from poor-to-moderate in the ACL reconstructed limb. These are different than what is observed in healthy athletic subjects as Ford et al[15] and Mok et al[28] reported good reliability for knee abduction angles. This discrepancy may be attributed to the ACL reconstruction procedure. The reliability study by Ford et al[15] was completed on healthy middle- and high-school soccer and basketball players, while Mok et al[28] included healthy elite handball athletes. The subjects in Study 2 were 6 months post ACL reconstruction. Despite completing an ACL rehabilitation protocol, they were still rehabilitating from surgery, and it has been well documented that even years following ACL reconstruction, muscle weakness and altered landing mechanics persist[9,37,50]. Furthermore, as our participants had sustained an ACL rupture with subsequent reconstruction, perhaps their initial biomechanical movement properties already had instability and risky movement patterns[37] such as increased valgus loading and movement, thereby increasing the error in measurement in the frontal plane.

A study by Paterno et al[37] identified transverse plane net hip moment impulse in the initial 10% of the landing phase of the DVJ to be the strongest predictor for secondary injury. Patients who succumbed a secondary ACL injury had a contralateral net hip internal rotator moment, as opposed to an external rotator moment seen in patients with primary ACL injury only. Study 2 reported novel reliability data for the transverse plane net hip moment impulse in the contralateral limb. Moderate reliability in this measure is possible when evaluating patients 6 months post ACL reconstruction.

5.2.5 ACL Rehabilitation Strategies

Evaluating landing biomechanics of known secondary ACL injury is paramount as re-injury rate after ACL reconstruction is considerably higher than primary ACL injury. Studies have reported that as many as 1 in 4 will sustain a second knee injury[21,24,26,35,38,39,47]. These secondary injuries tend to be highly related to modifiable post-surgery risk factors[21], and typically occur early after return to sport[35], or within the first years after surgery[52]. Targeted neuromuscular training has had success in reducing the prevalence of primary ACL injury[50,51]. Implementing targeted neuromuscular training strategies during the late stages of rehabilitation[32,50] to reduce the risk of secondary injury has been proposed. However, adherence and compliance to longer rehabilitation programs is problematic[5,54].

Alternative rehabilitation strategies in the early stages after ACL reconstruction have been examined. Several studies evaluating home-based rehabilitation following ACL reconstruction have reported no differences between rehabilitation modalities on outcomes such as ROM, ligament laxity and strength[14,17,18,22,46]. Home-based rehabilitation programs following ACL reconstruction are promising. Considering the success of home-based ACL rehabilitation, ~~s~~hifting the focus of rehabilitation to the late-stage portion where targeted neuromuscular training to reduce secondary risk factors is warranted. Using reliability data from Study 2, Study 3 (Chapter 4) used an evidence-based approach evaluating functional outcomes of known predictors of secondary ACL injury evaluating landing biomechanics during the DVJ to compare two rehabilitation programs including staged and usual care physiotherapy.

In Study 3 (Chapter 4), primary outcome measures of transverse plane net hip moment impulse and peak KAM at 6 months post ACL reconstruction had no differences between rehabilitation groups. Figures 5.4 shows mean peak KAM for each group at 6 months post ACL reconstruction. Six-months post-operatively is a typical time for ACL reconstruction patients to consider RTS[54]. Hip impulse and peak KAM have been identified as important predictors of ACL injury risk[20,39,50]. The findings of Study 3 therefore support a staged-physiotherapy program as a viable option following ACL reconstruction.

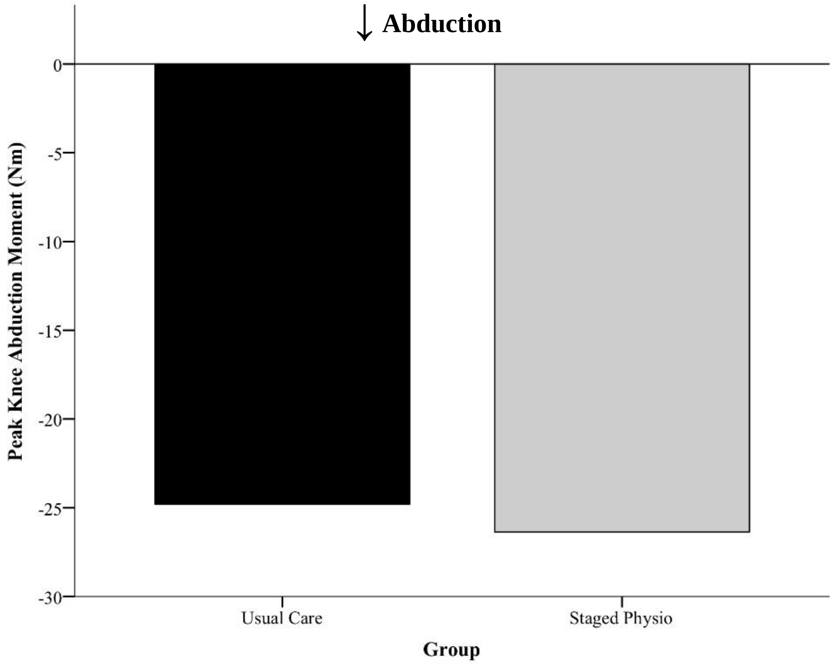

Figure 5.4: No differences between groups for peak knee abduction moment at 6 months post ACL reconstruction. A net abduction moment is negative.

5.3 Limitations and Future Research

5.3.1 Limitations

There are certain limitations in this thesis that should be discussed. The fact that the data for Studies 2 and 3 were filtered at different low cut-off frequencies (14 Hz for markers, 50 Hz for forces), means there is likely more noise or artefacts that remain in the signal, yet less physiological information will be lost for the sake of smoother joint moment curves. This may in turn affect the reliability data and could account for differences observed, for example the reliability of knee abduction variables seems lower in our study compared to other studies[15,28]. Furthermore, participants were likely using compensatory mechanisms[13,33,37,45] during their jumping to accommodate weakness in the reconstructed limb. Since the reliability of asymmetry percentage in VGRFs was good, the reduced reliability seen in other measures could also be attributed to the participants as sources of error[27], or marker placement between sessions. Marker placement has no bearing on the reliability of VGRFs, whereas it plays a significant role in joint moments and angles. Variability in the participant's ability to consistently complete the DVJ can therefore impact on consistent movement mechanics and reliability measures. Milner et al[27] reported moderate within-session reliability (ICC = 0.63) in VGRF on a stop jump landing task. As marker placement is not an issue for within-session reliability, they attributed their moderate reliability to participant variability. They however reported excellent reliability for VGRF between sessions for the stop jump landing (ICC = 0.96).

5.3.2 Future Research

The Clinician-Rated DVJS was developed, and now further research on its' measurement properties is recommended before widespread clinical implementation can occur. Findings from Study 3 support a staged-physiotherapy approach after ACL reconstruction. Secondary ACL injury risk factors were measured using the DVJ to compare rehabilitation strategies. It has been proposed that targeted neuromuscular training is warranted in the late stage of rehabilitation[32,50] as it has been shown to reduce the prevalence of primary ACL injury[50,51]. While Study 3 did not specifically evaluate targeted neuromuscular training, which should be included during the late-stages of rehabilitation, future studies should consider using the staged physiotherapy approach and implement targeted neuromuscular training to see if secondary ACL risk factors can be altered. Future consideration of neuromuscular function and the long-term success of rehabilitation programs is an ongoing problem that is necessary to continue to investigate.

5.4 Recommendations

1. The developed Clinician-Rated DVJS can be used to assist clinicians and researchers identify desirable and undesirable landing mechanics and guide rehabilitation efforts, monitor change in landing performance, and participate in clinical research. The scale is not, however, intended to determine readiness for RTS.
2. A separate residual analysis prior to studies investigating biomechanical movement properties in jump landing adds rigour to such studies.
3. Researchers and practitioners can confidently assess patient performance on the DVJ in patients with ACL reconstruction. Vertical ground reaction forces, peak knee abduction and flexion moments, and knee flexion angles can be evaluated with good reliability in patients as early as 6 months after ACL reconstruction.
4. A staged (home and clinic based) physiotherapy program after ACL reconstruction does not appear to compromise landing biomechanics compared to usual care.
5. Given the risk of subsequent ACL injuries and knee osteoarthritis, future consideration of neuromuscular function and the long-term success of rehabilitation programs after ACL reconstruction is an important area for continued research.

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Appendices

Appendix A: Ethics Approval for Study 1.

Research Western

Use of Human Participants - Ethics Approval Notice

Principal Investigator: Dr. Trevor Birmingham
Review Number: 18634E
Review Level: Delegated
Approved Local Adult Participants: 4
Approved Local Minor Participants: 0
Protocol Title: Delphi study to establish consensus on the content and scoring of a jump landing scale as a clinical tool for patients undergoing rehabilitation after ACL reconstruction
Department & Institution: Physical Therapy, University of Western Ontario
Sponsor:
Ethics Approval Date: February 02, 2012 **Expiry Date:** December 31, 2015
Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
UWO Protocol		
Letter of Information		2012/01/30
Other	Email Recruitment	

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above. The membership of this REB also complies with the *membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.*

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the UWO Updated Approval Request Form.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

The Chair of the HSREB is Dr. Joseph Gilbert. The UWO HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

[redacted]

Signature

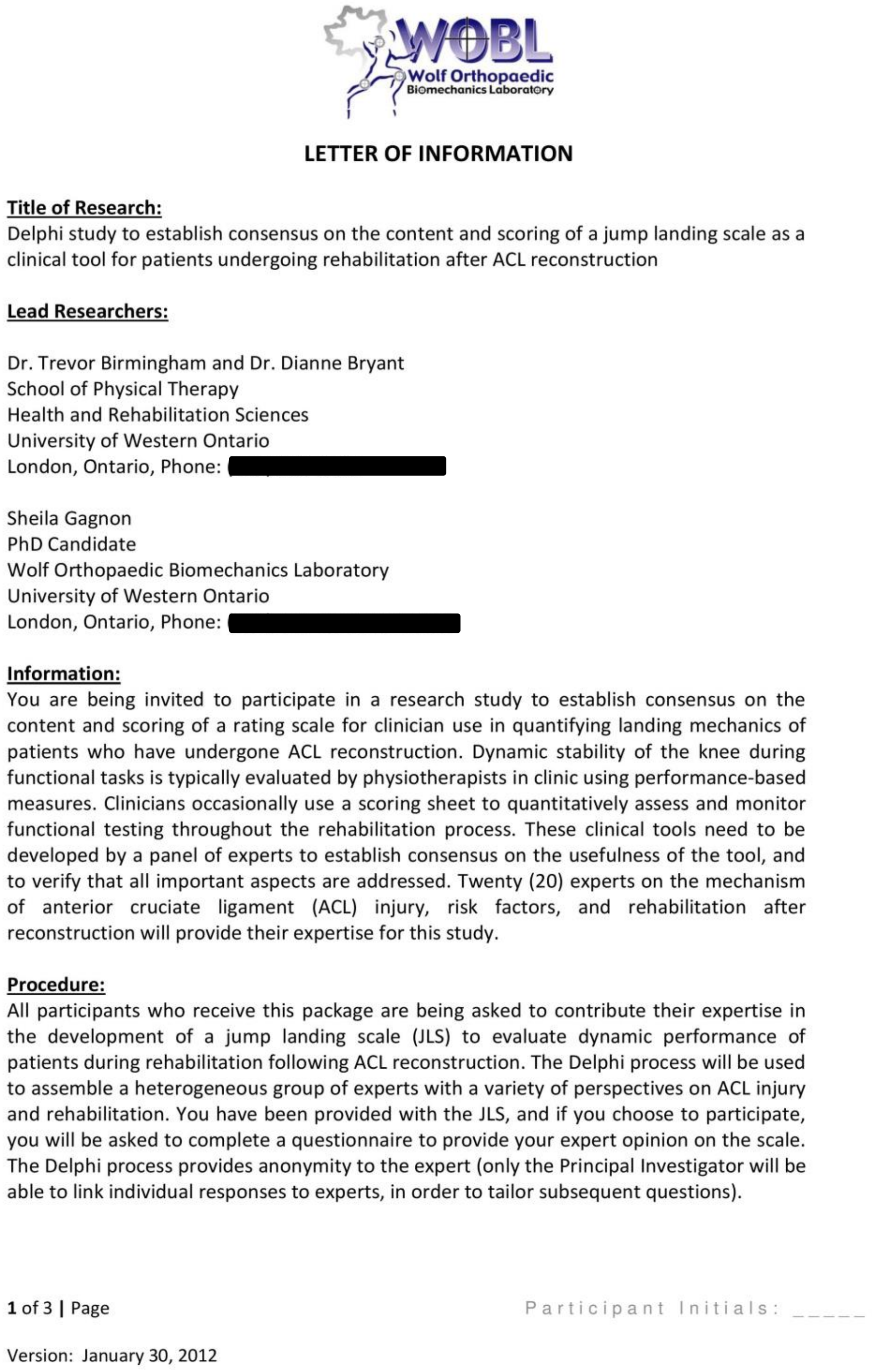
Ethics Officer to Contact for Further Information

Janice Sutherland [redacted]	✓ Grace Kelly [redacted]	Shantel Walcott [redacted]

This is an official document. Please retain the original in your files.

***The* University *of* Western Ontario**
Office of Research Ethics
Support Services Building Room 5150 • London, Ontario • CANADA - N6G 1G9
PH: 519-661-3036 • F: 519-850-2466 • ethics@uwo.ca • www.uwo.ca/research/ethics

Appendix B: Letter of Information for Study 1.



WOBL
Wolf Orthopaedic
Biomechanics Laboratory

LETTER OF INFORMATION

Title of Research:
Delphi study to establish consensus on the content and scoring of a jump landing scale as a clinical tool for patients undergoing rehabilitation after ACL reconstruction

Lead Researchers:

Dr. Trevor Birmingham and Dr. Dianne Bryant
School of Physical Therapy
Health and Rehabilitation Sciences
University of Western Ontario
London, Ontario, Phone: [redacted]

Sheila Gagnon
PhD Candidate
Wolf Orthopaedic Biomechanics Laboratory
University of Western Ontario
London, Ontario, Phone: [redacted]

Information:
You are being invited to participate in a research study to establish consensus on the content and scoring of a rating scale for clinician use in quantifying landing mechanics of patients who have undergone ACL reconstruction. Dynamic stability of the knee during functional tasks is typically evaluated by physiotherapists in clinic using performance-based measures. Clinicians occasionally use a scoring sheet to quantitatively assess and monitor functional testing throughout the rehabilitation process. These clinical tools need to be developed by a panel of experts to establish consensus on the usefulness of the tool, and to verify that all important aspects are addressed. Twenty (20) experts on the mechanism of anterior cruciate ligament (ACL) injury, risk factors, and rehabilitation after reconstruction will provide their expertise for this study.

Procedure:
All participants who receive this package are being asked to contribute their expertise in the development of a jump landing scale (JLS) to evaluate dynamic performance of patients during rehabilitation following ACL reconstruction. The Delphi process will be used to assemble a heterogeneous group of experts with a variety of perspectives on ACL injury and rehabilitation. You have been provided with the JLS, and if you choose to participate, you will be asked to complete a questionnaire to provide your expert opinion on the scale. The Delphi process provides anonymity to the expert (only the Principal Investigator will be able to link individual responses to experts, in order to tailor subsequent questions).

1 of 3 **|** Page

Participant Initials: _____

Version: January 30, 2012

The study will last a few rounds, until consensus has been reached. Each round will be open for responses for 2 weeks, with a 2-week turnaround between rounds. Therefore, the maximum length of participation is 3 questionnaires in 2 and one half months. After the first round, you will be provided with your initial opinion, as well as the global opinion of the expert panel. You will be asked to re-rate the JLS during the second round. This process will repeat until consensus is reached or termination criteria have been met. The goal is to have 2-3 rounds of the Delphi.

Completion of the online survey indicates your consent to participate in this research.

Benefits:
There are no direct benefits of this study to the research participants. However, their expertise may provide a means to develop a rating scale for clinic and research use. There are no known risks to participation in this study.

Cost/Compensation:
You will not be compensated for your participation in this study.

Voluntary Participation:
Your participation in this study is voluntary. You may refuse to participate, refuse to answer any questions or withdraw from the study at any time with no effect to yourself. Should you choose to withdraw from this study, we will keep all data obtained up to the point that you chose to withdraw.

Participation in this study does not prevent you from participating in any other research studies at the present time or future.

Request for Study Results:
Should you decide to participate and want to receive a copy of the study results, please provide your contact information. Once the study has been published, a copy will be mailed to you. Please note that the results of this study may not be published for 5 years. Should your mailing information change, please let us know.

Confidentiality:
All information will be kept in strict confidence. Survey Monkey has been coded with a unique identifier in order to maintain your anonymity that will be used for all of your information and data collection. Data that is collected will be username and password protected and stored on a server at The University of Western Ontario. Your identifying information will not appear on the database used to analyze data. In any publication, presentation or report, your name will not be used and any information that discloses your identity will not be released or published. Representatives of The University of Western Ontario Health Sciences Research Ethics Board may require access to your study related records or may follow up with you to monitor the conduct of the study.

<u>Questions:</u>

If you have questions about the conduct of the study or your rights as a research participant, you may contact The Office of Research Ethics at (519) 661-3036 or by email at ethics@uwo.ca.

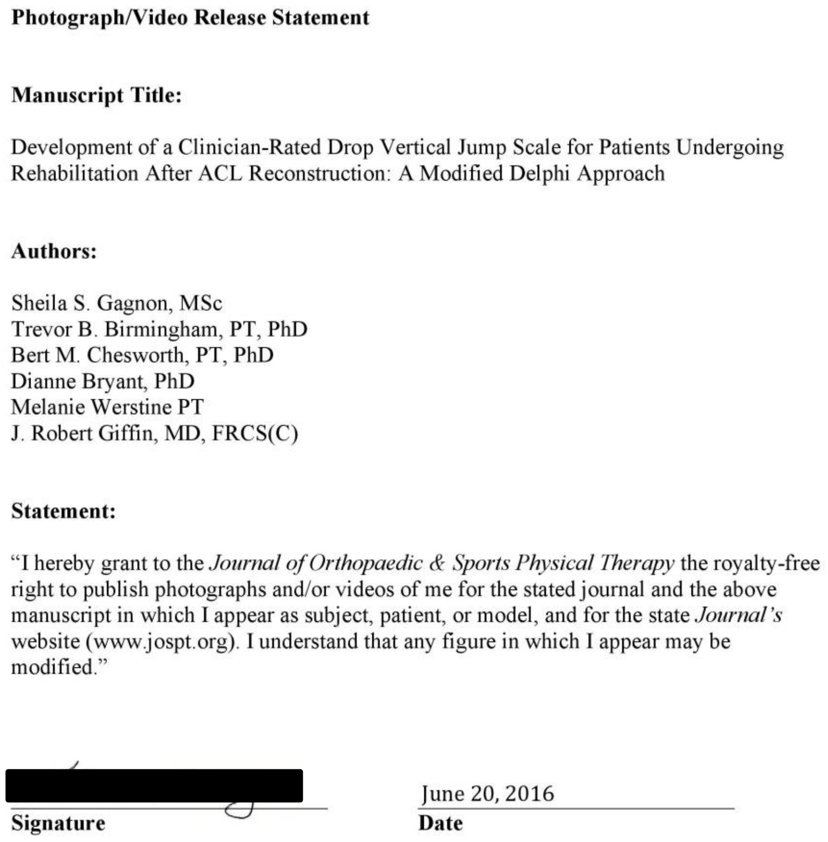
If you have any questions or concerns about this research, please contact Sheila Gagnon at [redacted] or [redacted], or Dr. Trevor Birmingham at [redacted] or [redacted].

This letter is yours to keep.

Sincerely,

Sheila Gagnon, MSc, PhD (can.)
Dr. Trevor Birmingham, PT PhD
Dr. Dianne Bryant, PhD
Dr. Bert Chesworth, PT PhD
Dr. J. Robert Giffin, MD

Appendix C: Photograph Release Statement for Study 1.



Photograph/Video Release Statement

Manuscript Title:

Development of a Clinician-Rated Drop Vertical Jump Scale for Patients Undergoing Rehabilitation After ACL Reconstruction: A Modified Delphi Approach

Authors:

Sheila S. Gagnon, MSc
Trevor B. Birmingham, PT, PhD
Bert M. Chesworth, PT, PhD
Dianne Bryant, PhD
Melanie Werstine PT
J. Robert Giffin, MD, FRCS(C)

Statement:

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[redacted]
Signature

June 20, 2016
Date

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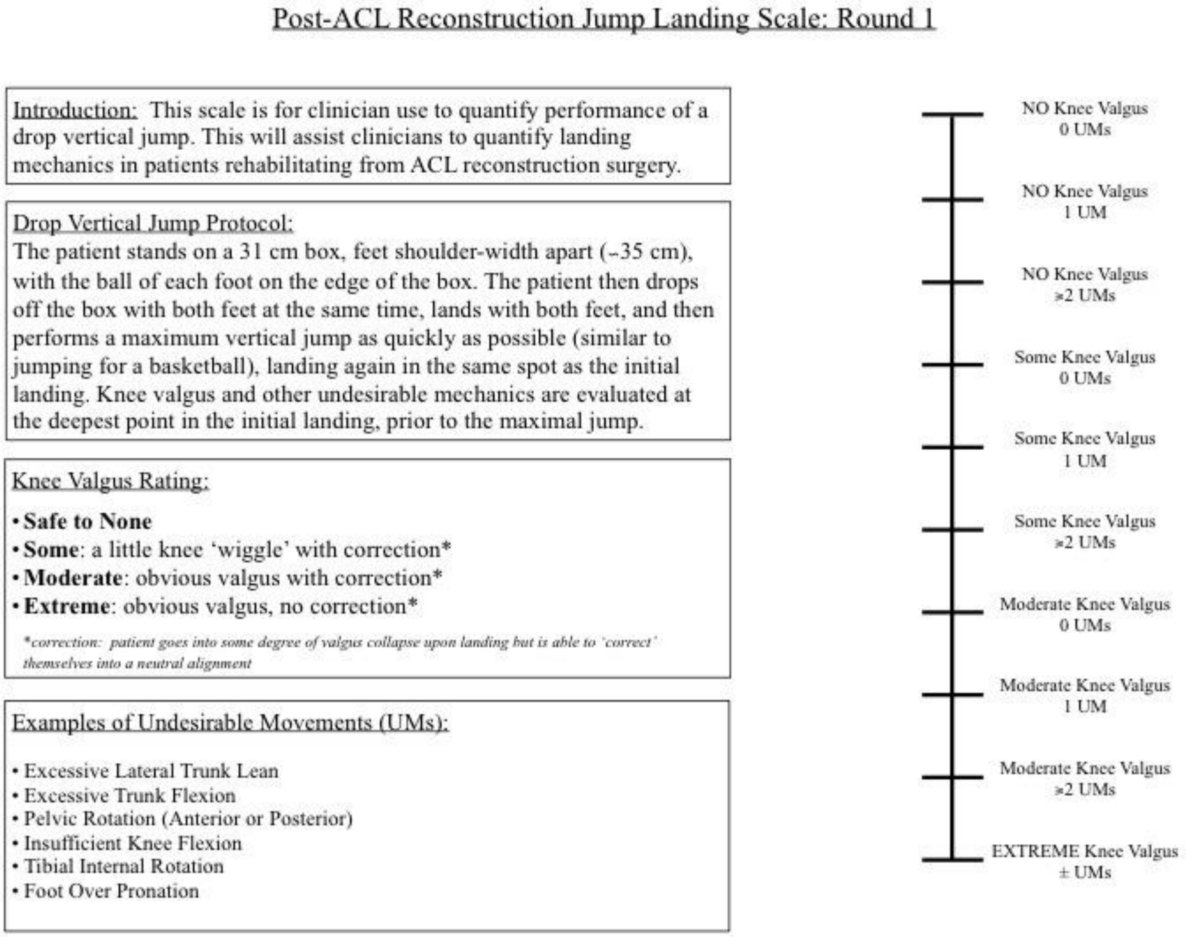
Appendix D: Study 1 Delphi Survey Rounds 1 – 4.

Delphi ACL Rehabilitation Survey Round 1

Consult the Jump Landing Scale provided here to answer QUESTIONS 1 – 10. Rate how important each of the following undesirable movements are for double limb jump landing performance for ACL injury risk.

To minimize scrolling, you may want to print this scale now.



Post-ACL Reconstruction Jump Landing Scale: Round 1

Introduction: This scale is for clinician use to quantify performance of a drop vertical jump. This will assist clinicians to quantify landing mechanics in patients rehabilitating from ACL reconstruction surgery.

Drop Vertical Jump Protocol:
The patient stands on a 31 cm box, feet shoulder-width apart (~35 cm), with the ball of each foot on the edge of the box. The patient then drops off the box with both feet at the same time, lands with both feet, and then performs a maximum vertical jump as quickly as possible (similar to jumping for a basketball), landing again in the same spot as the initial landing. Knee valgus and other undesirable mechanics are evaluated at the deepest point in the initial landing, prior to the maximal jump.

Knee Valgus Rating:

- **Safe to None**
- **Some**: a little knee 'wiggle' with correction*
- **Moderate**: obvious valgus with correction*
- **Extreme**: obvious valgus, no correction*

**correction: patient goes into some degree of valgus collapse upon landing but is able to 'correct' themselves into a neutral alignment*

Examples of Undesirable Movements (UMs):

- Excessive Lateral Trunk Lean
- Excessive Trunk Flexion
- Pelvic Rotation (Anterior or Posterior)
- Insufficient Knee Flexion
- Tibial Internal Rotation
- Foot Over Pronation

NO Knee Valgus
0 UMs

NO Knee Valgus
1 UM

NO Knee Valgus
≥2 UMs

Some Knee Valgus
0 UMs

Some Knee Valgus
1 UM

Some Knee Valgus
≥2 UMs

Moderate Knee Valgus
0 UMs

Moderate Knee Valgus
1 UM

Moderate Knee Valgus
≥2 UMs

EXTREME Knee Valgus
± UMs

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1. **Rate how important EXCESSIVE LATERAL TRUNK LEAN is for double limb jump landing performance.**

☐ I do not believe this should be included on the scale.
☐ I consider this less important than exhibited on the scale.
☐ I agree with the scale
☐ I believe this is more important than exhibited on the scale.

2. **Rate how important EXCESSIVE TRUNK FLEXION is for double limb jump landing performance.**

☐ I do not believe this should be included on the scale.
☐ I consider this less important than exhibited on the scale.
☐ I agree with the scale
☐ I believe this is more important than exhibited on the scale.

3. **Rate how important PELVIC ROTATION (ANTERIOR OR POSTERIOR) is for double limb jump landing performance.**

☐ I do not believe this should be included on the scale.
☐ I consider this less important than exhibited on the scale.
☐ I agree with the scale
☐ I believe this is more important than exhibited on the scale.

4. **Rate how important INSUFFICIENT KNEE FLEXION is for double limb jump landing performance.**

☐ I do not believe this should be included on the scale.
☐ I consider this less important than exhibited on the scale.
☐ I agree with the scale
☐ I believe this is more important than exhibited on the scale.

5. **Rate how important KNEE VALGUS is for double limb jump landing performance.**

☐ I do not believe this should be included on the scale.
☐ I consider this less important than exhibited on the scale.
☐ I agree with the scale
☐ I believe this is more important than exhibited on the scale.

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6. Rate how important TIBIAL INTERNAL ROTATION is for double limb jump landing performance.

☐ I do not believe this should be included on the scale.
☐ I consider this less important than exhibited on the scale.
☐ I agree with the scale
☐ I believe this is more important than exhibited on the scale.

7. Rate how important FOOT OVER PRONATION is for double limb jump landing performance.

☐ I do not believe this should be included on the scale.
☐ I consider this less important than exhibited on the scale.
☐ I agree with the scale
☐ I believe this is more important than exhibited on the scale.

8. Are there other important undesirable movements (or other biomechanics) that should be considered in this scale?

☐ YES – if yes, please comment below
☐ NO – if no, continue to the next question

Name all other important undesirable movements that should be included, and their level of importance out of 10 (0 = no importance, 10 = utmost importance).

9. The Jump Landing Scale clearly denotes ________ as the most important factor in jump landing performance for ACL injury risk.

☐ Excessive lateral trunk lean
☐ Excessive trunk flexion
☐ Pelvic rotation (anterior or posterior)
☐ Insufficient knee flexion
☐ Knee valgus
☐ Tibial internal rotation
☐ Foot over pronation
☐ Does not denote an important factor

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10. Consulting the Jump Landing Scale, how do you suggest scoring it? Please insert numbers in the boxes provided.

NO Knee Valgus AND 0 UMs (undesirable movements) ☐
NO Knee Valgus AND 1 UM ☐
NO Knee Valgus AND ≥ 2 UMs ☐
Some Knee Valgus AND 0 UMs ☐
Some Knee Valgus AND 1 UM ☐
Some Knee Valgus AND ≥ 2 UMs ☐
Moderate Knee Valgus AND 0 UMs ☐
Moderate Knee Valgus AND 1 UM ☐
Moderate Knee Valgus AND ≥ 2 UMs ☐
EXTREME Knee Valgus AND ± UMs ☐

11. According to your scoring system in question 10, what would you consider as a safe score for return to PRACTICE after ACL reconstruction?

12. According to your scoring system in question 10, what would you consider as a safe score for return to FULL COMPETITION after ACL reconstruction?

13. What else would you, as a clinician / biomechanist, suggest is necessary for safe return-to-sport after ACL reconstruction, and why?

14. Please make any other comments about the Jump Landing Scale that you feel would be helpful.

15. How many years of experience do you have as an MSK Clinician OR Biomechanist?

☐ > 20 years
☐ 15 – 20 years
☐ 10 – 15 years
☐ 5 – 10 years
☐ < 5 years

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16. CLINICIANS ONLY: How frequently do you work with patients following ACL reconstruction?

☐ Daily
☐ Weekly (2 – 3x per week)
☐ Monthly (2 – 3x per month)
☐ Yearly (2 – 3x per year)
☐ Never

17. BIOMECHANISTS ONLY: What proportion of your research involves ACL studies?

☐ > 81%
☐ 61 – 80%
☐ 41 – 60%
☐ 21 – 40%
☐ < 20%

18. CLINICINS AND BIOMECHANISTS: Do you feel confident in your ability to evaluate knee valgus in jump landing performance?

☐ Extremely Confident
☐ Very Confident
☐ Confident
☐ Somewhat Confident
☐ Not Confident

19. CLINICIANS ONLY: Compared to your peers, how do you rate your skills as a clinician treating patients with ACL injuries or rehabilitation?

☐ Superior
☐ Above Average
☐ Average
☐ Below Average
☐ Inferior

20. BIOMECHANISTS ONLY: Compared to your peers, how do you rate your skills as a researcher when considering ACL injuries?

☐ Superior
☐ Above Average
☐ Average
☐ Below Average
☐ Inferior

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21. CLINICIANS ONLY: How familiar are you with current ACL rehabilitation protocols?

☐ Extremely Familiar
☐ Mostly Familiar
☐ Moderately Familiar
☐ Kind of Familiar
☐ Not Familiar

22. BIOMECHANISTS ONLY: How familiar are you with the ACL injury risk factors and mechanisms of injury?

☐ Extremely Familiar
☐ Mostly Familiar
☐ Moderately Familiar
☐ Kind of Familiar
☐ Not Familiar

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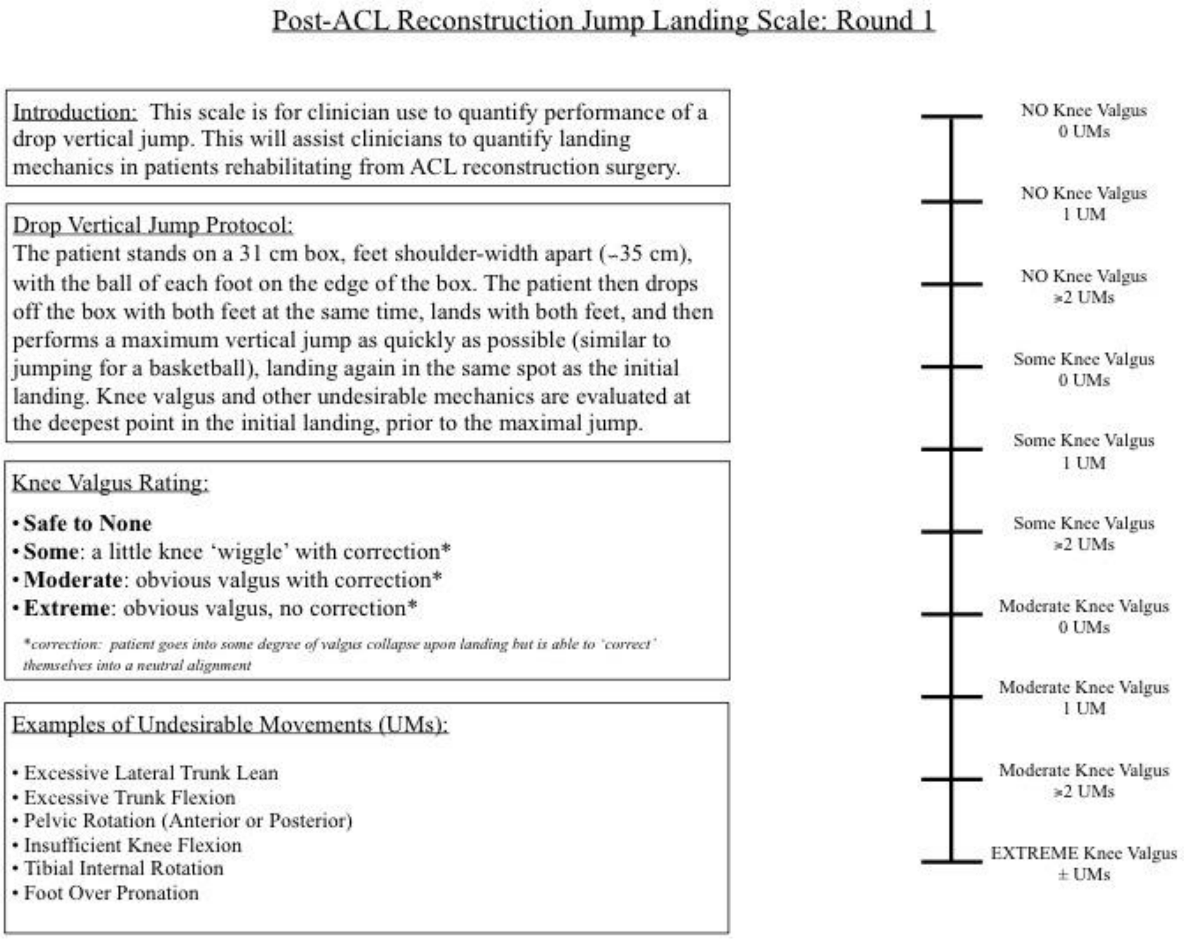
Delphi ACL Rehabilitation Survey Round 2

Fowler Kennedy ACL Survey Round 1 Results and Feedback

Below you will find the Jump Landing Scale provided in round 1 of this Delphi study, and the collective results from the questionnaire. Please review the collective responses and provide your feedback.



Post-ACL Reconstruction Jump Landing Scale: Round 1

Introduction: This scale is for clinician use to quantify performance of a drop vertical jump. This will assist clinicians to quantify landing mechanics in patients rehabilitating from ACL reconstruction surgery.

Drop Vertical Jump Protocol:
The patient stands on a 31 cm box, feet shoulder-width apart (~35 cm), with the ball of each foot on the edge of the box. The patient then drops off the box with both feet at the same time, lands with both feet, and then performs a maximum vertical jump as quickly as possible (similar to jumping for a basketball), landing again in the same spot as the initial landing. Knee valgus and other undesirable mechanics are evaluated at the deepest point in the initial landing, prior to the maximal jump.

Knee Valgus Rating:

- **Safe to None**
- **Some**: a little knee 'wiggle' with correction*
- **Moderate**: obvious valgus with correction*
- **Extreme**: obvious valgus, no correction*

**correction: patient goes into some degree of valgus collapse upon landing but is able to 'correct' themselves into a neutral alignment*

Examples of Undesirable Movements (UMs):

- Excessive Lateral Trunk Lean
- Excessive Trunk Flexion
- Pelvic Rotation (Anterior or Posterior)
- Insufficient Knee Flexion
- Tibial Internal Rotation
- Foot Over Pronation

A) For the 7 questions rating the Jump Landing Scale, you will find the collective opinion of the experts, including your individual response. Please indicate if you wish to keep your original response or change it. Please also feel free to provide an explanation or additional comments.

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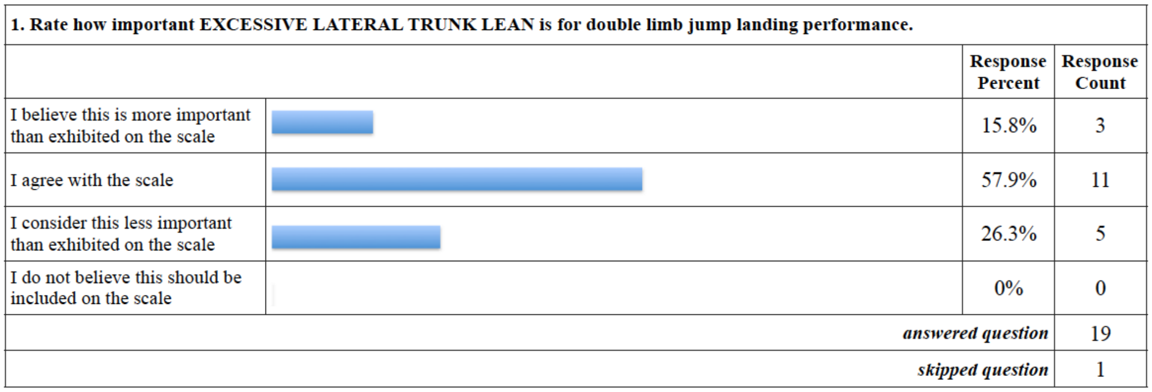


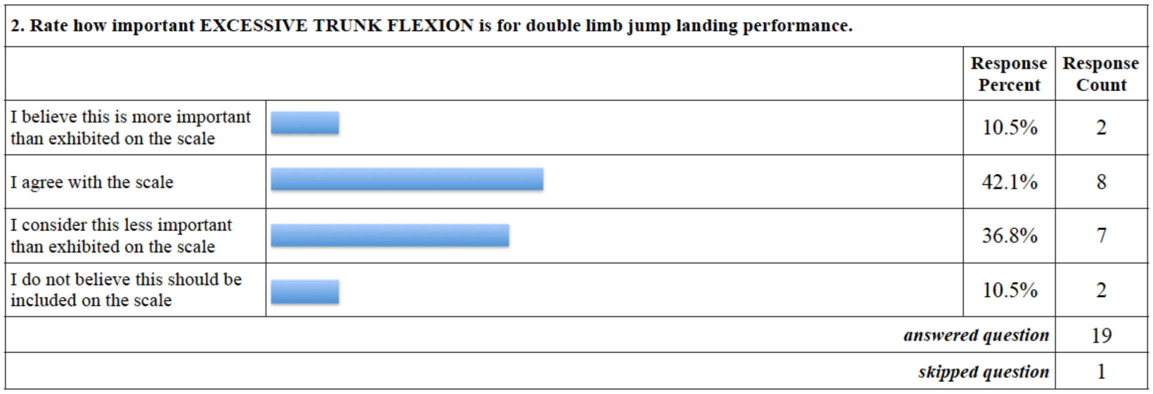
1. Rate how important EXCESSIVE LATERAL TRUNK LEAN is for double limb jump landing performance.

		Response Percent	Response Count
I believe this is more important than exhibited on the scale		15.8%	3
I agree with the scale		57.9%	11
I consider this less important than exhibited on the scale		26.3%	5
I do not believe this should be included on the scale		0%	0
	answered question		19
	skipped question		1

You Answered: ____________________

Do you want to: ☐ Keep my original response
☐ Change my response to:
- ☐ I believe this is more important than exhibited on the scale
- ☐ I agree with the scale
- ☐ I consider this less important than exhibited on the scale
- ☐ I do not believe this should be included on the scale

Explanation / Feedback: ☐



2. Rate how important EXCESSIVE TRUNK FLEXION is for double limb jump landing performance.

		Response Percent	Response Count
I believe this is more important than exhibited on the scale		10.5%	2
I agree with the scale		42.1%	8
I consider this less important than exhibited on the scale		36.8%	7
I do not believe this should be included on the scale		10.5%	2
	answered question		19
	skipped question		1

You Answered: ____________________

Do you want to: ☐ Keep my original response
☐ Change my response to:
- ☐ I believe this is more important than exhibited on the scale
- ☐ I agree with the scale
- ☐ I consider this less important than exhibited on the scale
- ☐ I do not believe this should be included on the scale

Explanation / Feedback: ☐

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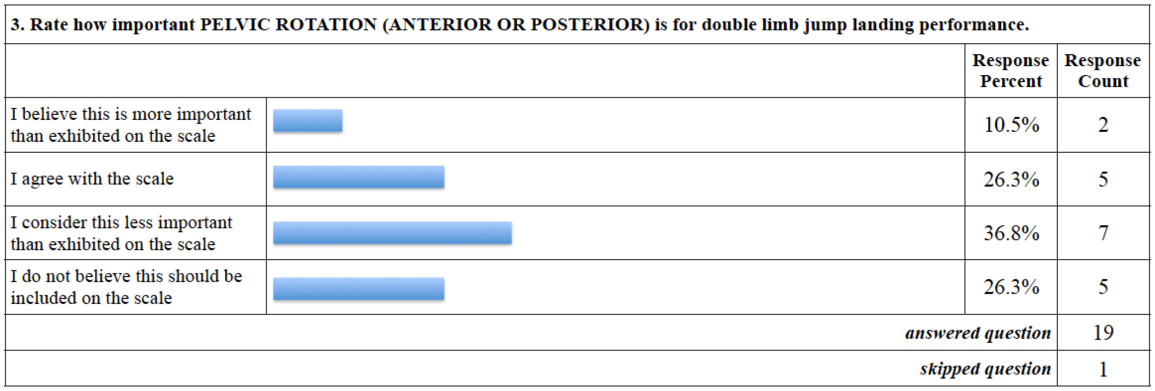


3. Rate how important PELVIC ROTATION (ANTERIOR OR POSTERIOR) is for double limb jump landing performance.

		Response Percent	Response Count
I believe this is more important than exhibited on the scale		10.5%	2
I agree with the scale		26.3%	5
I consider this less important than exhibited on the scale		36.8%	7
I do not believe this should be included on the scale		26.3%	5
		answered question	19
		skipped question	1

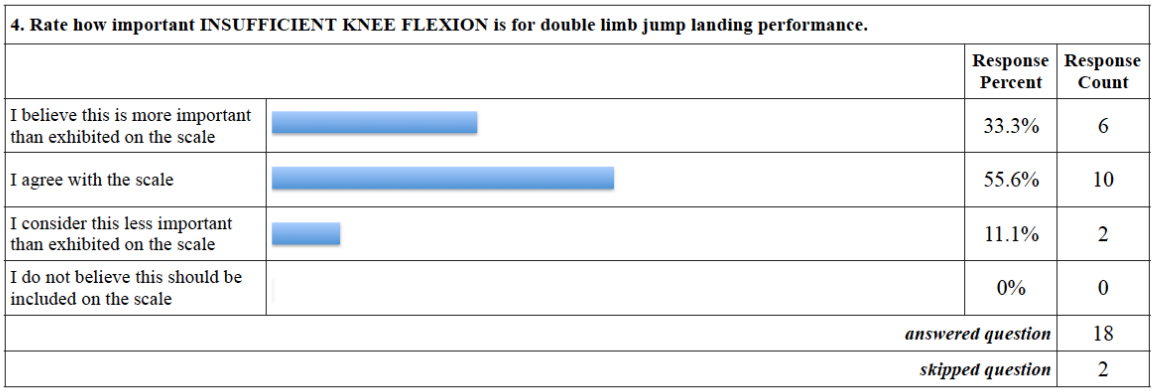
You Answered: ______________________

Do you want to: ☐ Keep my original response

☐ Change my response to:

- ☐ I believe this is more important than exhibited on the scale
- ☐ I agree with the scale
- ☐ I consider this less important than exhibited on the scale
- ☐ I do not believe this should be included on the scale

Explanation / Feedback: ☐



4. Rate how important INSUFFICIENT KNEE FLEXION is for double limb jump landing performance.

		Response Percent	Response Count
I believe this is more important than exhibited on the scale		33.3%	6
I agree with the scale		55.6%	10
I consider this less important than exhibited on the scale		11.1%	2
I do not believe this should be included on the scale		0%	0
		answered question	18
		skipped question	2

You Answered: ______________________

Do you want to: ☐ Keep my original response

☐ Change my response to:

- ☐ I believe this is more important than exhibited on the scale
- ☐ I agree with the scale
- ☐ I consider this less important than exhibited on the scale
- ☐ I do not believe this should be included on the scale

Explanation / Feedback: ☐

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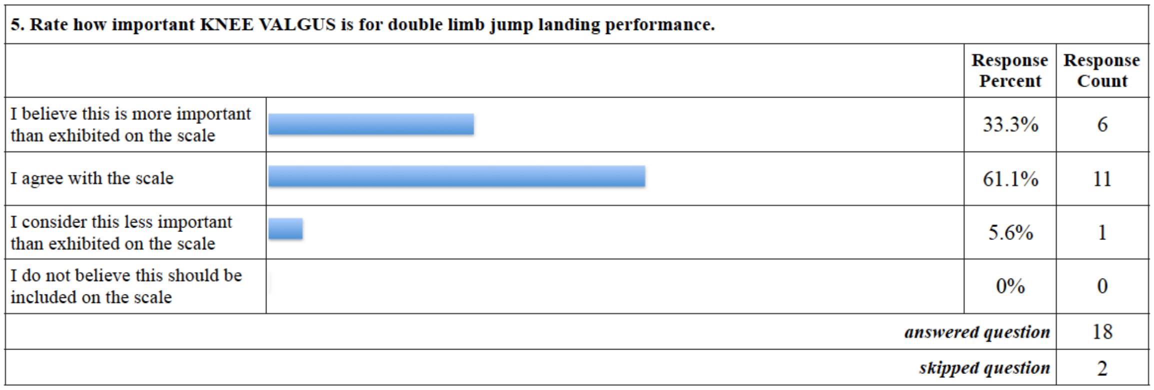


5. Rate how important KNEE VALGUS is for double limb jump landing performance.			
		Response Percent	**Response Count**
I believe this is more important than exhibited on the scale		33.3%	6
I agree with the scale		61.1%	11
I consider this less important than exhibited on the scale		5.6%	1
I do not believe this should be included on the scale		0%	0
		answered question	18
		skipped question	2

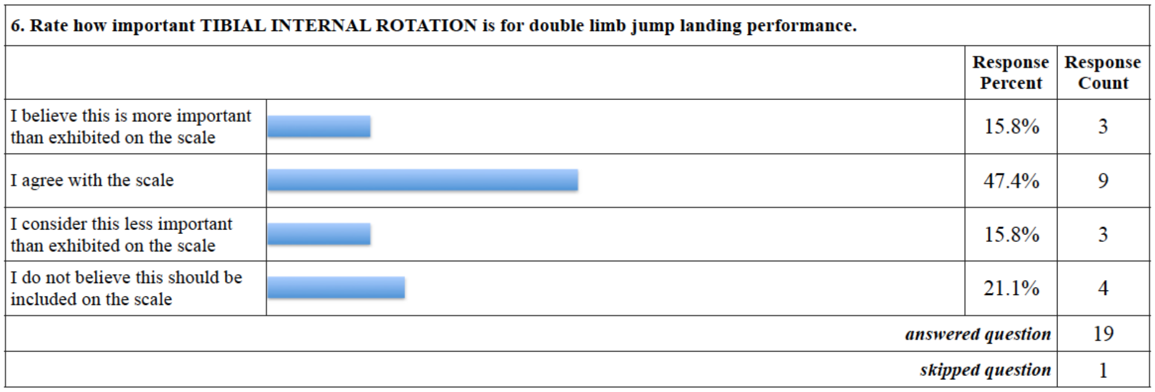
You Answered: ____________________

Do you want to: ☐ Keep my original response

☐ Change my response to:

- ☐ I believe this is more important than exhibited on the scale
- ☐ I agree with the scale
- ☐ I consider this less important than exhibited on the scale
- ☐ I do not believe this should be included on the scale

Explanation / Feedback: ☐



6. Rate how important TIBIAL INTERNAL ROTATION is for double limb jump landing performance.			
		Response Percent	**Response Count**
I believe this is more important than exhibited on the scale		15.8%	3
I agree with the scale		47.4%	9
I consider this less important than exhibited on the scale		15.8%	3
I do not believe this should be included on the scale		21.1%	4
		answered question	19
		skipped question	1

You Answered: ____________________

Do you want to: ☐ Keep my original response

☐ Change my response to:

- ☐ I believe this is more important than exhibited on the scale
- ☐ I agree with the scale
- ☐ I consider this less important than exhibited on the scale
- ☐ I do not believe this should be included on the scale

Explanation / Feedback: ☐

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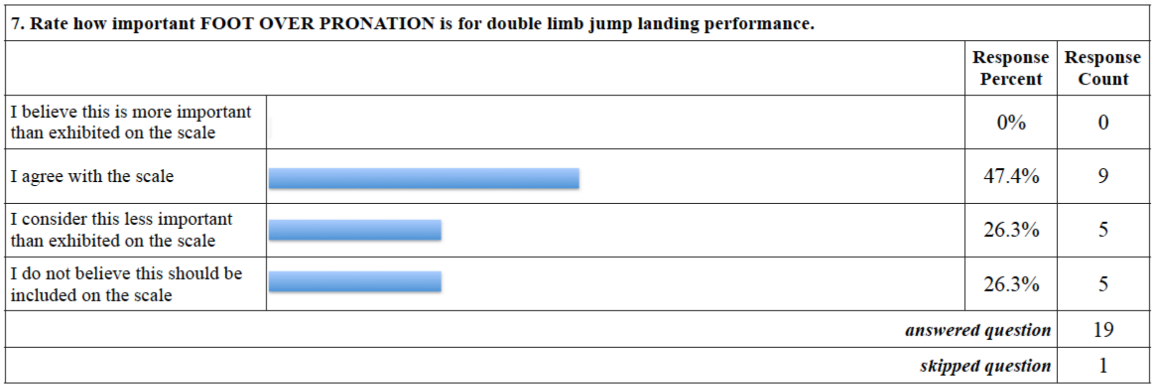


7. Rate how important FOOT OVER PRONATION is for double limb jump landing performance.			
		Response Percent	**Response Count**
I believe this is more important than exhibited on the scale		0%	0
I agree with the scale		47.4%	9
I consider this less important than exhibited on the scale		26.3%	5
I do not believe this should be included on the scale		26.3%	5
		answered question	19
		skipped question	1

You Answered: ______________________________

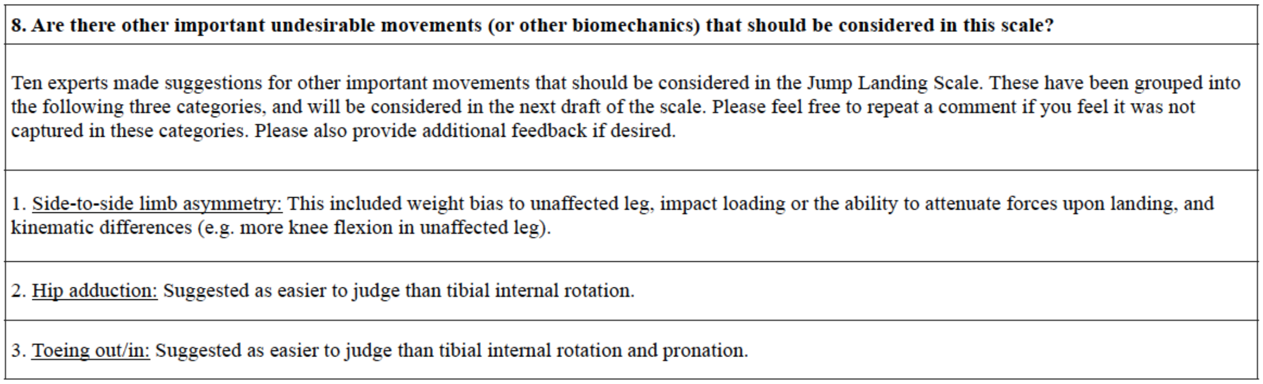
Do you want to: ☐ Keep my original response

☐ Change my response to:

- ☐ I believe this is more important than exhibited on the scale
- ☐ I agree with the scale
- ☐ I consider this less important than exhibited on the scale
- ☐ I do not believe this should be included on the scale

Explanation / Feedback: ☐

B) For questions 8 to 14 from round 1, the collective responses included the following information that we will consider in the development of the second draft of the Jump Landing Scale. Please feel free to provide additional feedback.



8. Are there other important undesirable movements (or other biomechanics) that should be considered in this scale?

Ten experts made suggestions for other important movements that should be considered in the Jump Landing Scale. These have been grouped into the following three categories, and will be considered in the next draft of the scale. Please feel free to repeat a comment if you feel it was not captured in these categories. Please also provide additional feedback if desired.

1. Side-to-side limb asymmetry: This included weight bias to unaffected leg, impact loading or the ability to attenuate forces upon landing, and kinematic differences (e.g. more knee flexion in unaffected leg).

2. Hip adduction: Suggested as easier to judge than tibial internal rotation.

3. Toeing out/in: Suggested as easier to judge than tibial internal rotation and pronation.

Explanation / Feedback: ☐

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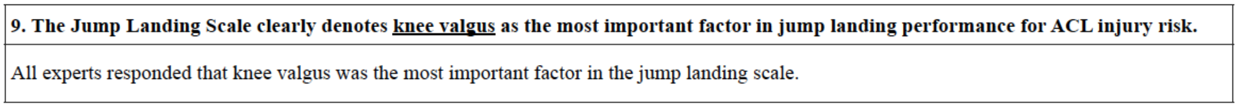
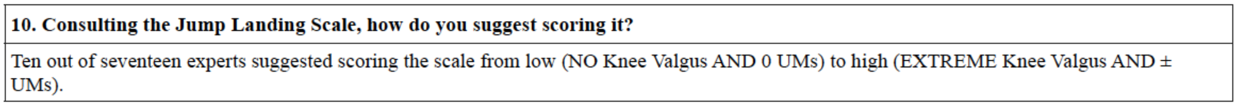


9. The Jump Landing Scale clearly denotes knee valgus as the most important factor in jump landing performance for ACL injury risk.

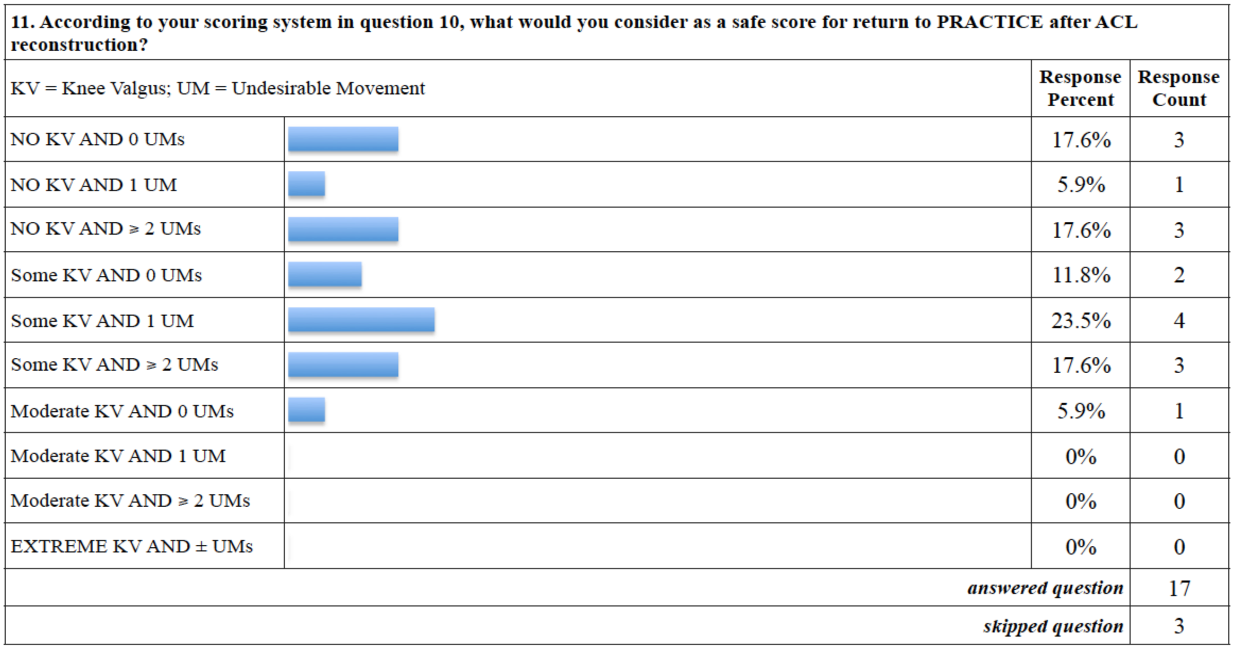
All experts responded that knee valgus was the most important factor in the jump landing scale.



10. Consulting the Jump Landing Scale, how do you suggest scoring it?

Ten out of seventeen experts suggested scoring the scale from low (NO Knee Valgus AND 0 UMs) to high (EXTREME Knee Valgus AND ± UMs).

Scoring for the scale will be addressed in draft 2. Please add additional comments if desired.



11. According to your scoring system in question 10, what would you consider as a safe score for return to PRACTICE after ACL reconstruction?

KV = Knee Valgus; UM = Undesirable Movement		**Response Percent**	**Response Count**
NO KV AND 0 UMs		17.6%	3
NO KV AND 1 UM		5.9%	1
NO KV AND ≥ 2 UMs		17.6%	3
Some KV AND 0 UMs		11.8%	2
Some KV AND 1 UM		23.5%	4
Some KV AND ≥ 2 UMs		17.6%	3
Moderate KV AND 0 UMs		5.9%	1
Moderate KV AND 1 UM		0%	0
Moderate KV AND ≥ 2 UMs		0%	0
EXTREME KV AND ± UMs		0%	0
		answered question	17
		skipped question	3

You Answered: ____________________

Do you want to: ☐ Keep my original response

☐ Change my response to:

- ☐ NO KV AND 0 UMs
- ☐ NO KV AND 1 UM
- ☐ NO KV AND ≥ 2 UMs
- ☐ Some KV AND 0 UMs
- ☐ Some KV AND 1 UM
- ☐ Some KV AND ≥ 2 UMs
- ☐ Moderate KV AND 0 UMs
- ☐ Moderate KV AND 1 UM
- ☐ Moderate KV AND ≥ 2 UMs
- ☐ EXTREME KV AND ± UMs

Explanation / Feedback:

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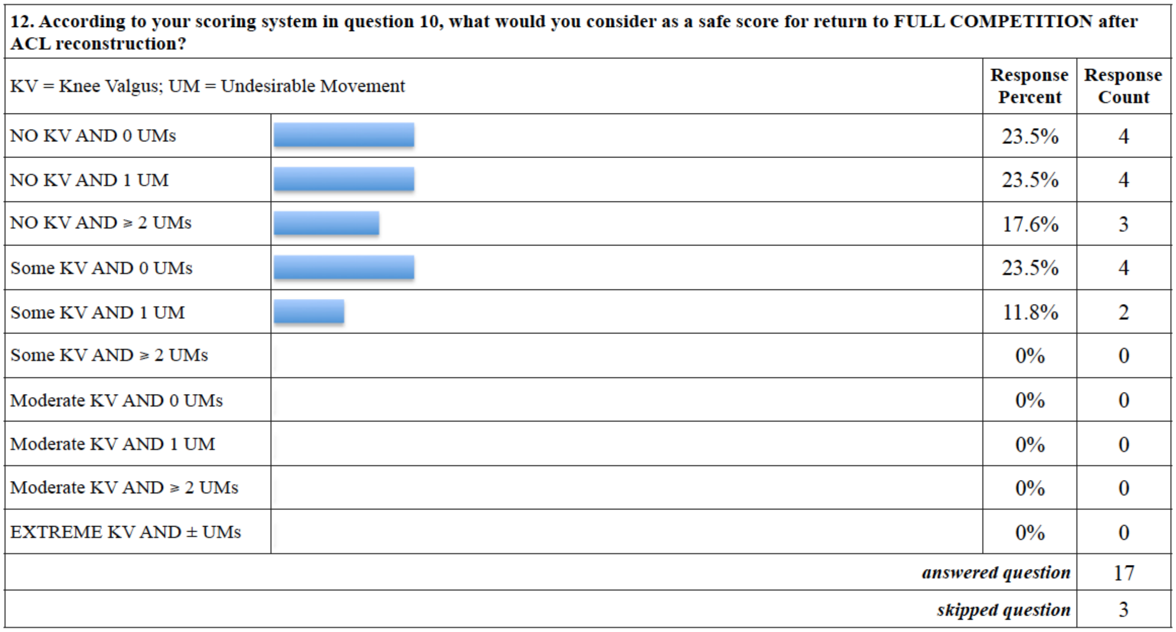

12. According to your scoring system in question 10, what would you consider as a safe score for return to FULL COMPETITION after ACL reconstruction?

KV = Knee Valgus; UM = Undesirable Movement	**Response Percent**	**Response Count**
NO KV AND 0 UMs	23.5%	4
NO KV AND 1 UM	23.5%	4
NO KV AND ≥ 2 UMs	17.6%	3
Some KV AND 0 UMs	23.5%	4
Some KV AND 1 UM	11.8%	2
Some KV AND ≥ 2 UMs	0%	0
Moderate KV AND 0 UMs	0%	0
Moderate KV AND 1 UM	0%	0
Moderate KV AND ≥ 2 UMs	0%	0
EXTREME KV AND ± UMs	0%	0
	answered question	17
	skipped question	3

You Answered: ______________________

Do you want to: ☐ Keep my original response

☐ Change my response to:

- ☐ NO KV AND 0 UMs
- ☐ NO KV AND 1 UM
- ☐ NO KV AND ≥ 2 UMs
- ☐ Some KV AND 0 UMs
- ☐ Some KV AND 1 UM
- ☐ Some KV AND ≥ 2 UMs
- ☐ Moderate KV AND 0 UMs
- ☐ Moderate KV AND 1 UM
- ☐ Moderate KV AND ≥ 2 UMs
- ☐ EXTREME KV AND ± UMs

Explanation / Feedback: ☐

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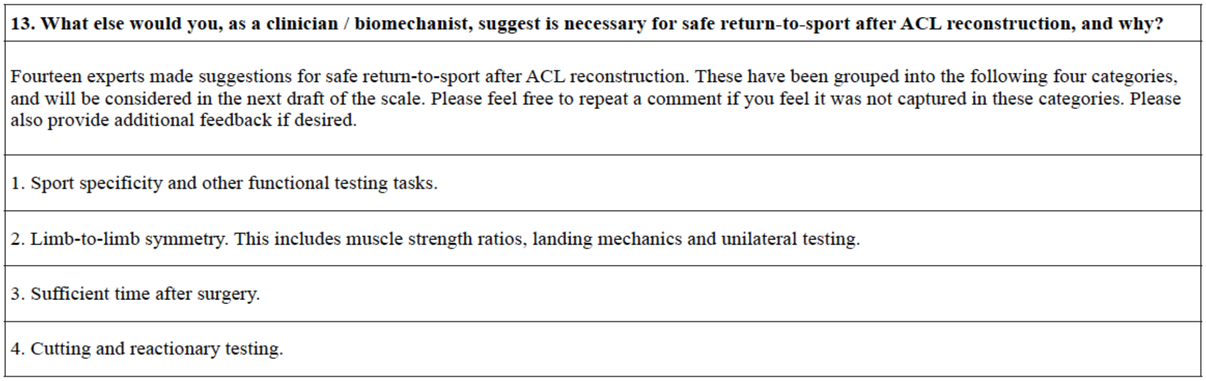
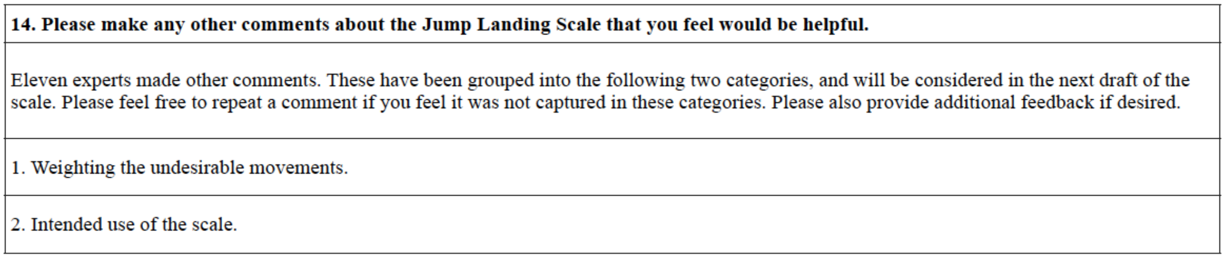


13. What else would you, as a clinician / biomechanist, suggest is necessary for safe return-to-sport after ACL reconstruction, and why?
Fourteen experts made suggestions for safe return-to-sport after ACL reconstruction. These have been grouped into the following four categories, and will be considered in the next draft of the scale. Please feel free to repeat a comment if you feel it was not captured in these categories. Please also provide additional feedback if desired.
1. Sport specificity and other functional testing tasks.
2. Limb-to-limb symmetry. This includes muscle strength ratios, landing mechanics and unilateral testing.
3. Sufficient time after surgery.
4. Cutting and reactionary testing.

Explanation / Feedback:



14. Please make any other comments about the Jump Landing Scale that you feel would be helpful.
Eleven experts made other comments. These have been grouped into the following two categories, and will be considered in the next draft of the scale. Please feel free to repeat a comment if you feel it was not captured in these categories. Please also provide additional feedback if desired.
1. Weighting the undesirable movements.
2. Intended use of the scale.

Explanation / Feedback:

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Delphi ACL Rehabilitation Survey Round 3

PART A) This Delphi Survey is being conducted to help develop a Clinician Rated Drop Vertical Jump Scale.

In Round 1 of this survey, 20 experts provided their input on the proposed scale. Based on this input, we have made the following major revisions:

- brief rationale and instructions for use were added
- “knee valgus” was replaced with “knee valgus collapse movement pattern” with an operational definition included
- the list of undesirable movements was limited to only those with most agreement (described below)
- a scoring system for each limb was added

Undesirable Movements: In Rounds 1 and 2, the following percent of experts agreed that the following undesirable movements was “as important or more important” than exhibited on the scale. Based on the threshold of 66.7% (ie. two thirds of the experts), we retained the top four undesirable movements and removed the bottom three listed below.

- Knee Valgus	94.4%
- Insufficient Knee Flexion	89.5%
- Excessive Lateral Trunk Lean	78.9%
- Tibial Internal Rotation	68.4%
- Excessive Trunk Flexion	47.4%
- Foot Over Pronation	47.4%
- Pelvic Rotation (Anterior or Posterior)	31.6%

Please consult the revised scale (below) to answer questions 1 – 8.

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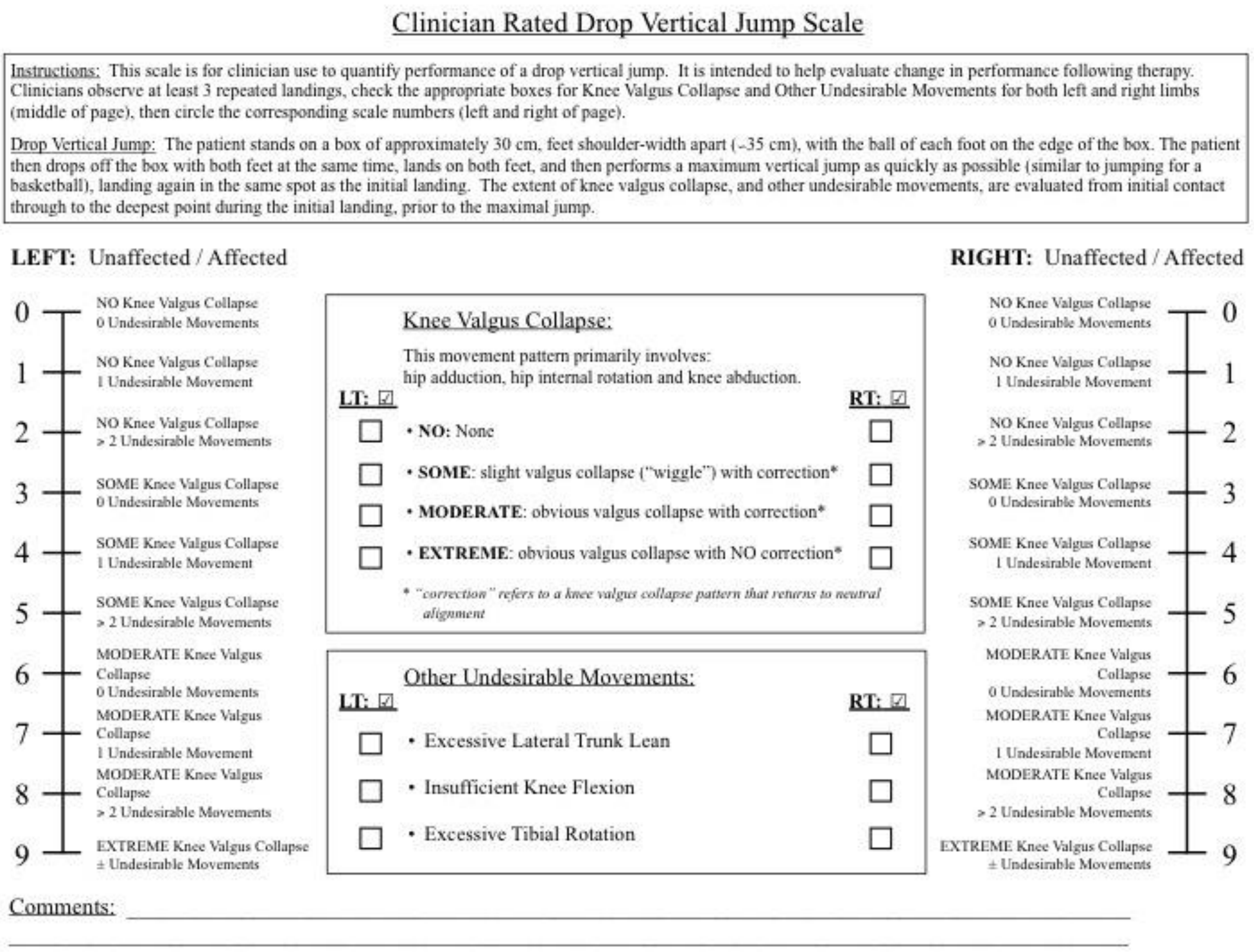

Clinician Rated Drop Vertical Jump Scale

Instructions: This scale is for clinician use to quantify performance of a drop vertical jump. It is intended to help evaluate change in performance following therapy. Clinicians observe at least 3 repeated landings, check the appropriate boxes for Knee Valgus Collapse and Other Undesirable Movements for both left and right limbs (middle of page), then circle the corresponding scale numbers (left and right of page).

Drop Vertical Jump: The patient stands on a box of approximately 30 cm, feet shoulder-width apart (~35 cm), with the ball of each foot on the edge of the box. The patient then drops off the box with both feet at the same time, lands on both feet, and then performs a maximum vertical jump as quickly as possible (similar to jumping for a basketball), landing again in the same spot as the initial landing. The extent of knee valgus collapse, and other undesirable movements, are evaluated from initial contact through to the deepest point during the initial landing, prior to the maximal jump.

LEFT: Unaffected / Affected

RIGHT: Unaffected / Affected

0	NO Knee Valgus Collapse 0 Undesirable Movements	NO Knee Valgus Collapse 0 Undesirable Movements	0
1	NO Knee Valgus Collapse 1 Undesirable Movement	NO Knee Valgus Collapse 1 Undesirable Movement	1
2	NO Knee Valgus Collapse ≥ 2 Undesirable Movements	NO Knee Valgus Collapse ≥ 2 Undesirable Movements	2
3	SOME Knee Valgus Collapse 0 Undesirable Movements	SOME Knee Valgus Collapse 0 Undesirable Movements	3
4	SOME Knee Valgus Collapse 1 Undesirable Movement	SOME Knee Valgus Collapse 1 Undesirable Movement	4
5	SOME Knee Valgus Collapse ≥ 2 Undesirable Movements	SOME Knee Valgus Collapse ≥ 2 Undesirable Movements	5
6	MODERATE Knee Valgus Collapse 0 Undesirable Movements	MODERATE Knee Valgus Collapse 0 Undesirable Movements	6
7	MODERATE Knee Valgus Collapse 1 Undesirable Movement	MODERATE Knee Valgus Collapse 1 Undesirable Movement	7
8	MODERATE Knee Valgus Collapse ≥ 2 Undesirable Movements	MODERATE Knee Valgus Collapse ≥ 2 Undesirable Movements	8
9	EXTREME Knee Valgus Collapse ± Undesirable Movements	EXTREME Knee Valgus Collapse ± Undesirable Movements	9

Knee Valgus Collapse:

This movement pattern primarily involves:
hip adduction, hip internal rotation and knee abduction.

LT: ☑		RT: ☑
☐	• **NO:** None	☐
☐	• **SOME**: slight valgus collapse ("wiggle") with correction*	☐
☐	• **MODERATE**: obvious valgus collapse with correction*	☐
☐	• **EXTREME**: obvious valgus collapse with NO correction*	☐

** "correction" refers to a knee valgus collapse pattern that returns to neutral alignment*

Other Undesirable Movements:

LT: ☑		RT: ☑
☐	• Excessive Lateral Trunk Lean	☐
☐	• Insufficient Knee Flexion	☐
☐	• Excessive Tibial Rotation	☐

Comments: ______________________________

____

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1. **As presented, does the scale allow for an appropriate rating of knee valgus collapse?**

☐ Agree
☐ Somewhat Agree
☐ Neutral
☐ Somewhat Disagree
☐ Disagree

Explanation: ☐

2. **As presented, does the scale allow for an appropriate rating of undesirable movements?**

☐ Agree
☐ Somewhat Agree
☐ Neutral
☐ Somewhat Disagree
☐ Disagree

Explanation: ☐

3. **As presented, does the scale allow for both limbs to be adequately evaluated?**

☐ Agree
☐ Somewhat Agree
☐ Neutral
☐ Somewhat Disagree
☐ Disagree

Explanation: ☐

4. **Using this scale, does an additional (quantitative) measure of asymmetry need to be developed?**

☐ Agree
☐ Somewhat Agree
☐ Neutral
☐ Somewhat Disagree
☐ Disagree

Explanation: ☐

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5. As presented, is the scale adequately concise for use as a clinical tool?

☐ Agree
☐ Somewhat Agree
☐ Neutral
☐ Somewhat Disagree
☐ Disagree

Explanation: ☐

6. As presented, is the scale complete/representative of drop vertical jump performance?

☐ Agree
☐ Somewhat Agree
☐ Neutral
☐ Somewhat Disagree
☐ Disagree

Explanation: ☐

7. Is there anything you suggest should be considered in the development of the scale?

☐ Agree
☐ Somewhat Agree
☐ Neutral
☐ Somewhat Disagree
☐ Disagree

Explanation: ☐

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PART B) A potential future use of the Clinician Rated Drop Vertical Jump Scale is to evaluate progress during rehabilitation after ACL reconstruction. Therefore, it might provide information that could be used in conjunction with several other tests to help determine readiness for return to sport. In Rounds 1 and 2, we asked you to consider when it is considered safe to return to practice or to return to full competition after ACL reconstruction based on the performance on the drop vertical jump. Below you will find those results (Table 1).

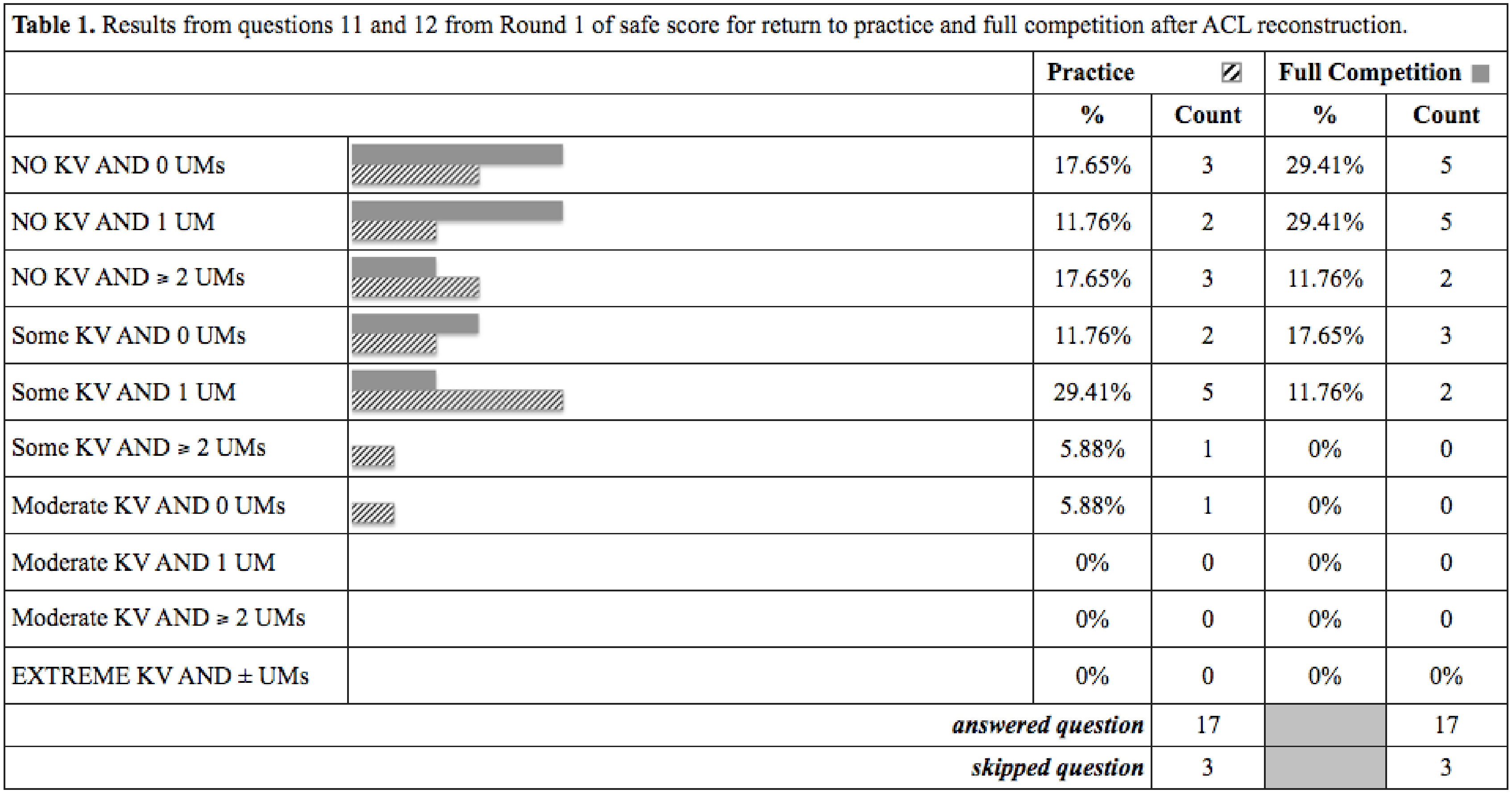

Table 1. Results from questions 11 and 12 from Round 1 of safe score for return to practice and full competition after ACL reconstruction.

		Practice ▨		**Full Competition** ■	
		%	**Count**	**%**	**Count**
NO KV AND 0 UMs		17.65%	3	29.41%	5
NO KV AND 1 UM		11.76%	2	29.41%	5
NO KV AND ≥ 2 UMs		17.65%	3	11.76%	2
Some KV AND 0 UMs		11.76%	2	17.65%	3
Some KV AND 1 UM		29.41%	5	11.76%	2
Some KV AND ≥ 2 UMs		5.88%	1	0%	0
Moderate KV AND 0 UMs		5.88%	1	0%	0
Moderate KV AND 1 UM		0%	0	0%	0
Moderate KV AND ≥ 2 UMs		0%	0	0%	0
EXTREME KV AND ± UMs		0%	0	0%	0%
answered question			17		17
skipped question			3		3

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8. Based on the revised scale, what would you consider as a safe score for return to PRACTICE and FULL COMPETITION after ACL reconstruction? (Check one for practice and one for full competition).

	PRACTICE	FULL COMPETITION
NO Knee Valgus Collapse, 0 Undesirable Movements	☐	☐
NO Knee Valgus Collapse, 1 Undesirable Movement	☐	☐
NO Knee Valgus Collapse, ≥ 2 Undesirable Movements	☐	☐
SOME Knee Valgus Collapse, 0 Undesirable Movements	☐	☐
SOME Knee Valgus Collapse, 1 Undesirable Movement	☐	☐
SOME Knee Valgus Collapse, ≥ 2 Undesirable Movements	☐	☐
MODERATE Knee Valgus Collapse, 0 Undesirable Movements	☐	☐
MODERATE Knee Valgus Collapse, 1 Undesirable Movement	☐	☐
MODERATE Knee Valgus Collapse, ≥ 2 Undesirable Movements	☐	☐
EXTREME Knee Valgus Collapse, ± Undesirable Movements	☐	☐

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Delphi ACL Rehabilitation Survey Round 4

Summary from Round 3 of the Delphi:

Following two rounds, we had agreement (≥ 75%) on all components of the scale, with the exception of how to handle the undesirable movements, which had 68.75% agreement. There was also considerable variation on whether or not to add an additional quantitative measure of asymmetry; 43.75% agreed asymmetry should be included, 18.75% were neutral, and 37.5% did not believe an additional measure was required. Based on the specific feedback received from round three, we have adjusted the scale to incorporate asymmetry as one of the undesirable movements used in scoring, and to include an instruction booklet describing the drop vertical jump, positions of knee valgus collapse and undesirable movements, as well as how to use the scale. The booklet also includes brief rationale and interpretation of movements observed, and supporting references. We hope that this added information will aid the clinician in using the scale and improve reliability and validity.

Another common suggestion from round three was to include pictures. The booklet includes images of good mechanics as well as various degrees of dynamic knee valgus collapse and undesirable movements.

Based on the Delphi, we hope to have a Beta version of the scale established. Since validation of any scale is an ongoing process, we plan to continue to refine the scale based on further input and testing, including feedback after clinician use and the evaluation of measurement properties.

Below you will find the revised version of the Clinician Rated Drop Vertical Jump Scale, and a few questions. Please take a minute to review this version of the Scale and answer the following questions. Of course, any additional comments or feedback is always appreciated.

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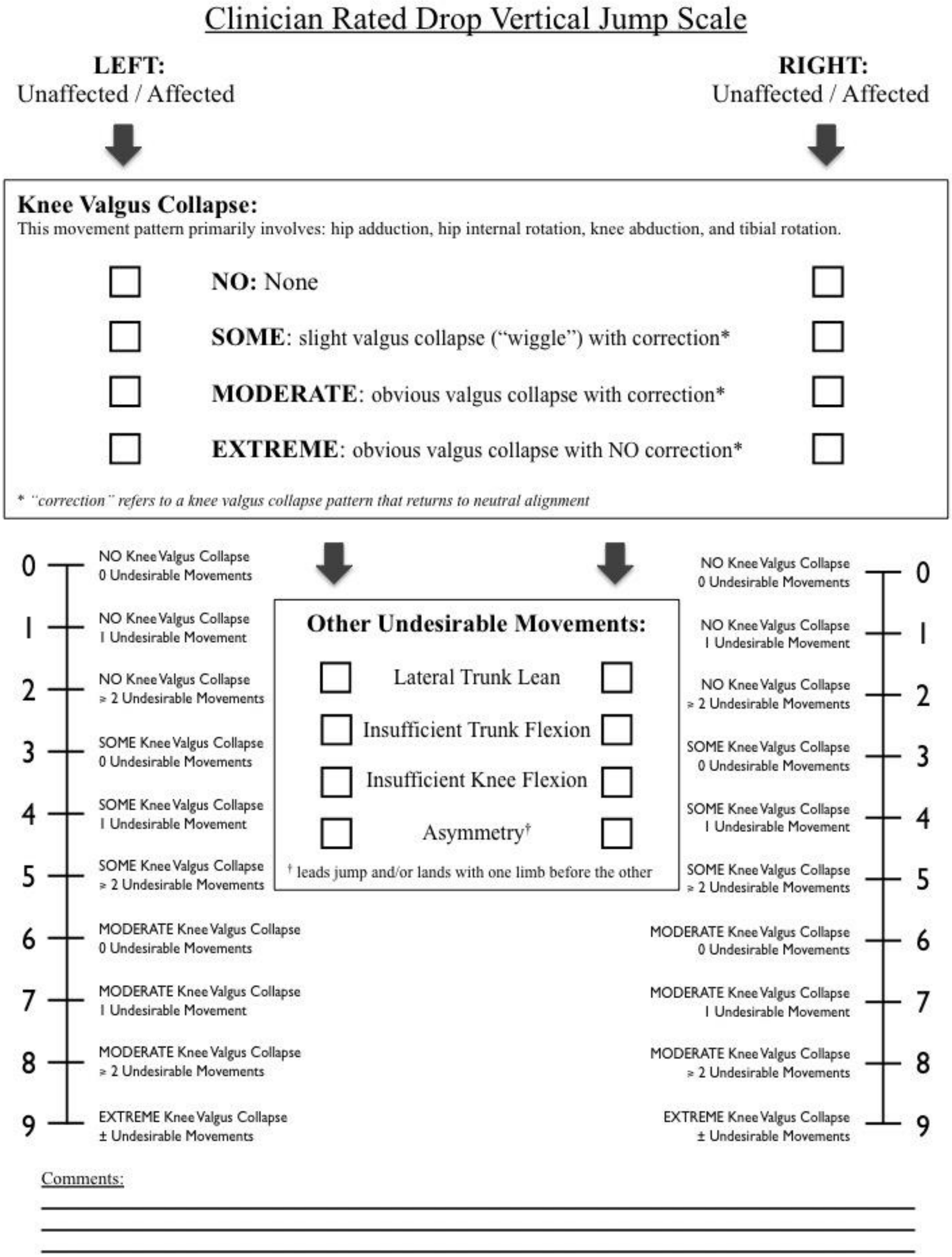

Clinician Rated Drop Vertical Jump Scale

LEFT:
Unaffected / Affected

RIGHT:
Unaffected / Affected

Knee Valgus Collapse:

This movement pattern primarily involves: hip adduction, hip internal rotation, knee abduction, and tibial rotation.

☐	**NO:** None	☐
☐	**SOME**: slight valgus collapse (“wiggle”) with correction*	☐
☐	**MODERATE**: obvious valgus collapse with correction*	☐
☐	**EXTREME**: obvious valgus collapse with NO correction*	☐

** “correction” refers to a knee valgus collapse pattern that returns to neutral alignment*

Other Undesirable Movements:

☐	Lateral Trunk Lean	☐
☐	Insufficient Trunk Flexion	☐
☐	Insufficient Knee Flexion	☐
☐	Asymmetry[†]	☐

[†] leads jump and/or lands with one limb before the other

0	NO Knee Valgus Collapse 0 Undesirable Movements	NO Knee Valgus Collapse 0 Undesirable Movements	0
1	NO Knee Valgus Collapse 1 Undesirable Movement	NO Knee Valgus Collapse 1 Undesirable Movement	1
2	NO Knee Valgus Collapse ≥ 2 Undesirable Movements	NO Knee Valgus Collapse ≥ 2 Undesirable Movements	2
3	SOME Knee Valgus Collapse 0 Undesirable Movements	SOME Knee Valgus Collapse 0 Undesirable Movements	3
4	SOME Knee Valgus Collapse 1 Undesirable Movement	SOME Knee Valgus Collapse 1 Undesirable Movement	4
5	SOME Knee Valgus Collapse ≥ 2 Undesirable Movements	SOME Knee Valgus Collapse ≥ 2 Undesirable Movements	5
6	MODERATE Knee Valgus Collapse 0 Undesirable Movements	MODERATE Knee Valgus Collapse 0 Undesirable Movements	6
7	MODERATE Knee Valgus Collapse 1 Undesirable Movement	MODERATE Knee Valgus Collapse 1 Undesirable Movement	7
8	MODERATE Knee Valgus Collapse ≥ 2 Undesirable Movements	MODERATE Knee Valgus Collapse ≥ 2 Undesirable Movements	8
9	EXTREME Knee Valgus Collapse ± Undesirable Movements	EXTREME Knee Valgus Collapse ± Undesirable Movements	9

Comments:

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Instructions:* This scale is for clinician use to quantify performance of a drop vertical jump. It is intended to help evaluate change in performance following therapy.

Clinicians observe at least 3 repeated landings, check the appropriate boxes for *Knee Valgus Collapse and Other Undesirable Movements* for both left and right limbs, then circle the corresponding scale numbers (left and right of page).

[†]Asymmetry: Observed as leading with one limb to initiate movement, or making initial contact with one limb prior to the other.

Drop Vertical Jump: The patient stands on a box of approximately 30 cm, feet shoulder-width apart (~35 cm), with the ball of each foot on the edge of the box. The patient then drops off the box with both feet at the same time, lands on both feet, and then performs a maximum vertical jump as quickly as possible (similar to jumping for a basketball), landing again in the same spot as the initial landing[1].

The extent of knee valgus collapse, and other undesirable movements, are evaluated from initial contact through to the deepest point during the initial landing, prior to the maximal jump.

Example of sequence of DVJ. A) Start position; B) Drop; C) Deepest point during initial landing; D) Maximal jump; E) Second landing and completion of jump.

---

* For more detailed instructions and example pictures, please consult the Clinician Rated Drop Vertical Jump Scale Instruction Booklet.

1. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *MSSE* 2003;35(10):1745-1750.

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Round 4 Delphi Questions:

1. **As presented, does the scale adequately evaluate asymmetry and other undesirable movements?**

☐ Agree
☐ Somewhat Agree
☐ Neutral
☐ Somewhat Disagree
☐ Disagree

Comments: ☐

2. **As presented, can the scale be implemented as a clinical tool?**

☐ Agree
☐ Somewhat Agree
☐ Neutral
☐ Somewhat Disagree
☐ Disagree

Comments: ☐

3. **Do you have any final comments about the scale?**

☐

4. **Does adding the instruction booklet provide appropriate instruction and answer the question about pictures?**

☐ Agree
☐ Somewhat Agree
☐ Neutral
☐ Somewhat Disagree
☐ Disagree

Comments: ☐

5. **Please add any comments you may have about the instruction booklet.**

☐

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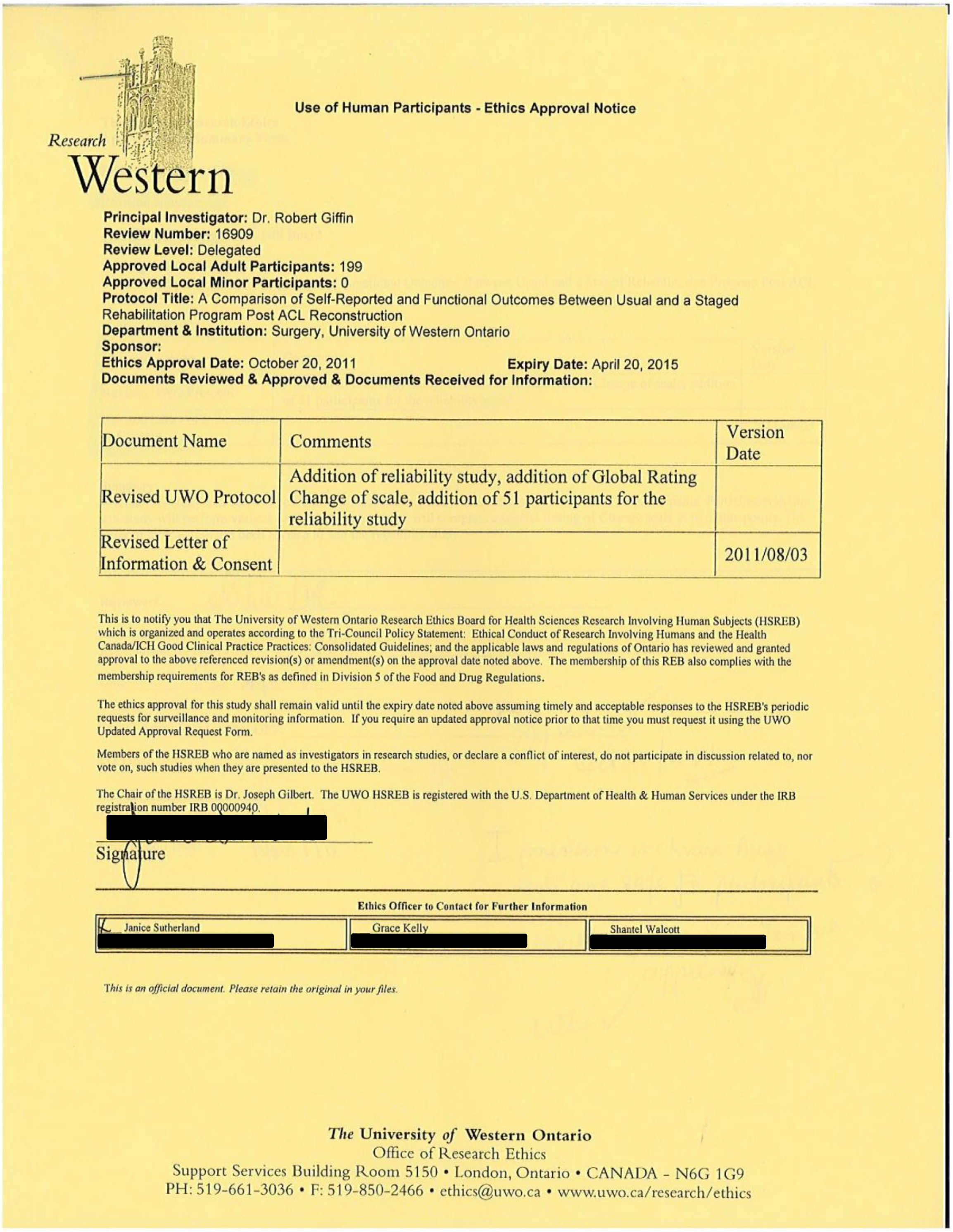
Appendix E: Ethics Approval for Studies 2 and 3.



Use of Human Participants - Ethics Approval Notice

Research
Western

Principal Investigator: Dr. Robert Giffin
Review Number: 16909
Review Level: Delegated
Approved Local Adult Participants: 199
Approved Local Minor Participants: 0
Protocol Title: A Comparison of Self-Reported and Functional Outcomes Between Usual and a Staged Rehabilitation Program Post ACL Reconstruction
Department & Institution: Surgery, University of Western Ontario
Sponsor:
Ethics Approval Date: October 20, 2011 **Expiry Date:** April 20, 2015
Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Revised UWO Protocol	Addition of reliability study, addition of Global Rating Change of scale, addition of 51 participants for the reliability study	
Revised Letter of Information & Consent		2011/08/03

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the UWO Updated Approval Request Form.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

The Chair of the HSREB is Dr. Joseph Gilbert. The UWO HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

[redacted]

Signature

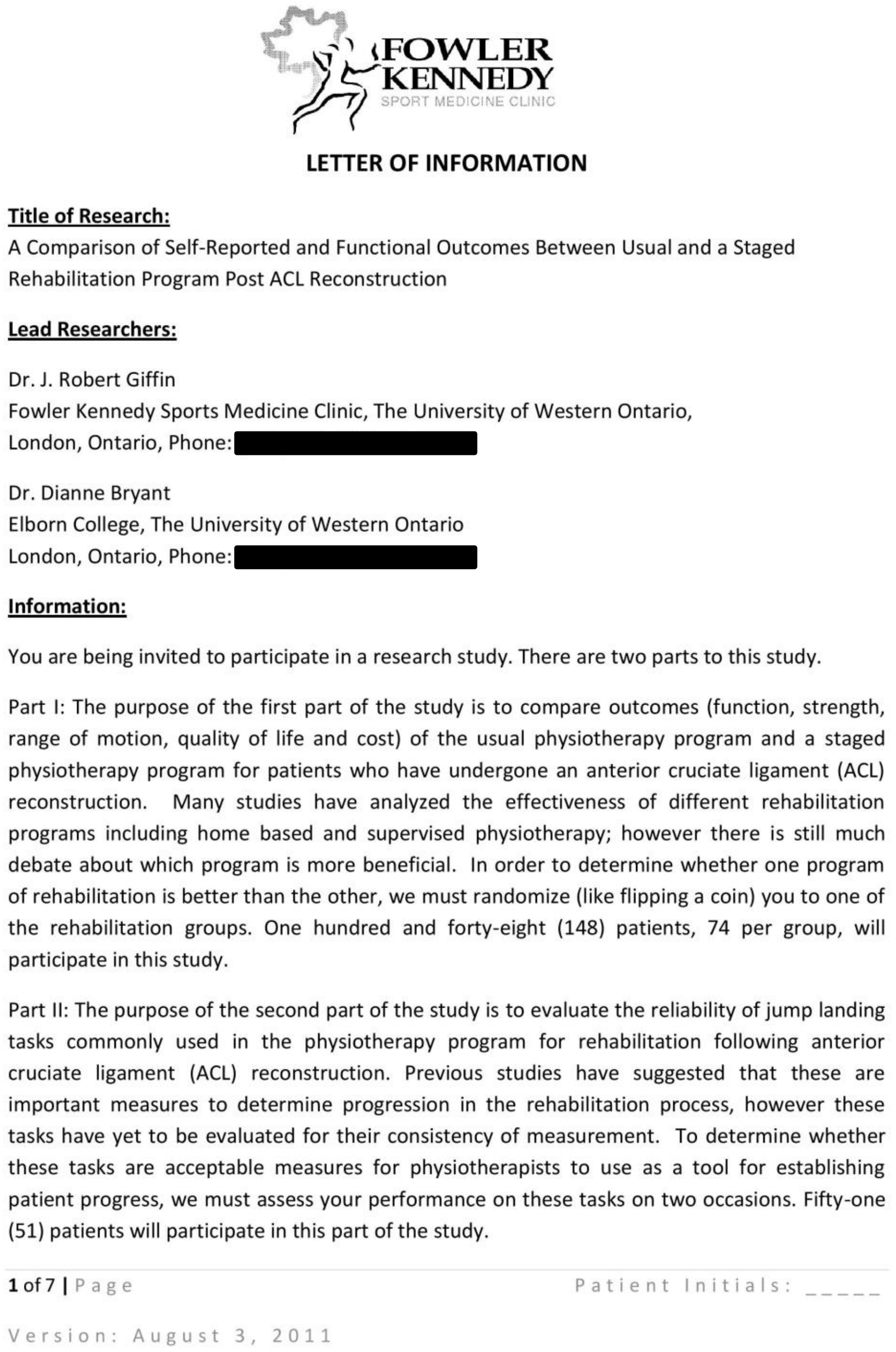
Ethics Officer to Contact for Further Information

Janice Sutherland [redacted]	Grace Kelly [redacted]	Shantel Walcott [redacted]

This is an official document. Please retain the original in your files.

The **University** ***of*** **Western Ontario**
Office of Research Ethics
Support Services Building Room 5150 • London, Ontario • CANADA - N6G 1G9
PH: 519-661-3036 • F: 519-850-2466 • ethics@uwo.ca • www.uwo.ca/research/ethics

Appendix F: Letter of Information and Informed Consent for Studies 2 and 3.



FOWLER KENNEDY
SPORT MEDICINE CLINIC

LETTER OF INFORMATION

Title of Research:

A Comparison of Self-Reported and Functional Outcomes Between Usual and a Staged Rehabilitation Program Post ACL Reconstruction

Lead Researchers:

Dr. J. Robert Giffin
Fowler Kennedy Sports Medicine Clinic, The University of Western Ontario,
London, Ontario, Phone: [redacted]

Dr. Dianne Bryant
Elborn College, The University of Western Ontario
London, Ontario, Phone: [redacted]

Information:

You are being invited to participate in a research study. There are two parts to this study.

Part I: The purpose of the first part of the study is to compare outcomes (function, strength, range of motion, quality of life and cost) of the usual physiotherapy program and a staged physiotherapy program for patients who have undergone an anterior cruciate ligament (ACL) reconstruction. Many studies have analyzed the effectiveness of different rehabilitation programs including home based and supervised physiotherapy; however there is still much debate about which program is more beneficial. In order to determine whether one program of rehabilitation is better than the other, we must randomize (like flipping a coin) you to one of the rehabilitation groups. One hundred and forty-eight (148) patients, 74 per group, will participate in this study.

Part II: The purpose of the second part of the study is to evaluate the reliability of jump landing tasks commonly used in the physiotherapy program for rehabilitation following anterior cruciate ligament (ACL) reconstruction. Previous studies have suggested that these are important measures to determine progression in the rehabilitation process, however these tasks have yet to be evaluated for their consistency of measurement. To determine whether these tasks are acceptable measures for physiotherapists to use as a tool for establishing patient progress, we must assess your performance on these tasks on two occasions. Fifty-one (51) patients will participate in this part of the study.

1 of 7 | Page Patient Initials: _____

Version: August 3, 2011

Procedures:

All patients between the ages of 15 and 40 who are scheduled to have a surgery for an anterior cruciate ligament (ACL) reconstruction using a hamstring graft will be invited to take part in this study.

Part I: If you are randomized to receive usual care, you will receive a copy of the ACL Protocol to take to your physiotherapist. You and your physiotherapist will determine a visit schedule for your rehabilitation over the next 6 months. If you are randomized to receive the staged regimen, you will receive a copy of a home-based program and meet with a physiotherapist at Fowler Kennedy Sports medicine clinic at 2 weeks, 6 weeks post-surgery to review this program. After 12 weeks, you will receive a copy of the ACL Protocol and asked to meet with a physiotherapist of your choice (either at Fowler Kennedy or a community clinic near you) to continue your rehabilitation for the remaining 6 months.

Visits for this study will coincide with visits to your surgeon. Before your surgery, you will be asked to complete six questionnaires, along with an activity rating scale, return to sport questionnaire, strength assessment and range of motion measurement. After surgery, you will come in for an appointment with your surgeon at 2 weeks, 6 weeks, 12 weeks, 6 months, 1 year, 18 months and 2 years where you will be asked to complete the same six questionnaires. At that time, we will also measure your range of motion. Completing these questionnaires will take approximately 15-20 minutes of your time and collection of range of motion measurements will take approximately 5 minutes.

Before your surgery and at 12 weeks after surgery, we will ask you to perform some simple walking and balancing tasks in the Wolf Orthopaedic Biomechanics Laboratory at the Fowler Kennedy Sports Medicine Clinic. The tasks will involve you walking across the laboratory floor over a force plate while sensors are attached to your body monitor your movements and activity of your muscles. You will also be asked to balance, squat on one leg without letting your hands or opposite toe touch the ground, and perform a single leg jump/drop landing from a 15 cm height. The rubber sensors that will be used will be placed on your skin over your feet, knees, hips, arms and shoulders and are attached using double-sided tape. You will be asked to wear shorts (or tights) and a T-shirt or tank top in order to assist with the placement of these sensors. Although these sensors are removed easily, they may cause some pulling of hair. In order to limit discomfort, we may shave some areas with a plastic disposable razor.

At 6 months, 1 year, and 2 years after surgery, we will measure your strength and how far you can hop forward. Strength tests will be performed by bending and extending your knee 3 times to measure your strength against resistance. This is done using a computerized machine called an isokinetic dynamometer. During each test session, you will be seated with your back against a backrest with a seat belt securing you into place. The single hop for distance test is performed by having you stand on your leg to be tested, and hop forward on the same leg. The timed 6-m hop test is performed by having you perform large one-legged hops in series over the 6 metres. The triple hops for distance test is performed by having you stand on one leg and perform three hops in a row on the same leg, landing as far away as possible. The crossover hop for distance is performed by having you hop forward three times while making a "Z' pattern. During this time, we will also have you perform a drop vertical jump, bilateral jump/drop landing and a single leg jump/drop landing in the Wolf Orthopaedic Biomechanics Laboratory, along with the same squatting on one leg task you performed during the walking and balancing task. This will involve using the same equipment as the walking and balancing tasks. During the drop vertical jump, we will ask you to drop/hop off a box and land on both legs. You will then perform a vertical jump, as if rebounding a basketball, as high as you can, and land on both legs. For the bilateral jump/drop landing, we will ask you to perform the same technique where you will drop/hop off a box and land on both legs. Finally, for the single leg jump/drop landing, we will ask you to stand on a box on a single leg, jump off the box and land on the same leg. For this task, a clinician will also watch you perform the single leg squat and jumping tasks and will rate how you perform them. You will also be asked to complete a Global Rating of Change scale 6 months and 1 year post-surgery.

You will also be asked to complete an activity rating scale and return to sport questionnaire at 1 year, 18 months and 2 years after surgery. All tests will be performed at the Fowler Kennedy Sports Medicine Clinic and Wolf Orthopaedic Biomechanics Laboratory (total completion time of 1 hour and 45 minutes).

Part II: If you agree to participate in Part II of the study (reliability), you will be asked to come in for an additional visit between 4 and 7 months post surgery for two sessions within 7 days time, but more than 24 hours apart, where you will be asked to complete the single leg squat and jump landing tasks. You will also be asked to complete a Global Rating of Change Scale during the second session. These visits will take approximately 1 hour of your time per session. For subjects participating in Part I, this will only require one extra testing session at 6 months post surgery.

Alternatives to Participation:

If you do not choose to participate in this study, you will receive the usual physiotherapy protocol for patients who have undergone ACL reconstruction.

Risks:

The patient could fall, injure or re-injure themselves when performing tests, however, the risks are no greater than those encountered with typical postoperative rehab protocols. There are no known health risks associated with this study. The data that is collected from you is protected by a username and password. It travels in a scrambled format to a server (storage computer) that is located in Toronto. The company that houses the server is a professional company with extremely high standards of physical and virtual security. We want to let you know however, that even with this high level of security, there is always a remote chance that your information could be accessed or "hacked" by someone who is not supposed to have your information. If we became aware that this had happened, we would inform you immediately.

Benefits:

There are no direct benefits to you for participating in this study; however your participation may help inform surgeons and physiotherapists as to which rehabilitation program offers patients who undergo ACL reconstruction, the best outcome. The reliability study will help inform physiotherapists as to whether these tasks are appropriate to use to determine whether a patients is progressing through the rehabilitation stages following ACL reconstruction, which will provide clinicians with additional tools to evaluate safe return-to-activity/sport and minimize the risk for re-injury.

Cost/Compensation:

You will not be compensated for your participation in this study. The assessments for this study will coincide with your routine follow-ups with your surgeon. This study has no requirements as to the number of physiotherapy sessions you attend. Therefore, you should plan to pay for your physiotherapy costs as you would have done without study participation.

Voluntary Participation:

Your participation in this study is voluntary. You may refuse to participate, refuse to answer any questions or withdraw from the study at any time with no effect on your future care. Should you choose to withdraw from this study, we will keep all data obtained up to the point that you chose to withdraw.

Participation in this study does not prevent you from participating in any other research studies at the present time or future. If you are participating in another research study, we ask that you please inform of us of your participation. You do not waive any legal rights by signing the consent form.

Patient Initials: _____

Request for Study Results:

Should you decide to participate and want to receive a copy of the study results, please provide your contact information on a separate piece of paper. Once the study has been published, a copy will be mailed to you. Please note that the results of this study are not expected for at least 5 years. Should your mailing information change, please let us know.

Confidentiality:

All information will be kept in strict confidence. Upon agreeing to participate in this study, you will be assigned a unique number that will be used for all your information and data collection. Data that is collected will be username and password protected and stored on a server located in Toronto through a scrambled format. Your identifying information will not appear on the database used to analyze data. In any publication, presentation or report, your name will not be used and any information that discloses your identity will not be released or published. Representatives of The University of Western Ontario Health Sciences Research Ethics Board may require access to your study related records or may follow up with you to monitor the conduct of the study.

Questions:

If you have questions about the conduct of the study or your rights as a research participant, you may contact Dr. David Hill, Scientific Director, Lawson Health Research Institute [redacted]

If you have questions or concerns about your surgery or physiotherapy, please contact your orthopaedic surgeon or physiotherapist. If you have any questions about this research, please contact Alliya Remtulla at [redacted], Sheila Kocay at [redacted] Dr. Dianne Bryant at [redacted] or your orthopaedic surgeon.

This letter is yours to keep.

Sincerely,

Dr. J Robert Giffin, MD
Dr. Dianne Bryant, PhD
Alliya Remtulla, M.Sc (can.)
Sheila Kocay, M.Sc, PhD (can.)

FOWLER KENNEDY
SPORT MEDICINE CLINIC

CONSENT FORM

Title of Research:

A Comparison of Self-Reported and Functional Outcomes Between Usual and a Staged Rehabilitation Program Post ACL Reconstruction

I have read the letter of information, have had the nature of the study explained to me, and I agree to participate in the study. All questions have been answered to my satisfaction.

I agree to participate in (check box that applies):

- ☐ Both parts of the study (RCT and Reliability Study)
- ☐ RCT ONLY (Part I)
- ☐ Reliability ONLY (Part II)

Printed Name of the Participant	Signature of the Participant	Date
Printed Name of the Parent or Legally Authorized Representative (if required)	Signature of the Parent or Legally Authorized Representative (if required)	Date
Printed Name of the Person Responsible for Obtaining Informed Consent	Signature of the Person Person Responsible for Obtaining Informed Consent	Date

☐ I would like to receive a copy of the results of this study.

Please mail to:

____

____

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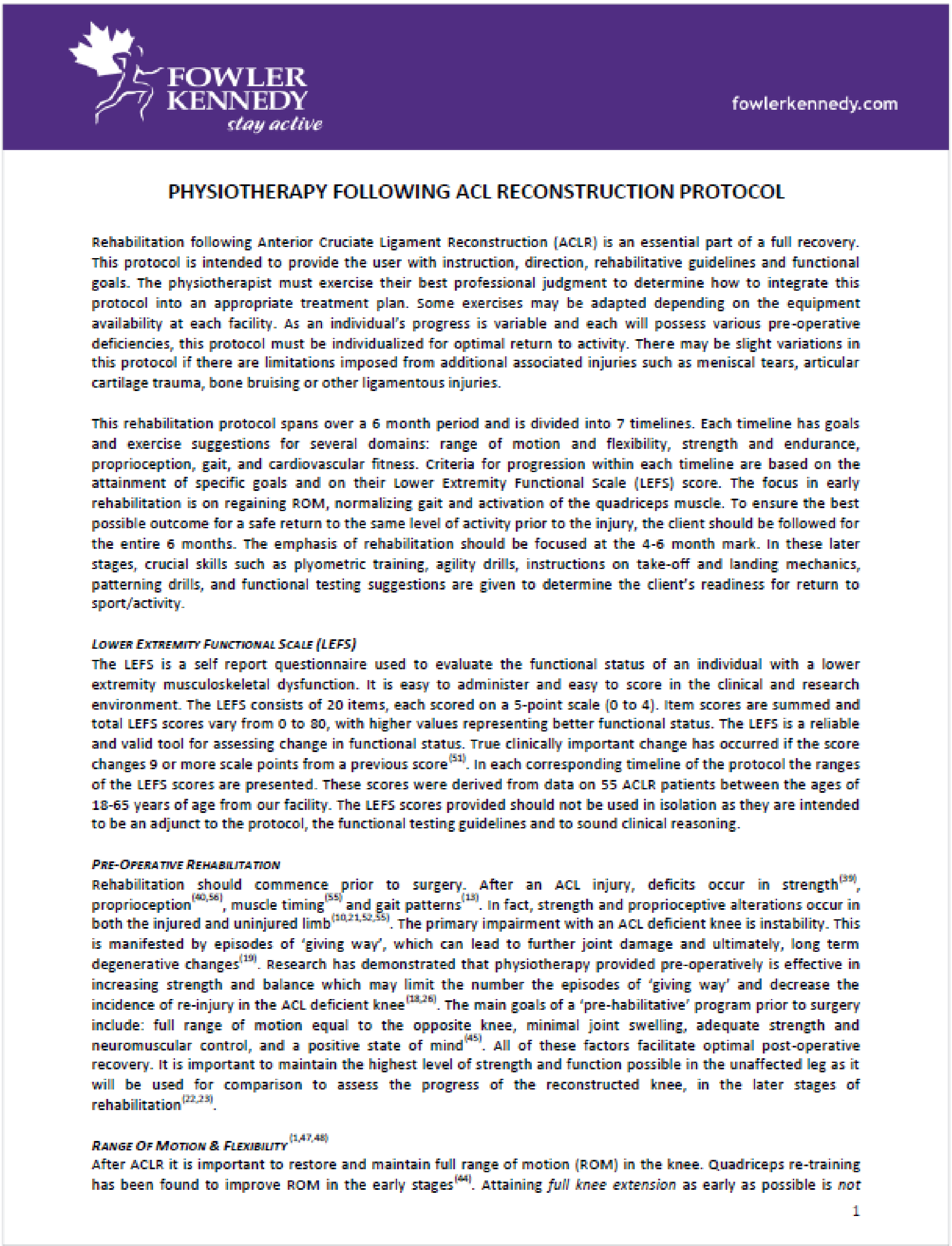
Appendix G: ACL Protocol



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PHYSIOTHERAPY FOLLOWING ACL RECONSTRUCTION PROTOCOL

Rehabilitation following Anterior Cruciate Ligament Reconstruction (ACLR) is an essential part of a full recovery. This protocol is intended to provide the user with instruction, direction, rehabilitative guidelines and functional goals. The physiotherapist must exercise their best professional judgment to determine how to integrate this protocol into an appropriate treatment plan. Some exercises may be adapted depending on the equipment availability at each facility. As an individual's progress is variable and each will possess various pre-operative deficiencies, this protocol must be individualized for optimal return to activity. There may be slight variations in this protocol if there are limitations imposed from additional associated injuries such as meniscal tears, articular cartilage trauma, bone bruising or other ligamentous injuries.

This rehabilitation protocol spans over a 6 month period and is divided into 7 timelines. Each timeline has goals and exercise suggestions for several domains: range of motion and flexibility, strength and endurance, proprioception, gait, and cardiovascular fitness. Criteria for progression within each timeline are based on the attainment of specific goals and on their Lower Extremity Functional Scale (LEFS) score. The focus in early rehabilitation is on regaining ROM, normalizing gait and activation of the quadriceps muscle. To ensure the best possible outcome for a safe return to the same level of activity prior to the injury, the client should be followed for the entire 6 months. The emphasis of rehabilitation should be focused at the 4-6 month mark. In these later stages, crucial skills such as plyometric training, agility drills, instructions on take-off and landing mechanics, patterning drills, and functional testing suggestions are given to determine the client's readiness for return to sport/activity.

Lower Extremity Functional Scale (LEFS)

The LEFS is a self report questionnaire used to evaluate the functional status of an individual with a lower extremity musculoskeletal dysfunction. It is easy to administer and easy to score in the clinical and research environment. The LEFS consists of 20 items, each scored on a 5-point scale (0 to 4). Item scores are summed and total LEFS scores vary from 0 to 80, with higher values representing better functional status. The LEFS is a reliable and valid tool for assessing change in functional status. True clinically important change has occurred if the score changes 9 or more scale points from a previous score(51). In each corresponding timeline of the protocol the ranges of the LEFS scores are presented. These scores were derived from data on 55 ACLR patients between the ages of 18-65 years of age from our facility. The LEFS scores provided should not be used in isolation as they are intended to be an adjunct to the protocol, the functional testing guidelines and to sound clinical reasoning.

Pre-Operative Rehabilitation

Rehabilitation should commence prior to surgery. After an ACL injury, deficits occur in strength(39), proprioception(40,56), muscle timing(55) and gait patterns(13). In fact, strength and proprioceptive alterations occur in both the injured and uninjured limb(10,21,52,55). The primary impairment with an ACL deficient knee is instability. This is manifested by episodes of 'giving way', which can lead to further joint damage and ultimately, long term degenerative changes(19). Research has demonstrated that physiotherapy provided pre-operatively is effective in increasing strength and balance which may limit the number the episodes of 'giving way' and decrease the incidence of re-injury in the ACL deficient knee(18,26). The main goals of a 'pre-habilitative' program prior to surgery include: full range of motion equal to the opposite knee, minimal joint swelling, adequate strength and neuromuscular control, and a positive state of mind(45). All of these factors facilitate optimal post-operative recovery. It is important to maintain the highest level of strength and function possible in the unaffected leg as it will be used for comparison to assess the progress of the reconstructed knee, in the later stages of rehabilitation(22,23).

Range Of Motion & Flexibility(1,47,48)

After ACLR it is important to restore and maintain full range of motion (ROM) in the knee. Quadriceps re-training has been found to improve ROM in the early stages(44). Attaining *full knee extension* as early as possible is *not*

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deleterious to the graft or to joint stability(43) and may prevent patellofemoral pain and compensatory gait pathologies. A stretching program is incorporated to maintain lower extremity flexibility. Research recommends that a 30 second stretch is sufficient to increase ROM in most healthy people. It is likely that longer periods of time, or more repetitions, are required for those individuals with injuries or with larger muscles. Body mass has been shown to be positively correlated with muscle stiffness (i.e., the bigger the muscle, the more stiffness/tension there exists)(34). Therefore, for larger muscle groups in the lower extremity, it is suggested to increase in the number of repetitions (ie. 3-5 times) for optimal flexibility.

GAIT RETRAINING

Altered gait kinematics from quadriceps dysfunction is typical during the first stages post ACL reconstruction. Typical adaptations include reduced cadence, stride length, altered swing and stance phase knee ROM, and decreased knee extensor torque with hip and/or ankle extensor adaptations(11,13,15,30). Early weight bearing is advocated post ACLR in an attempt to restore gait kinematics in a timely fashion, facilitate vastus medialis function and decrease the incidence of anterior knee pain(53).

Treadmill training in the middle stages of rehabilitation can further assist in normalizing lower extremity ROM across all joints, especially with incline or backwards walking. Backwards treadmill walking has been shown in the literature to increase ROM and increase functional quadriceps strength, while minimizing patellofemoral stress. It is also beneficial for specific return-to-sport preparation requiring a re-training of backwards locomotion(49).

MUSCULAR STRENGTH & ENDURANCE TRAINING

Muscle analyses of the quadriceps post ACL injury have shown: i) similar degrees of atrophy in both type I (oxidative/endurance) and II (glycolytic/fast-twitch) muscle fibres, and ii) physiological metabolic shifts in muscle fibres from gylcolytic into oxidative compositions (35,50). This means that ACL rehabilitation must include variable training parameters, which range from an endurance program of low load/high repetitions to a strength oriented phase of high load/low repetitions to focus on these deficits.

Depending on the graft type used for ACLR (patellar tendon vs. semitendonosis/gracilis), specific strength deficits have been found. With the patellar tendon graft, there are low velocity concentric extensor deficits specific to 60-95°; with the hamstring graft, there are high velocity, eccentric flexor deficits specific to 60-95°(23). Strengthening exercises need to be velocity, ROM and contraction specific to address these deficits.

Open (OKC) and Closed (CKC) Kinetic Chain Exercises

OKC exercises have previously been contraindicated in ACLR patients for 6 months up to a year post-operatively, although the concern about the safety of OKC training in the early period after ACLR may not be well founded. It was originally thought that OKC exercises increased anterior tibial translation, with the possibility of increasing strain on the new graft. However, research has demonstrated that there are minimal strain differences between OKC leg extension and CKC activities such as squatting(4,5). With the addition of OKC training, subjects have shown increased quadriceps torque increases without significant increases in laxity(25,37). Researchers are now advocating the addition OKC exercises, ***at the appropriate time and within a restricted range,*** to complement the classic CKC rehabilitative program(25,37,38).

Quality vs. Compensation

Physiotherapists often feel compelled to progress patients by giving them new exercises each time they are in for therapy. It cannot be stressed enough that it is ***not*** beneficial to give patients exercises they are not neuromuscularly ready for. It is very important to observe the *quality* of the exercises that are being performed, specifically with CKC exercises. Weaknesses in specific muscle groups lead to compensations, which produce faulty movement patterns. These faulty patterns are then integrated into unconscious motor programs, which perpetuate the original weakness. Specifically, the research has indicated that knee extensor moment deficits are compensated for by hip and/or ankle extensor moments(11,15). If these are allowed to occur and are not corrected, any joint or structure along the kinetic chain may be exposed to injury.

For example: A squat(16) or lunge must be performed with the trunk perpendicular to the ground (to avoid excessive hip flexion), the iliac crests must be level (to avoid Trendelenburg/hip hiking), and the knee must be over the foot with the tibia perpendicular to the floor (to avoid excessive dorsiflexion). It is better to decrease the range of movement (half squat vs. full squat) than to do the exercise at a level that is too difficult to perform correctly without compensation.

Precautions with Hamstring Grafts

The typical donor graft for ACLR at this facility is the hamstring (semitendinosis / gracilis). *Careful measures must be taken to avoid overstressing the donor area while it heals*. Although, isolated hamstring strengthening is initiated around the six-week mark in this group, it is important for the therapist to be aware of the natural stages of healing. There may be too much stress too early if the patient reports pain at the donor site during or after specific exercises.

Neuromuscular & Proprioceptive Retraining

Ideally proprioception should be initiated immediately after injury (prior to surgery), as it is known that proprioceptive input and neuromuscular control are altered after ACL injury(10,55). By challenging the proprioceptive system though specific exercises, other knee joint mechanoreceptors are activated that produce compensatory muscle activation patterns in the neuromuscular system that may assist with joint stability(9).

Post-operatively, proprioceptive training should commence early in the rehabilitation process in order to begin neuromuscular integration and should continue as proprioceptive deficits have been found beyond 1 year post ACLR(11,15,21,32). Proprioceptive exercises have been shown to enhance strength gains in the quadriceps and hamstring muscles post ACLR(31,57). In the later stages of rehabilitation, anticipated and unanticipated perturbation training is effective in improving dynamic stability of the knee(8,18). A dynamically stable joint is the result of an optimally functioning proprioceptive and neuromuscular system and functional outcome has been proven to be highly correlated with balance in the reconstructed ACL(46).

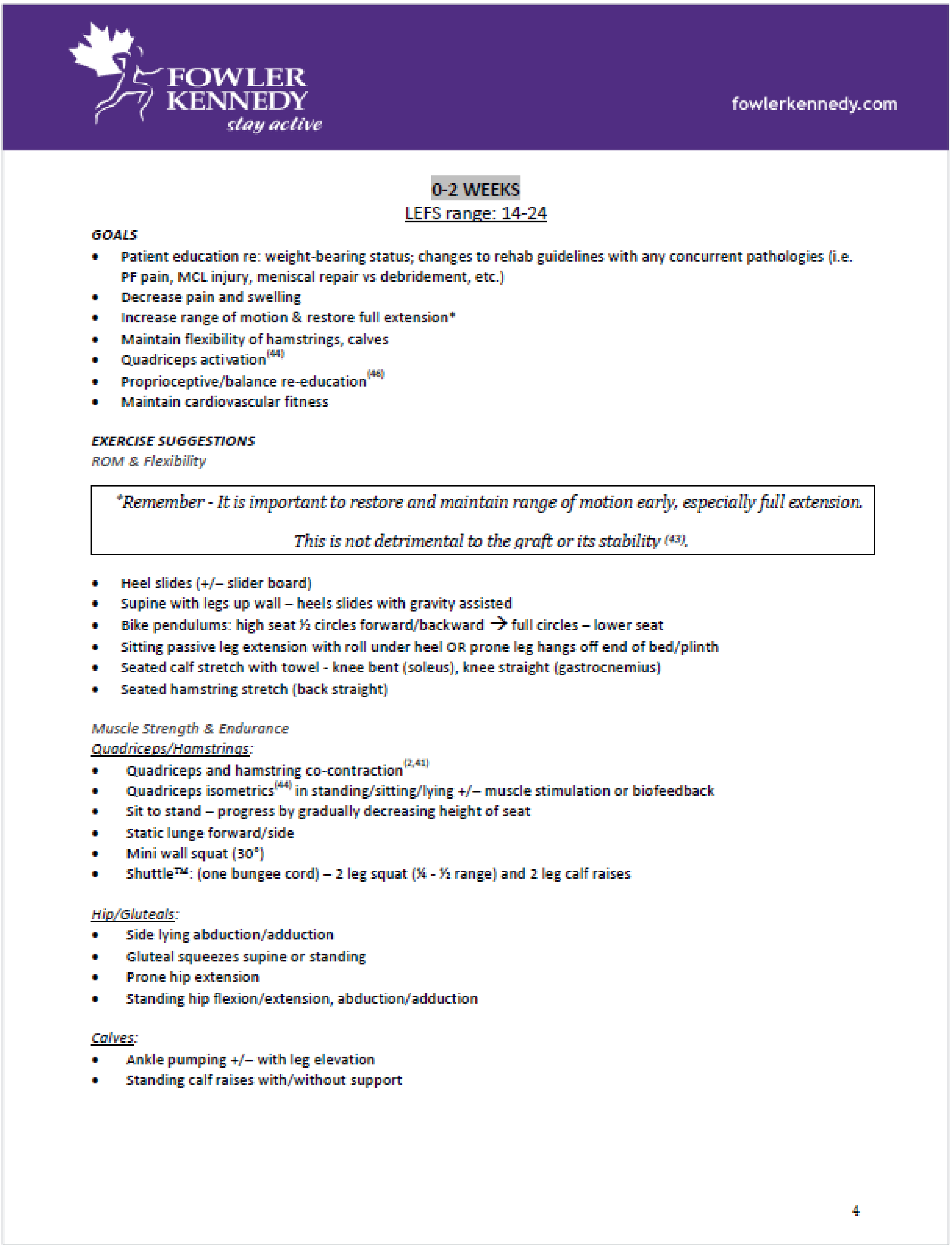
Return to Sport

Gradual return to sport is initiated at the 6-9 month mark *only* if the individual's knee does *not* present with pain or effusion, during or after functional sport specific training drills. LEFS scores should be 76 points or greater at this point in rehabilitation. The individual must also be able to demonstrate the appropriate strength and endurance needed for their specific sport. This recommendation is based on the evidence that knee cartilage and subchondral bone are damaged during the initial ACL trauma and may need additional time to recover in order to minimize the predisposition for future joint arthrosis(17,54,58).

A further consideration when returning the patient to sport is that a cautionary approach should be taken with the use of the uninjured limb as a comparison for a rehabilitation endpoint. It has been demonstrated in the literature that a significant detraining effect occurs in the quadriceps and hamstring muscles in both injured and uninjured extremities(22).

Bracing

Bracing should be discussed with the physiotherapist and surgeon prior to return to sport or strenuous activities post ACLR. The decision will be dependent on a number of factors including: type of sport, position, activity level and complexity of the initial injury. Some surgeons may recommend a rigid, functional knee brace or a neoprene sleeve. Research has demonstrated that a rigid knee brace does not provide superior outcomes when compared with a neoprene sleeve after ACLR(6). Bracing has not been proven to prevent re-injury or improve clinical outcomes after ACLR(33). However, there is evidence that any type of knee bracing (rigid /soft) improves proprioception measures(7,27).



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0-2 WEEKS

LEFS range: 14-24

GOALS

- Patient education re: weight-bearing status; changes to rehab guidelines with any concurrent pathologies (i.e. PF pain, MCL injury, meniscal repair vs debridement, etc.)
- Decrease pain and swelling
- Increase range of motion & restore full extension*
- Maintain flexibility of hamstrings, calves
- Quadriceps activation(44)
- Proprioceptive/balance re-education(46)
- Maintain cardiovascular fitness

EXERCISE SUGGESTIONS

ROM & Flexibility

> **Remember - It is important to restore and maintain range of motion early, especially full extension.*
>
> *This is not detrimental to the graft or its stability (43).*

- Heel slides (+/– slider board)
- Supine with legs up wall – heels slides with gravity assisted
- Bike pendulums: high seat ½ circles forward/backward → full circles – lower seat
- Sitting passive leg extension with roll under heel OR prone leg hangs off end of bed/plinth
- Seated calf stretch with towel - knee bent (soleus), knee straight (gastrocnemius)
- Seated hamstring stretch (back straight)

Muscle Strength & Endurance

Quadriceps/Hamstrings:

- Quadriceps and hamstring co-contraction(2,41)
- Quadriceps isometrics(44) in standing/sitting/lying +/– muscle stimulation or biofeedback
- Sit to stand – progress by gradually decreasing height of seat
- Static lunge forward/side
- Mini wall squat (30°)
- Shuttle™: (one bungee cord) – 2 leg squat (¼ - ½ range) and 2 leg calf raises

Hip/Gluteals:

- Side lying abduction/adduction
- Gluteal squeezes supine or standing
- Prone hip extension
- Standing hip flexion/extension, abduction/adduction

Calves:

- Ankle pumping +/– with leg elevation
- Standing calf raises with/without support

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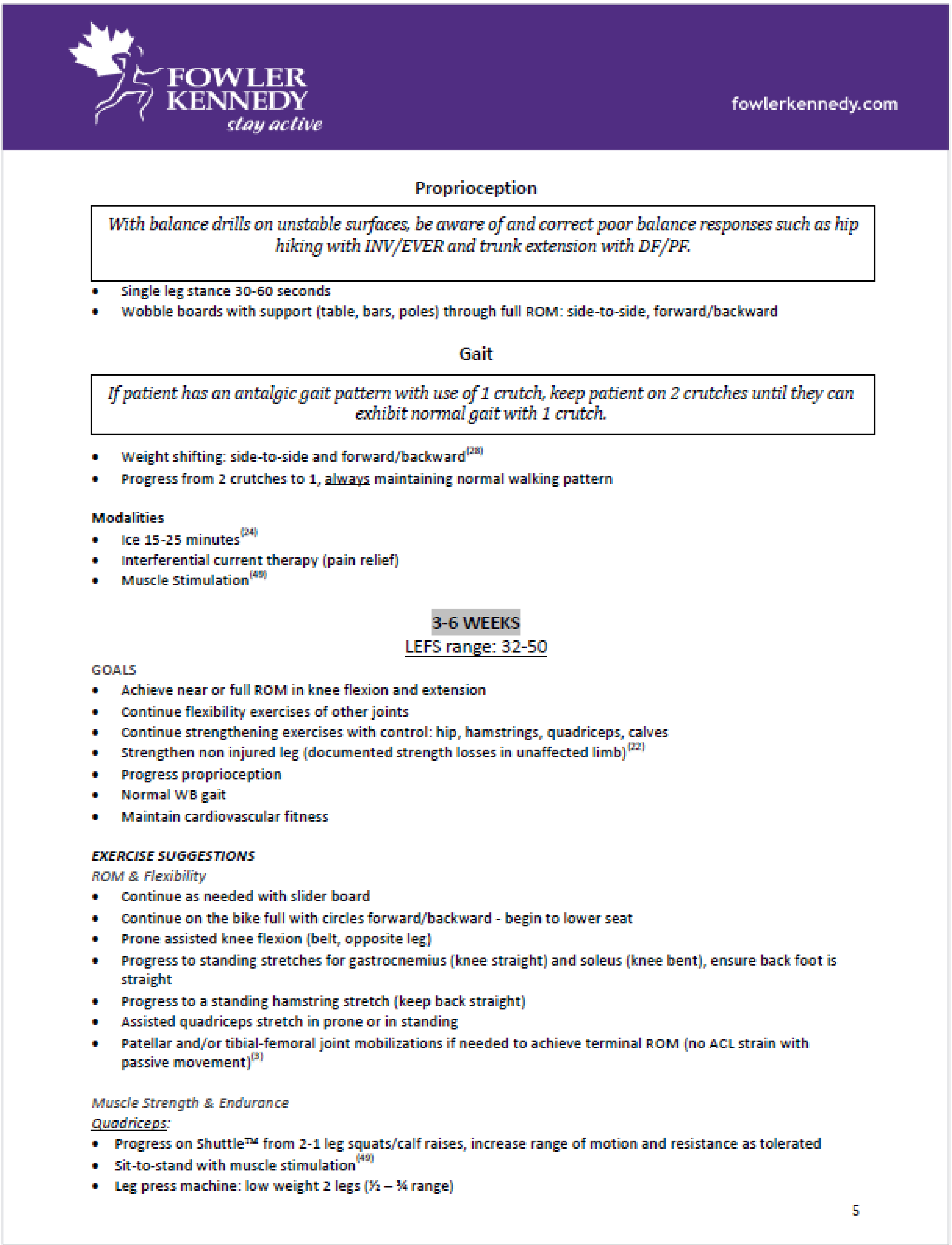


Proprioception

> *With balance drills on unstable surfaces, be aware of and correct poor balance responses such as hip hiking with INV/EVER and trunk extension with DF/PF.*

- Single leg stance 30-60 seconds
- Wobble boards with support (table, bars, poles) through full ROM: side-to-side, forward/backward

Gait

> *If patient has an antalgic gait pattern with use of 1 crutch, keep patient on 2 crutches until they can exhibit normal gait with 1 crutch.*

- Weight shifting: side-to-side and forward/backward(28)
- Progress from 2 crutches to 1, always maintaining normal walking pattern

Modalities

- Ice 15-25 minutes(24)
- Interferential current therapy (pain relief)
- Muscle Stimulation(49)

3-6 WEEKS

LEFS range: 32-50

GOALS

- Achieve near or full ROM in knee flexion and extension
- Continue flexibility exercises of other joints
- Continue strengthening exercises with control: hip, hamstrings, quadriceps, calves
- Strengthen non injured leg (documented strength losses in unaffected limb)(22)
- Progress proprioception
- Normal WB gait
- Maintain cardiovascular fitness

EXERCISE SUGGESTIONS

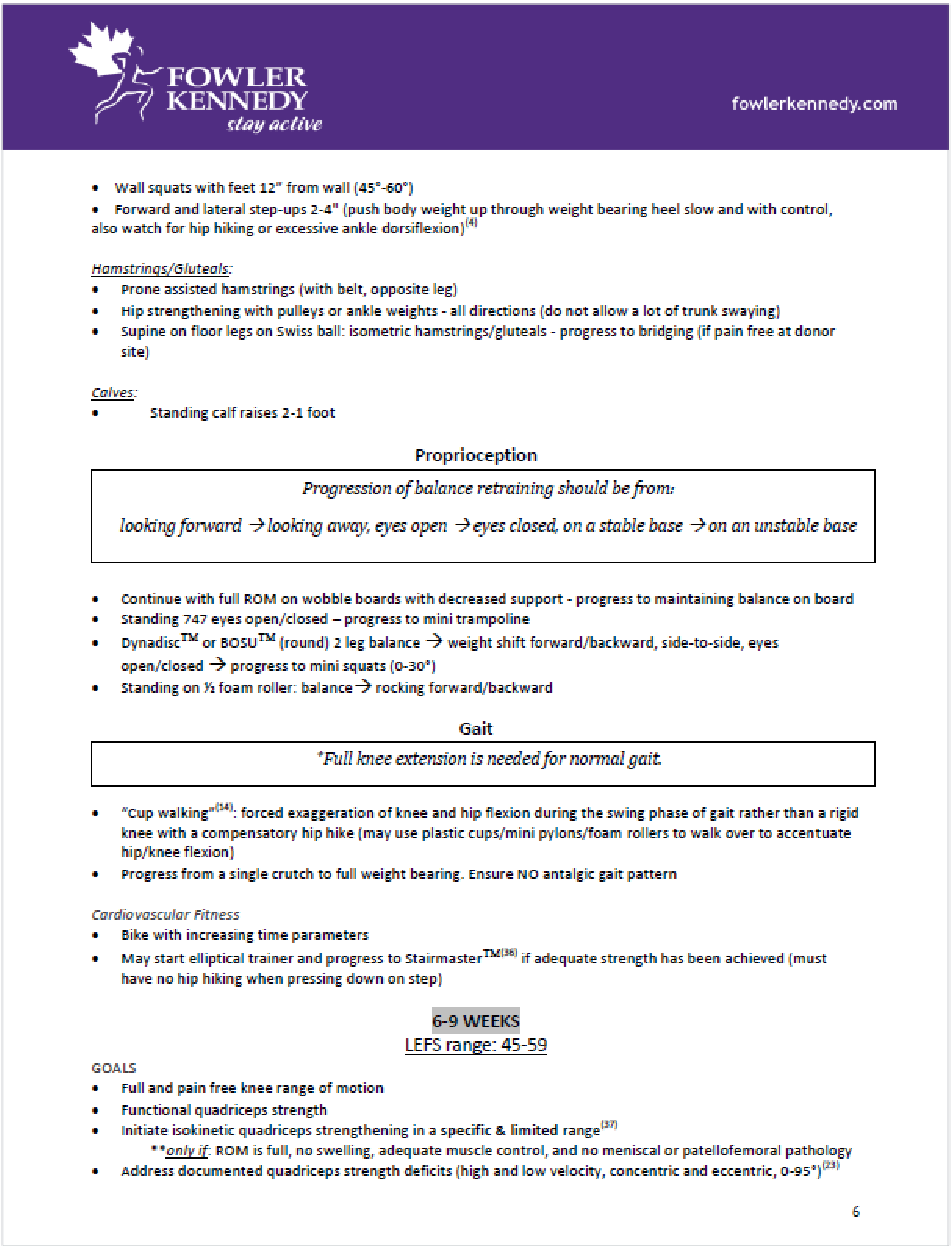
ROM & Flexibility

- Continue as needed with slider board
- Continue on the bike full with circles forward/backward - begin to lower seat
- Prone assisted knee flexion (belt, opposite leg)
- Progress to standing stretches for gastrocnemius (knee straight) and soleus (knee bent), ensure back foot is straight
- Progress to a standing hamstring stretch (keep back straight)
- Assisted quadriceps stretch in prone or in standing
- Patellar and/or tibial-femoral joint mobilizations if needed to achieve terminal ROM (no ACL strain with passive movement)(3)

Muscle Strength & Endurance

Quadriceps:

- Progress on Shuttle™ from 2-1 leg squats/calf raises, increase range of motion and resistance as tolerated
- Sit-to-stand with muscle stimulation(49)
- Leg press machine: low weight 2 legs (½ – ¾ range)



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- Wall squats with feet 12" from wall (45°-60°)
- Forward and lateral step-ups 2-4" (push body weight up through weight bearing heel slow and with control, also watch for hip hiking or excessive ankle dorsiflexion)(4)

Hamstrings/Gluteals:

- Prone assisted hamstrings (with belt, opposite leg)
- Hip strengthening with pulleys or ankle weights - all directions (do not allow a lot of trunk swaying)
- Supine on floor legs on Swiss ball: isometric hamstrings/gluteals - progress to bridging (if pain free at donor site)

Calves:

- Standing calf raises 2-1 foot

Proprioception

Progression of balance retraining should be from:

looking forward → looking away, eyes open → eyes closed, on a stable base → on an unstable base

- Continue with full ROM on wobble boards with decreased support - progress to maintaining balance on board
- Standing 747 eyes open/closed – progress to mini trampoline
- Dynadisc™ or BOSU™ (round) 2 leg balance → weight shift forward/backward, side-to-side, eyes open/closed → progress to mini squats (0-30°)
- Standing on ½ foam roller: balance → rocking forward/backward

Gait

**Full knee extension is needed for normal gait.*

- "Cup walking"(34): forced exaggeration of knee and hip flexion during the swing phase of gait rather than a rigid knee with a compensatory hip hike (may use plastic cups/mini pylons/foam rollers to walk over to accentuate hip/knee flexion)
- Progress from a single crutch to full weight bearing. Ensure NO antalgic gait pattern

Cardiovascular Fitness

- Bike with increasing time parameters
- May start elliptical trainer and progress to Stairmaster™(36) if adequate strength has been achieved (must have no hip hiking when pressing down on step)

6-9 WEEKS

LEFS range: 45-59

GOALS

- Full and pain free knee range of motion
- Functional quadriceps strength
- Initiate isokinetic quadriceps strengthening in a specific & limited range(37)
  - ***only if*: ROM is full, no swelling, adequate muscle control, and no meniscal or patellofemoral pathology
- Address documented quadriceps strength deficits (high and low velocity, concentric and eccentric, 0-95°)(23)

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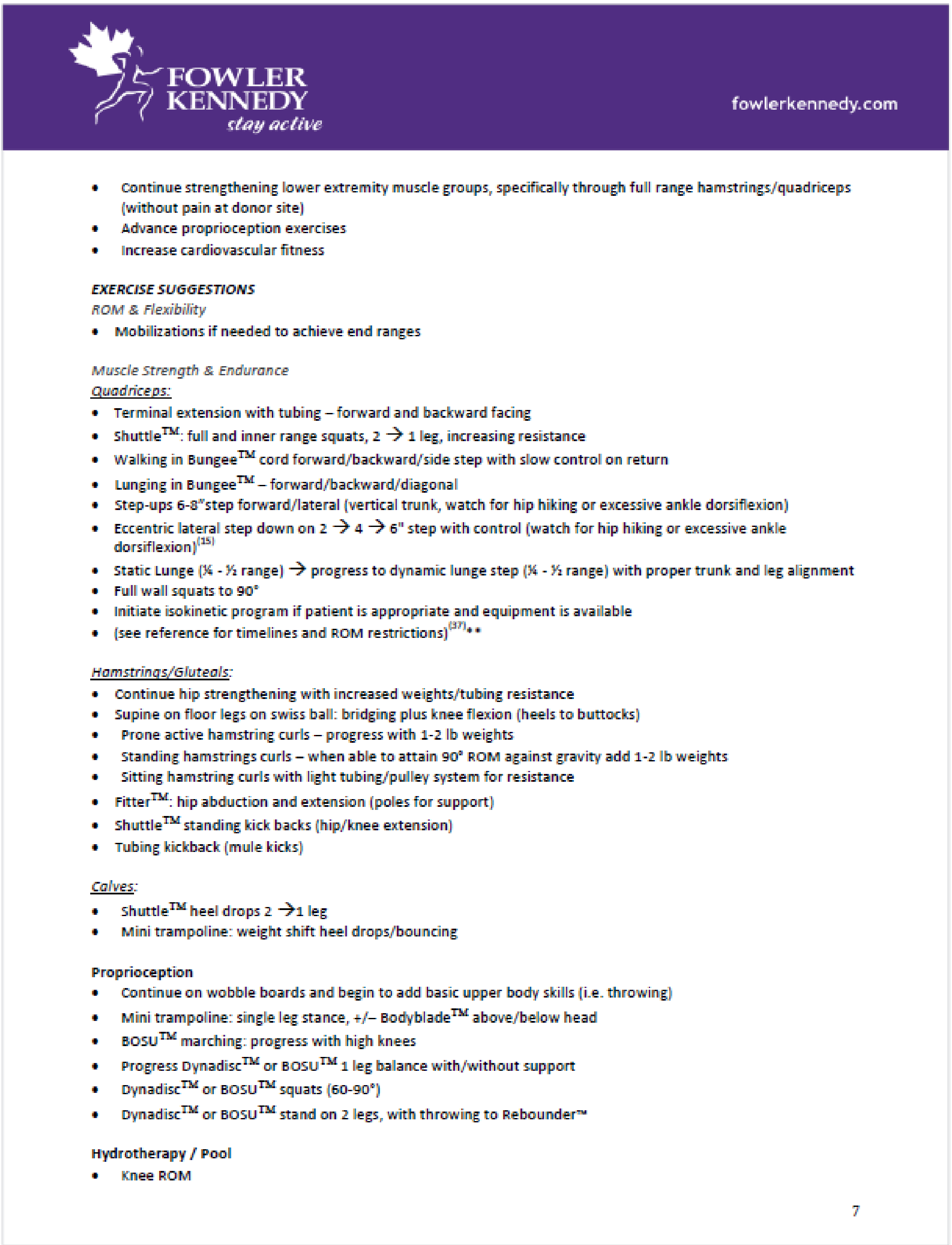

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- Continue strengthening lower extremity muscle groups, specifically through full range hamstrings/quadriceps (without pain at donor site)
- Advance proprioception exercises
- Increase cardiovascular fitness

EXERCISE SUGGESTIONS

ROM & Flexibility

- Mobilizations if needed to achieve end ranges

Muscle Strength & Endurance

Quadriceps:

- Terminal extension with tubing – forward and backward facing
- Shuttle^{TM}: full and inner range squats, 2 → 1 leg, increasing resistance
- Walking in Bungee^{TM} cord forward/backward/side step with slow control on return
- Lunging in Bungee^{TM} – forward/backward/diagonal
- Step-ups 6-8"step forward/lateral (vertical trunk, watch for hip hiking or excessive ankle dorsiflexion)
- Eccentric lateral step down on 2 → 4 → 6" step with control (watch for hip hiking or excessive ankle dorsiflexion)(15)
- Static Lunge (¼ - ½ range) → progress to dynamic lunge step (¼ - ½ range) with proper trunk and leg alignment
- Full wall squats to 90°
- Initiate isokinetic program if patient is appropriate and equipment is available
- (see reference for timelines and ROM restrictions)(37)**

Hamstrings/Gluteals:

- Continue hip strengthening with increased weights/tubing resistance
- Supine on floor legs on swiss ball: bridging plus knee flexion (heels to buttocks)
- Prone active hamstring curls – progress with 1-2 lb weights
- Standing hamstrings curls – when able to attain 90° ROM against gravity add 1-2 lb weights
- Sitting hamstring curls with light tubing/pulley system for resistance
- Fitter^{TM}: hip abduction and extension (poles for support)
- Shuttle^{TM} standing kick backs (hip/knee extension)
- Tubing kickback (mule kicks)

Calves:

- Shuttle^{TM} heel drops 2 →1 leg
- Mini trampoline: weight shift heel drops/bouncing

Proprioception

- Continue on wobble boards and begin to add basic upper body skills (i.e. throwing)
- Mini trampoline: single leg stance, +/– Bodyblade^{TM} above/below head
- BOSU^{TM} marching: progress with high knees
- Progress Dynadisc^{TM} or BOSU^{TM} 1 leg balance with/without support
- Dynadisc^{TM} or BOSU^{TM} squats (60-90°)
- Dynadisc^{TM} or BOSU^{TM} stand on 2 legs, with throwing to Rebounder™

Hydrotherapy / Pool

- Knee ROM

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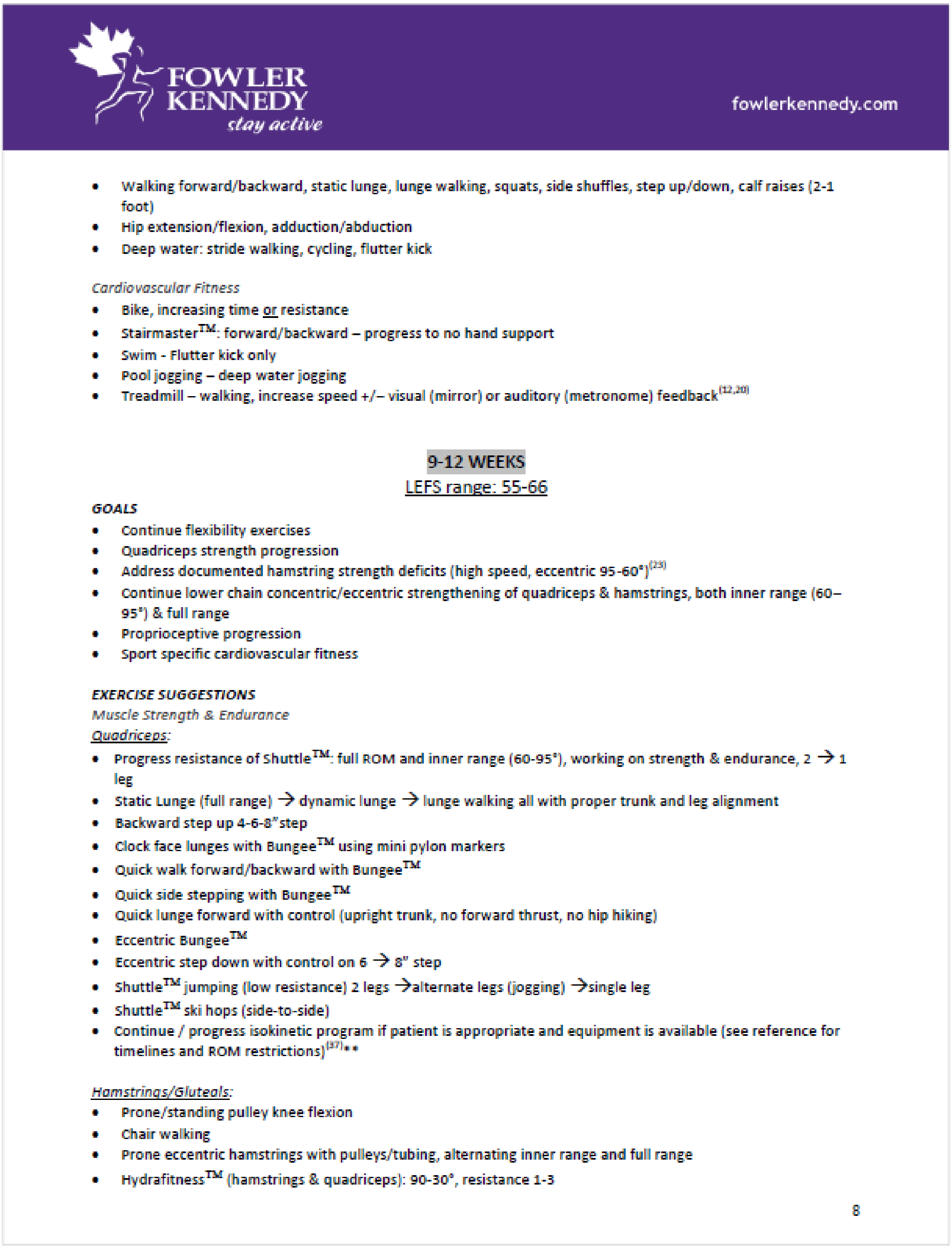


- Walking forward/backward, static lunge, lunge walking, squats, side shuffles, step up/down, calf raises (2-1 foot)
- Hip extension/flexion, adduction/abduction
- Deep water: stride walking, cycling, flutter kick

Cardiovascular Fitness

- Bike, increasing time <u>or</u> resistance
- Stairmaster™: forward/backward – progress to no hand support
- Swim - Flutter kick only
- Pool jogging – deep water jogging
- Treadmill – walking, increase speed +/– visual (mirror) or auditory (metronome) feedback(12,20)

9-12 WEEKS

<u>LEFS range: 55-66</u>

GOALS

- Continue flexibility exercises
- Quadriceps strength progression
- Address documented hamstring strength deficits (high speed, eccentric 95-60°)(23)
- Continue lower chain concentric/eccentric strengthening of quadriceps & hamstrings, both inner range (60–95°) & full range
- Proprioceptive progression
- Sport specific cardiovascular fitness

EXERCISE SUGGESTIONS

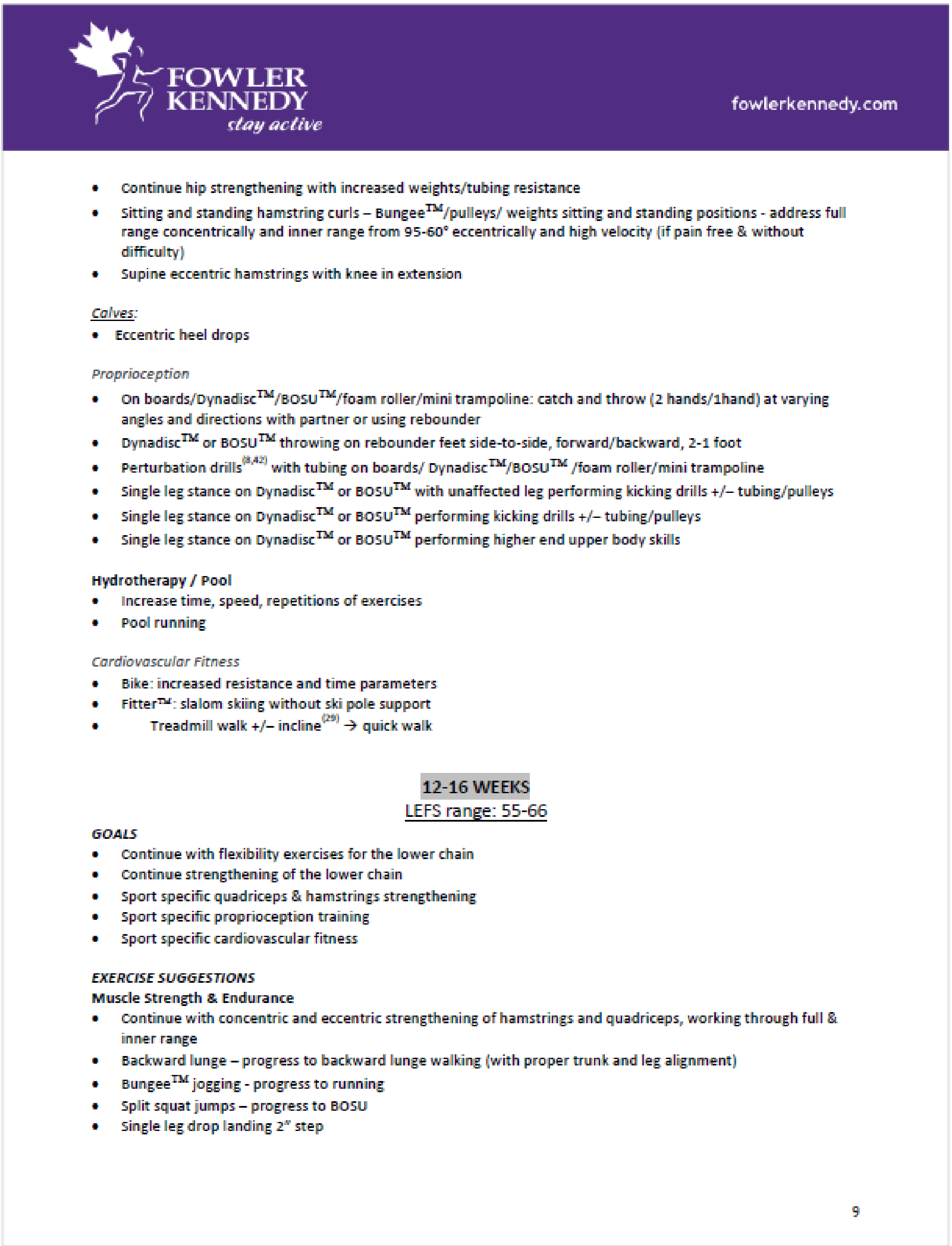
Muscle Strength & Endurance

<u>Quadriceps</u>:

- Progress resistance of Shuttle™: full ROM and inner range (60-95°), working on strength & endurance, 2 → 1 leg
- Static Lunge (full range) → dynamic lunge → lunge walking all with proper trunk and leg alignment
- Backward step up 4-6-8" step
- Clock face lunges with Bungee™ using mini pylon markers
- Quick walk forward/backward with Bungee™
- Quick side stepping with Bungee™
- Quick lunge forward with control (upright trunk, no forward thrust, no hip hiking)
- Eccentric Bungee™
- Eccentric step down with control on 6 → 8" step
- Shuttle™ jumping (low resistance) 2 legs →alternate legs (jogging) →single leg
- Shuttle™ ski hops (side-to-side)
- Continue / progress isokinetic program if patient is appropriate and equipment is available (see reference for timelines and ROM restrictions)(37)**

<u>Hamstrings/Gluteals</u>:

- Prone/standing pulley knee flexion
- Chair walking
- Prone eccentric hamstrings with pulleys/tubing, alternating inner range and full range
- Hydrafitness™ (hamstrings & quadriceps): 90-30°, resistance 1-3



- Continue hip strengthening with increased weights/tubing resistance
- Sitting and standing hamstring curls – Bungee™/pulleys/ weights sitting and standing positions - address full range concentrically and inner range from 95-60° eccentrically and high velocity (if pain free & without difficulty)
- Supine eccentric hamstrings with knee in extension

Calves:
- Eccentric heel drops

Proprioception
- On boards/Dynadisc™/BOSU™/foam roller/mini trampoline: catch and throw (2 hands/1hand) at varying angles and directions with partner or using rebounder
- Dynadisc™ or BOSU™ throwing on rebounder feet side-to-side, forward/backward, 2-1 foot
- Perturbation drills(8,42) with tubing on boards/ Dynadisc™/BOSU™ /foam roller/mini trampoline
- Single leg stance on Dynadisc™ or BOSU™ with unaffected leg performing kicking drills +/– tubing/pulleys
- Single leg stance on Dynadisc™ or BOSU™ performing kicking drills +/– tubing/pulleys
- Single leg stance on Dynadisc™ or BOSU™ performing higher end upper body skills

Hydrotherapy / Pool
- Increase time, speed, repetitions of exercises
- Pool running

Cardiovascular Fitness
- Bike: increased resistance and time parameters
- Fitter™: slalom skiing without ski pole support
- Treadmill walk +/– incline(29) → quick walk

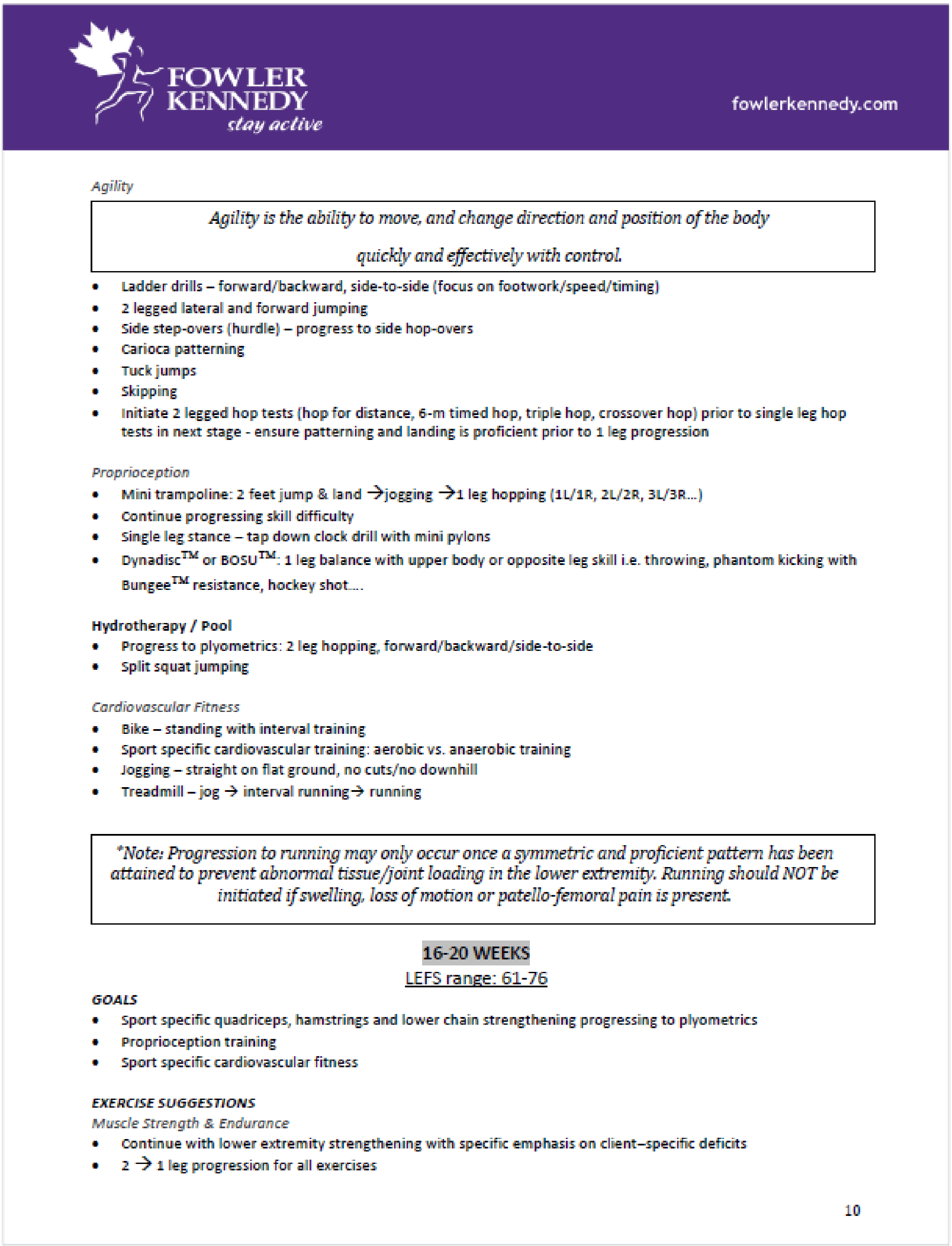
12-16 WEEKS

LEFS range: 55-66

GOALS
- Continue with flexibility exercises for the lower chain
- Continue strengthening of the lower chain
- Sport specific quadriceps & hamstrings strengthening
- Sport specific proprioception training
- Sport specific cardiovascular fitness

EXERCISE SUGGESTIONS

Muscle Strength & Endurance
- Continue with concentric and eccentric strengthening of hamstrings and quadriceps, working through full & inner range
- Backward lunge – progress to backward lunge walking (with proper trunk and leg alignment)
- Bungee™ jogging - progress to running
- Split squat jumps – progress to BOSU
- Single leg drop landing 2" step



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Agility

Agility is the ability to move, and change direction and position of the body quickly and effectively with control.

- Ladder drills – forward/backward, side-to-side (focus on footwork/speed/timing)
- 2 legged lateral and forward jumping
- Side step-overs (hurdle) – progress to side hop-overs
- Carioca patterning
- Tuck jumps
- Skipping
- Initiate 2 legged hop tests (hop for distance, 6-m timed hop, triple hop, crossover hop) prior to single leg hop tests in next stage - ensure patterning and landing is proficient prior to 1 leg progression

Proprioception

- Mini trampoline: 2 feet jump & land →jogging →1 leg hopping (1L/1R, 2L/2R, 3L/3R…)
- Continue progressing skill difficulty
- Single leg stance – tap down clock drill with mini pylons
- Dynadisc^{TM} or BOSU^{TM}: 1 leg balance with upper body or opposite leg skill i.e. throwing, phantom kicking with Bungee^{TM} resistance, hockey shot….

Hydrotherapy / Pool

- Progress to plyometrics: 2 leg hopping, forward/backward/side-to-side
- Split squat jumping

Cardiovascular Fitness

- Bike – standing with interval training
- Sport specific cardiovascular training: aerobic vs. anaerobic training
- Jogging – straight on flat ground, no cuts/no downhill
- Treadmill – jog → interval running→ running

**Note: Progression to running may only occur once a symmetric and proficient pattern has been attained to prevent abnormal tissue/joint loading in the lower extremity. Running should NOT be initiated if swelling, loss of motion or patello-femoral pain is present.*

16-20 WEEKS

LEFS range: 61-76

GOALS

- Sport specific quadriceps, hamstrings and lower chain strengthening progressing to plyometrics
- Proprioception training
- Sport specific cardiovascular fitness

EXERCISE SUGGESTIONS

Muscle Strength & Endurance

- Continue with lower extremity strengthening with specific emphasis on client–specific deficits
- 2 → 1 leg progression for all exercises

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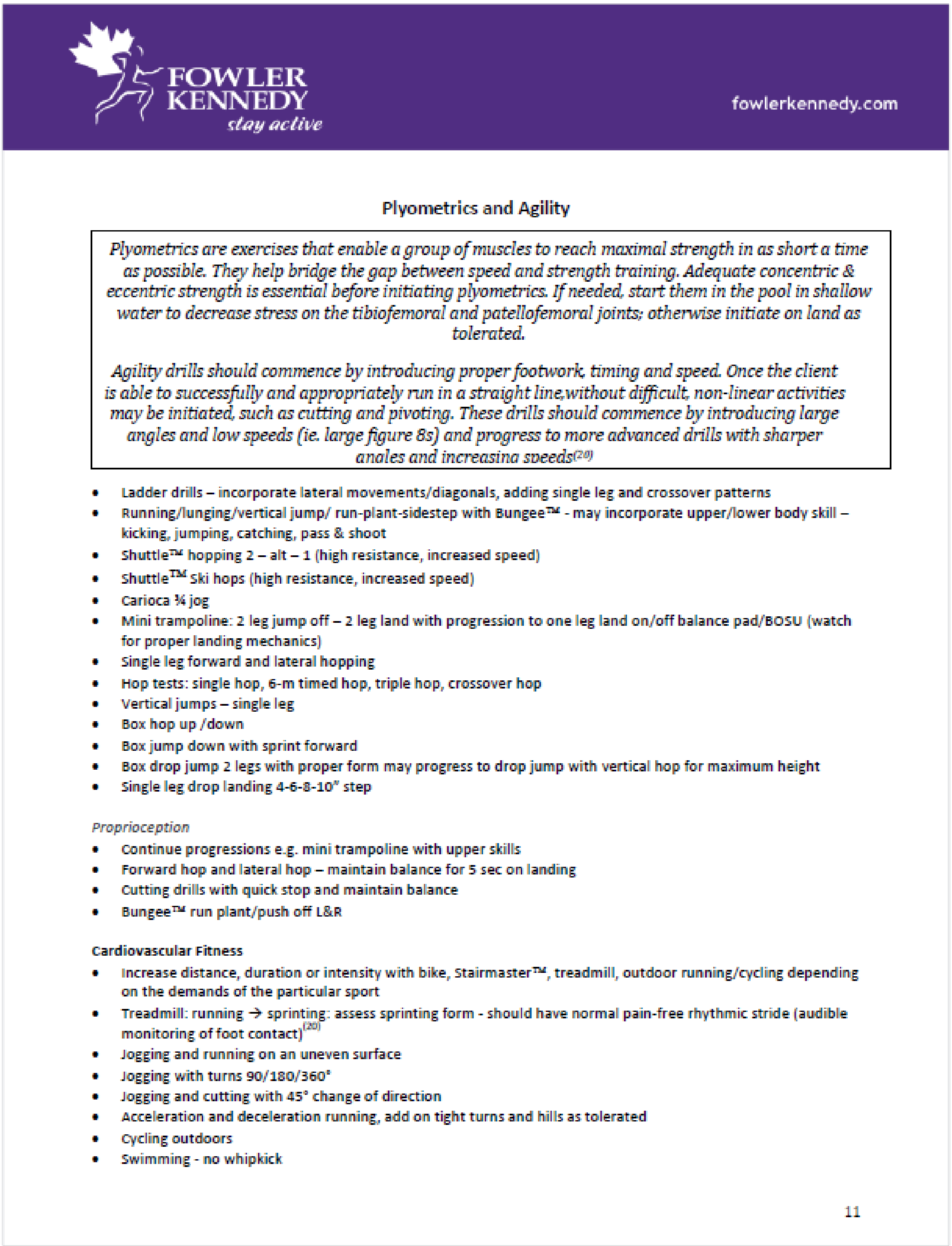


Plyometrics and Agility

Plyometrics are exercises that enable a group of muscles to reach maximal strength in as short a time as possible. They help bridge the gap between speed and strength training. Adequate concentric & eccentric strength is essential before initiating plyometrics. If needed, start them in the pool in shallow water to decrease stress on the tibiofemoral and patellofemoral joints; otherwise initiate on land as tolerated.

Agility drills should commence by introducing proper footwork, timing and speed. Once the client is able to successfully and appropriately run in a straight line,without difficult, non-linear activities may be initiated, such as cutting and pivoting. These drills should commence by introducing large angles and low speeds (ie. large figure 8s) and progress to more advanced drills with sharper angles and increasing speeds(20)

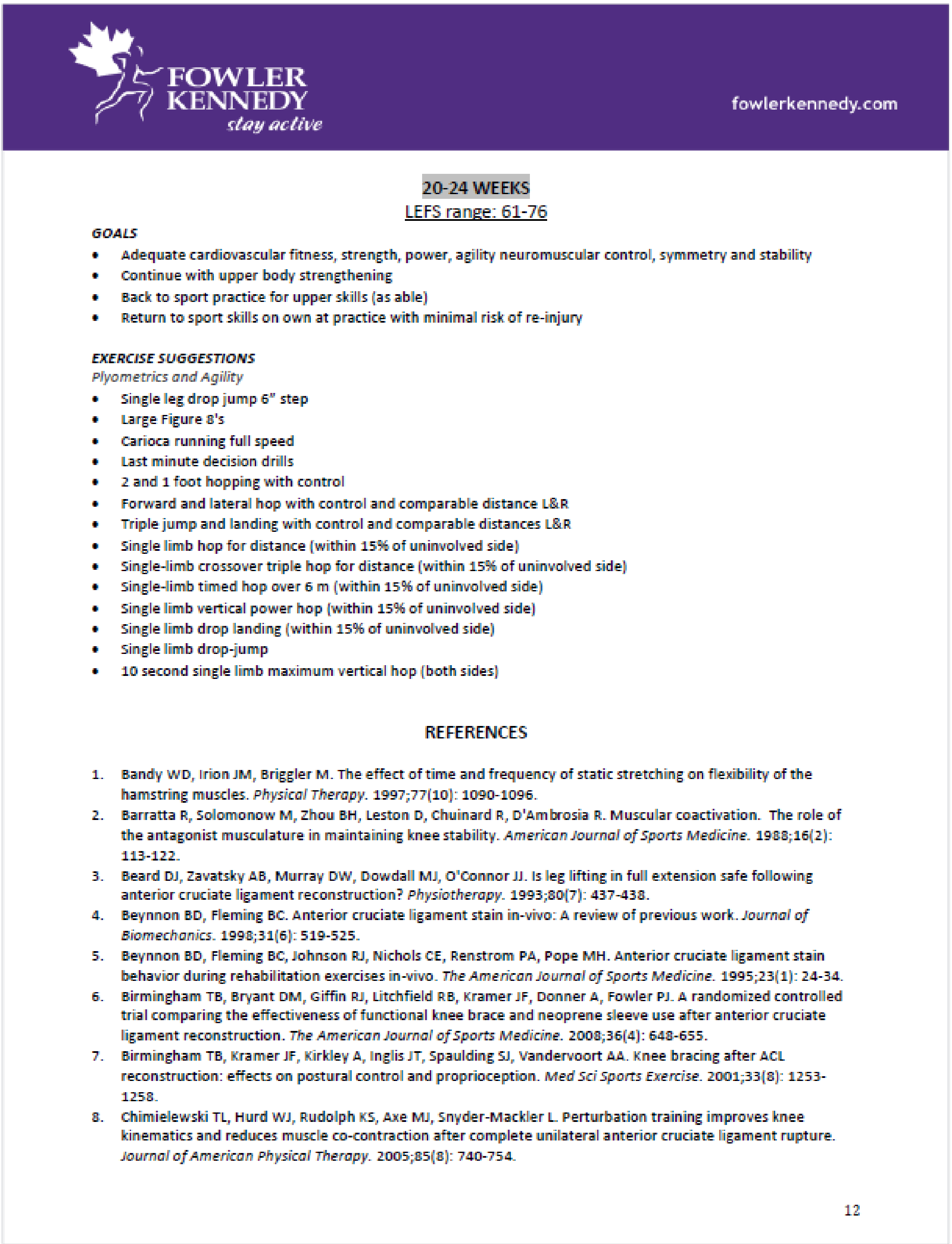
- Ladder drills – incorporate lateral movements/diagonals, adding single leg and crossover patterns
- Running/lunging/vertical jump/ run-plant-sidestep with Bungee™ - may incorporate upper/lower body skill – kicking, jumping, catching, pass & shoot
- Shuttle™ hopping 2 – alt – 1 (high resistance, increased speed)
- Shuttle™ Ski hops (high resistance, increased speed)
- Carioca ¾ jog
- Mini trampoline: 2 leg jump off – 2 leg land with progression to one leg land on/off balance pad/BOSU (watch for proper landing mechanics)
- Single leg forward and lateral hopping
- Hop tests: single hop, 6-m timed hop, triple hop, crossover hop
- Vertical jumps – single leg
- Box hop up /down
- Box jump down with sprint forward
- Box drop jump 2 legs with proper form may progress to drop jump with vertical hop for maximum height
- Single leg drop landing 4-6-8-10" step

Proprioception

- Continue progressions e.g. mini trampoline with upper skills
- Forward hop and lateral hop – maintain balance for 5 sec on landing
- Cutting drills with quick stop and maintain balance
- Bungee™ run plant/push off L&R

Cardiovascular Fitness

- Increase distance, duration or intensity with bike, Stairmaster™, treadmill, outdoor running/cycling depending on the demands of the particular sport
- Treadmill: running → sprinting: assess sprinting form - should have normal pain-free rhythmic stride (audible monitoring of foot contact)(20)
- Jogging and running on an uneven surface
- Jogging with turns 90/180/360°
- Jogging and cutting with 45° change of direction
- Acceleration and deceleration running, add on tight turns and hills as tolerated
- Cycling outdoors
- Swimming - no whipkick



FOWLER KENNEDY
stay active

fowlerkennedy.com

20-24 WEEKS

LEFS range: 61-76

GOALS

- Adequate cardiovascular fitness, strength, power, agility neuromuscular control, symmetry and stability
- Continue with upper body strengthening
- Back to sport practice for upper skills (as able)
- Return to sport skills on own at practice with minimal risk of re-injury

EXERCISE SUGGESTIONS

Plyometrics and Agility

- Single leg drop jump 6" step
- Large Figure 8's
- Carioca running full speed
- Last minute decision drills
- 2 and 1 foot hopping with control
- Forward and lateral hop with control and comparable distance L&R
- Triple jump and landing with control and comparable distances L&R
- Single limb hop for distance (within 15% of uninvolved side)
- Single-limb crossover triple hop for distance (within 15% of uninvolved side)
- Single-limb timed hop over 6 m (within 15% of uninvolved side)
- Single limb vertical power hop (within 15% of uninvolved side)
- Single limb drop landing (within 15% of uninvolved side)
- Single limb drop-jump
- 10 second single limb maximum vertical hop (both sides)

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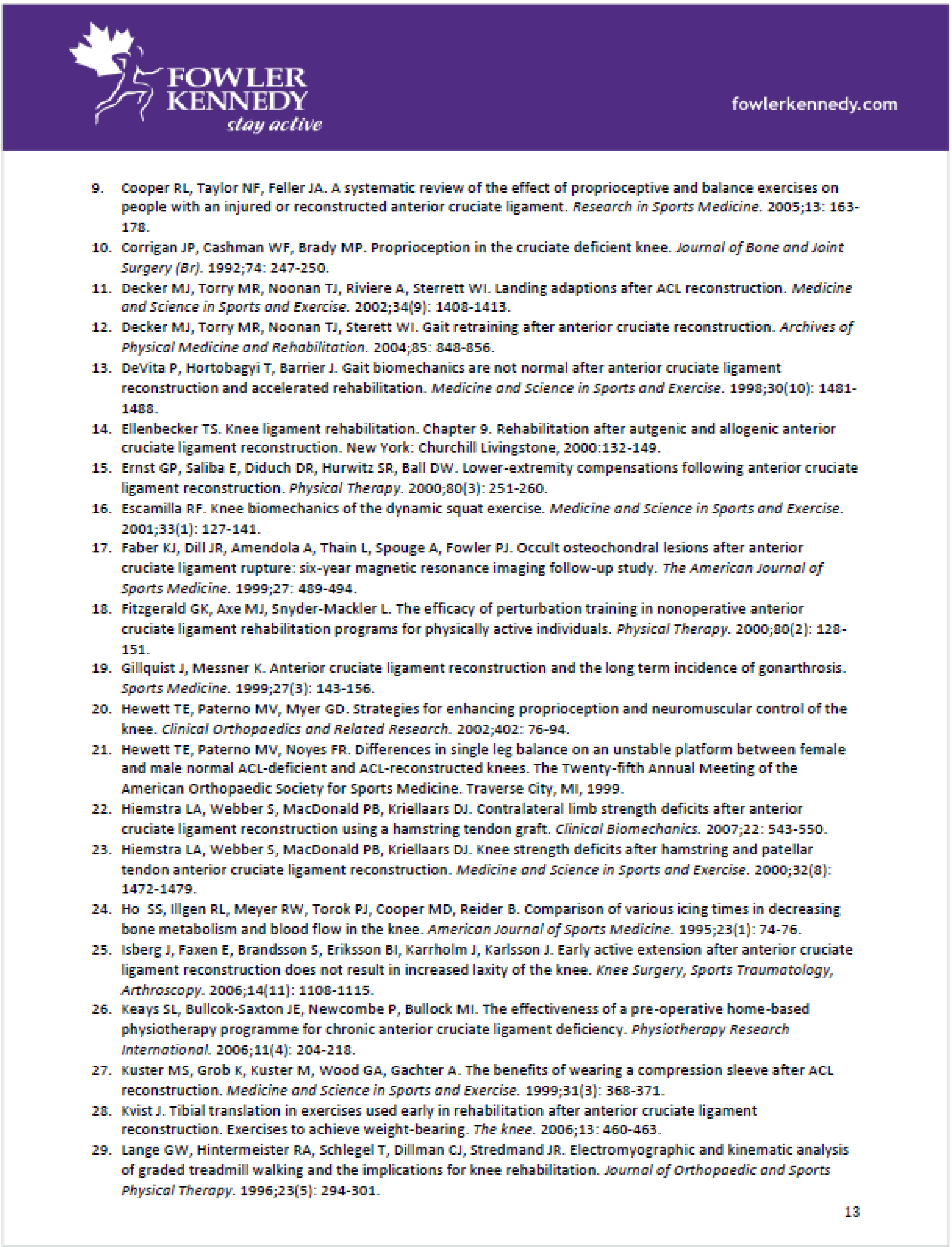

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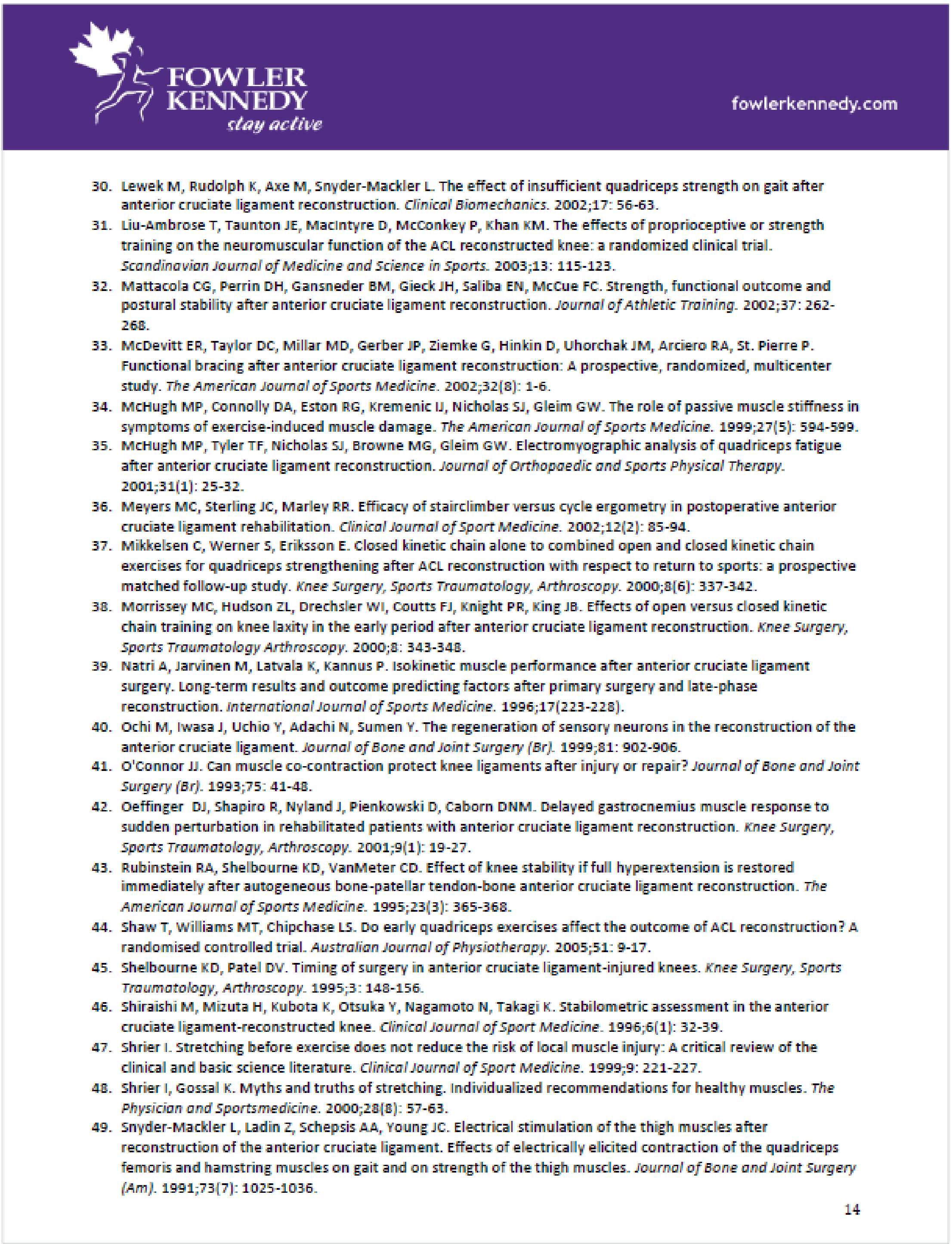

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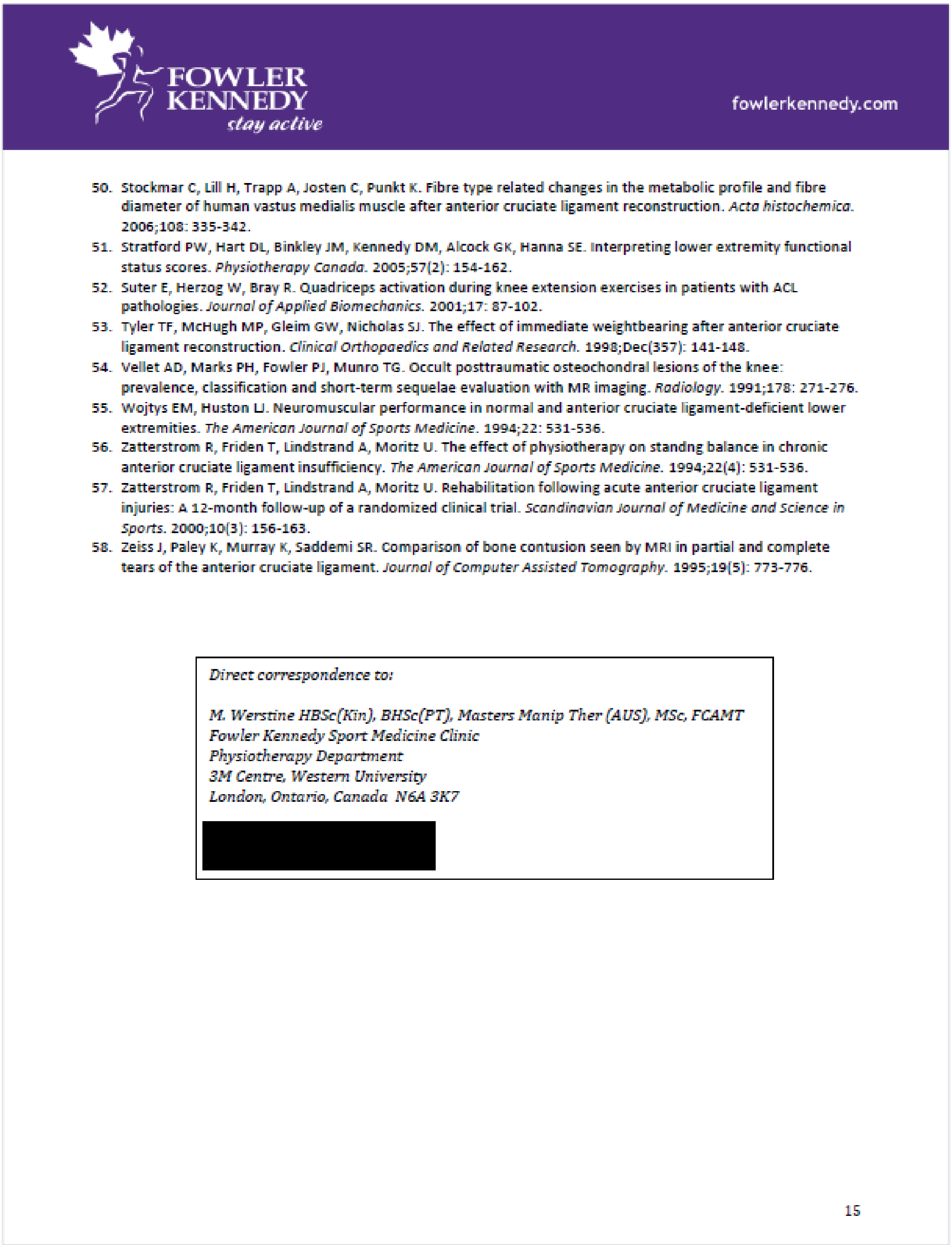

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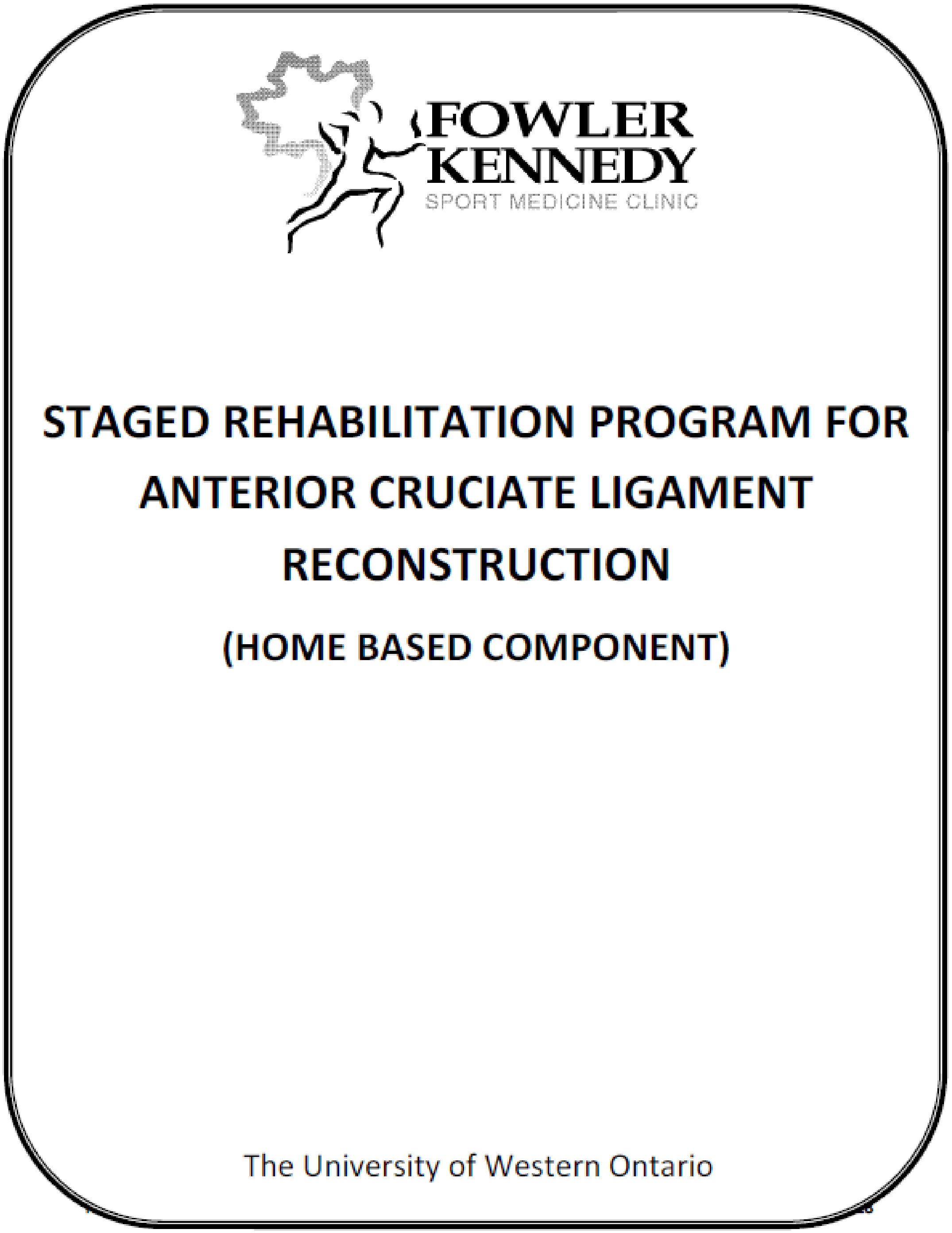
Appendix H: Staged Rehabilitation Program for Anterior Cruciate Ligament Reconstruction (Home Based Component)



FOWLER
KENNEDY
SPORT MEDICINE CLINIC

STAGED REHABILITATION PROGRAM FOR ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

(HOME BASED COMPONENT)

The University of Western Ontario

Rehabilitation is an essential part of a full recovery from ACL reconstruction and requires a minimum commitment of 6 months. This program has been developed in order to assist you with the first half of your rehabilitation for anterior cruciate ligament (ACL) reconstruction.

This booklet is intended to guide you with instruction, direction, and rehabilitative guidelines, with the assistance of a physiotherapist.

This booklet is to be used for the first 12 weeks (3 months) post surgery and is comprised of home exercises for you to complete on a daily basis. It is divided into two parts:

> Part 1: Week 2 to Week 6: The first timeframe focuses on regaining range of motion, retraining walking patterns and basic knee and hip strengthening.
>
> Part 2: Week 6 to Week 12: The second timeframe focuses on more advanced knee and hip strengthening.

To ensure you are progressing in a timely fashion, you will have two appointments in the first twelve weeks with a physiotherapist at Fowler Kennedy Sports Medicine Clinic.

> Appointment 1: Week 2: The physiotherapist will explain and review exercises for the first part (Week 2 to Week 6) of the booklet.
>
> Appointment 2: Week 6: The physiotherapist will examine knee range of motion and explain and review exercises for the second part (Week 6 to Week 12) of the booklet.

At week 12 (3 months), you will book an appointment with a physiotherapist and will formally commence supervised physiotherapy, in a physiotherapy clinic, for the second half of your rehabilitation until the 6 month mark. The frequency of these appointments will be determined between you and your physiotherapist. Formal physiotherapy sessions will focus on balance retraining, more advanced strengthening for the lower extremity, functional exercise patterning, speed, agility and return to sport exercises. Functional testing (jumping, landing, cutting…) will be evaluated at different timeframes within the 3 to 6 month period to determine your readiness and ability to return to activity.

In order to ensure a safe return to the same level of activity prior to injury, you should complete the FULL duration of the rehabilitation process. Your surgeon, physiotherapist(s) and health care team will use their professional judgement in order to assist you throughout your rehabilitation process; however, it is also your responsibility to take ownership of the rehabilitation. It is important that you meet the criteria set out for each timeframe and attend all recommended physiotherapy sessions in order to achieve a full recovery.

STAGED REHABILITATION PROGRAM FOR ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION (HOME BASED COMPONENT)

Part 1: Week 2 to Week 6

Range of Motion

1

Knee Extension
Heel Over Roll

2

Knee Extension
Prone Hangs

3

Knee Flexion
Heel Slides Supine/Sitting

4

Knee Flexion
Heel Slides up the Wall

Knee Strengthening

5

Knee
Quadriceps Tightening

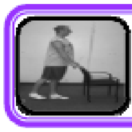
6

Knee
Standing Quadriceps Activation

Hip Strengthening

7

Hip
Flexion in Standing

8

Hip
Extension in Standing

9

Hip
Abduction in Standing

10

Hip
Adduction in Standing

Other

11

Gait
Protected Weight-Bearing (with crutches)

12

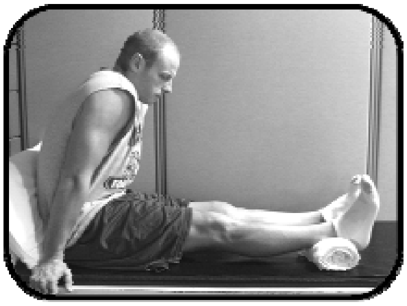
Ice
Knee in Extension

13

Additional Exercises
Stationary Bike

RANGE OF MOTION - KNEE EXTENSION

1



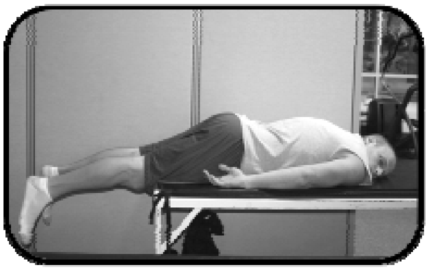
HEEL OVER ROLL

Lie on your back on a firm surface with the affected leg straight and place a rolled towel under your ankle.

Allow gravity to slowly straighten the knee.

GOAL: Hold for 3-5 minutes, 3 times a day

2



PRONE HANGS

Lie on your stomach with your knees and lower legs hanging over the end of a table or bed.

Allow gravity to slowly straighten the knee.

GOAL: Hold for 3-5 minutes, 3 times a day

RANGE OF MOTION - KNEE FLEXION

3

HEEL SLIDES SUPINE/SITTING

Lie on your back or sit with your back supported.
Bend your affected knee and gently slide the heel toward your buttocks.
Hold for 5 seconds.
Slowly lower your leg back to a straight position.

*If it is difficult/painful to bend the knee without assistance, you may grasp your thigh with both hands and lift the thigh to help the heel slide.

GOAL: 30 repetitions, 3 times a day

4

HEEL SLIDES UP THE WALL

Lie on the floor with your legs up the wall.
Bend your affected knee and allow gravity to gently slide the heel down the wall toward your buttocks.
Hold for 5 seconds.
Straighten your affected knee by sliding your heel back up the wall until your knee is as straight as possible.

*If you are unable to slide your heel back up, use your unaffected leg and place it underneath the affected heel, and push up for assistance.

*When your bending improves over the first few weeks, you can progress this exercise by placing your unaffected foot over the affected leg and pushing down with it to increase the bend.

GOAL: 30 repetitions, 3 times a day

5

QUADRICEPS TIGHTENING

Sit or lie on your back with your legs as straight as possible.
Tighten your thigh muscle by pushing your knee down while trying to lift your heel off the surface.
Hold for 10 seconds.

*If you are unable to tighten your thigh muscle in this position (in the first few weeks), place a rolled towel under the knee and try to push your knee down into the towel while trying to lift off your heel.

GOAL: 30 repetitions, 3 times a day

6

STANDING QUADRICEPS ACTIVATION

Stand with your crutches for support and evenly distribute your weight between your two legs.
Try to tighten your thigh as you straighten your knee by pushing your knee back.
Hold for 10 seconds.

GOAL: 30 repetitions, 3 times a day

HIP STRENGTHENING

7

FLEXION IN STANDING

Stand with a crutch or chair for some support and lift your affected leg forward, keeping your knee as straight as possible.
Hold for 2-3 seconds.
Relax and return back to the original position.

*If you can perform 10 repetitions easily, you can progress up to 30 repetitions.

GOAL: 10 repetitions with progression up to 30 repetitions on the affected leg, 3 times a day

8

EXTENSION IN STANDING

Stand with a crutch or chair for some support and lift your affected leg backward, keeping your knee as straight as possible.
Hold for 2-3 seconds.
Relax and return back to the original position.

*If you can perform 10 repetitions easily, you can progress up to 30 repetitions.

GOAL: 10 repetitions with progression up to 30 repetitions on the affected leg, 3 times a day

HIP STRENGTHENING

9

ABDUCTION IN STANDING

Stand with a crutch or chair for some support and raise your hip out to the side, keeping your knee as straight as possible without letting the leg come forward or lifting up your hip/pelvis.
Hold for 2-3 seconds.
Relax and return back to the original position.

*If you can perform 10 repetitions easily, you can progress up to 30 repetitions.

GOAL: 10 repetitions with progression up to 30 repetitions on the affected leg, 3 times a day

10

ADDUCTION IN STANDING

Stand with a crutch or chair for some support and bring your affected leg towards the midline of your body and cross the leg in front of your other leg.
Hold for 2-3 seconds.
Slowly relax and return back to the original position.

*If you can perform 10 repetitions easily, you can progress up to 30 repetitions.

GOAL: 10 repetitions with progression up to 30 repetitions on the affected leg, 3 times a day

OTHER – GAIT AND ICE

11

PROTECTED WEIGHT-BEARING
(AS TOLERATED WITH CRUTCHES)

Protected weight bearing means you can fully weight bear on the affected leg as long as you are using crutches for protection. When walking, place the crutches tips forward about one step's length.

At the same time, place the affected leg forward level with the crutches (i.e. crutch tips and heel/foot).
Push down on the hand grips and place weight on the affected leg at the same time and follow through with a normal step on the unaffected leg.

* Stay on two crutches until your knee is fully straight and you are not walking with a limp. Then, you can progress to one crutch by placing it on the opposite side of your affected leg (i.e. right side if left surgical knee). Place the affected leg and crutch tip forward, on the ground, at the same time and follow the same directions as above. You can discharge the crutches when you walk normally, without a limp, and with a straight knee.

GOAL: Crutches should be discharged by 6 weeks if you have a straight knee and pain free walking without a limp

12

ICE WITH KNEE IN EXTENSION

After completing all your exercises, place an ice pack on top of the affected knee. You may also place an additional ice pack over your shin area if it is sore.
Ensure that the knee is as straight as possible.

*It is important to make sure a towel or pillow is not placed underneath the knee.

GOAL: 15 minutes, 3 times a day, after exercises

OTHER – ADDITIONAL EXERCISES

13

STATIONARY BIKE

Set the seat the seat height so that your knee is almost straight when the pedal is at the bottom.

Begin pedalling in slow bottom half circles, with the affected leg, forward and backwards.

Progress as tolerated to full circles. When you can comfortably go all the way around, progress the exercise by lowering the seat of the bike

GOAL: 5-10 minutes

STAGED REHABILITATION PROGRAM FOR ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION (HOME BASED COMPONENT)

Part 2: Week 6 to Week 12

Note: The GOAL for range of motion by 6 weeks is full extension (a straight leg) and approximately 120° of knee bend (about 1 hand span between your buttocks and heel with the knee bent). If you have not yet attained that goal, continue with the Range of Motion exercises that were given at 2-6 weeks in conjunction with the new exercises outlined for week 6 to 12.

Knee Strengthening

1

Quadriceps Strengthening
Lateral Step Up

2

Quadriceps Strengthening
Lateral Step Down

3

Quadriceps Strengthening
Wall Slides

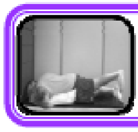
4

Calves
Calf Raises

Hip Strengthening

5

Hip Strengthening
Straight Leg Raise

6

Hip Strengthening
Extension (lying on stomach)

7

Hip Strengthening
Abduction (on side)

8

Hip Strengthening
Adduction (on side)

9

Hamstrings/Gluts
Bridge

Other

10

Balance
Single Leg Stance

11

Ice
Knee in Extension

12

Additional Exercises
Stationary Bike, Elliptical

1

LATERAL STEP UP

Place enough books on the floor to total 4-6 inches tall or use a small step/stair.

Use a wall, railing, or chair for some support.

Slowly step up onto the book/stair sideways with the affected foot.

Slowly step off.

*If you can perform 10 repetitions easily, you can progress up to 30 repetitions.

GOAL: 10 repetitions with progression up to 30 repetitions on the affected leg, 3 times a day

2

LATERAL STEP DOWN

Place enough books on the floor to total 4-6 inches tall or use a small step/stair.

Use a wall, railing, or chair for some support.

Slowly step up onto the book/stair sideways with the affected foot. The unaffected foot should be level but not touching the book/step.

Unlock/bend the affected knee and unaffected foot should dip down below the step. Ensure that your affected knee does NOT pass your toes and that you hip/pelvis remains level.

Slowly straighten your knee back up.

*If you can perform 10 repetitions easily, you can progress up to 30 repetitions.

GOAL: 10 repetitions with progression up to 30 repetitions on the affected leg, 3 times a day

3

WALL SLIDES

Begin by standing with your back against a wall; feet shoulder width apart and approximately 12-14 inches away from the wall.
Slowly slide down the wall until you are in a "chair" position. Try to put equal weight on both legs. Ensure that your knees do NOT pass your toes.
Hold for 5 seconds.
Slowly return back to the original position by pressing up through heels rather than front of the foot.

*If you can perform 10 repetitions easily, you can progress up to 30 repetitions.

GOAL: 10 repetitions with progression up to 30 repetitions on the affected leg, 3 times a day

4

CALF RAISES

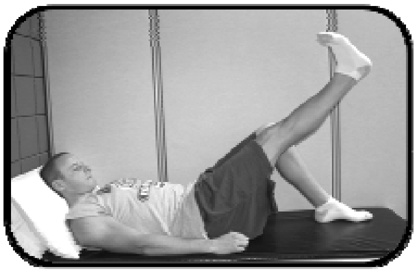
Stand with your legs straight and with even weight bearing.
Hold onto a chair for support and stand on one leg.
Push up onto your toes using your calf muscles to bring your heel off the ground. Do not curl your toes.
Slowly lower your heel back to the original position.

*If you can perform 10 repetitions easily, you can progress up to 30 repetitions.

GOAL: 10 repetitions with progression up to 30 repetitions on the affected leg, 3 times a day

5

STRAIGHT LEG RAISE



Lie on your back.

Straighten your affected leg and have the other knee bent with your foot flat.

While keeping the leg completely straight, slowly raise your leg.

Hold for 5 seconds.

Slowly lower your leg back to the original position.

Repeat this exercise with the opposite leg.

*If you can perform 10 repetitions easily, you can progress up to 30 repetitions.

GOAL: 10 repetitions with progression up to 30 repetitions on each leg, 3 times a day

6

HIP EXTENSION (LYING ON STOMACH)

Lie on your stomach with a pillow positioned under your stomach.

Keep the leg straight and slowly raise your thigh up.

Do not lift high, just enough to clear the surface.

Hold for 5 seconds.

Slowly lower your leg back to the original position.

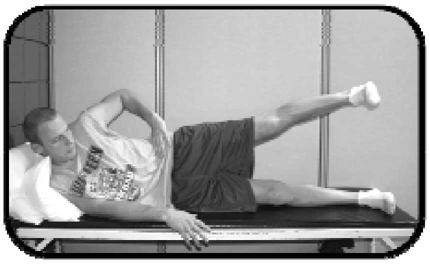
Repeat this exercise with the opposite leg.

*If you can perform 10 repetitions easily, you can progress up to 30 repetitions.

GOAL: 10 repetitions with progression up to 30 repetitions on each leg, 3 times a day

HIP STRENGTHENING

7



HIP ABDUCTION (ON SIDE)

Lie on your side.

Straighten your top and have the lower knee slightly bent.

Slowly lift your leg up without your pelvis rolling forward or backward.

Hold for 5 seconds.

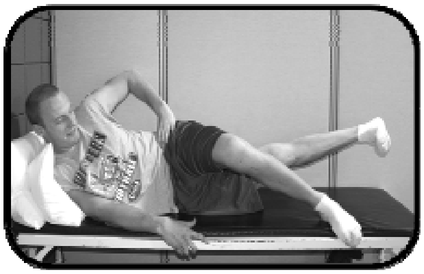
Slowly lower your leg back to the original position.

Repeat this exercise with the opposite leg.

*If you can perform 10 repetitions easily, you can progress up to 30 repetitions.

GOAL: 10 repetitions with progression up to 30 repetitions on each leg, 3 times a day

8



HIP ADDUCTION (ON SIDE)

Lie on your side.

Straighten your bottom leg and have the top knee slightly bent in front of your lower leg.

Slowly raise your bottom leg up toward the ceiling.

Hold for 5 seconds.

Slowly lower your leg back to the original position.

Repeat this exercise with the opposite leg.

*If you can perform 10 repetitions easily, you can progress up to 30 repetitions.

GOAL: 10 repetitions with progression up to 30 repetitions on each leg, 3 times a day

HIP STRENGTHENING – HAMSTRINGS/GLUTS

9

BRIDGE

Lie on your back with your arms at your sides.
Place your feet shoulder width apart on a chair or bed with your knees and hips bent to 90°.
Slowly press heels into the chair or bed, tightening your buttocks and lifting them off the floor while keeping your pelvis level. Try not to press down with your arms into the floor.
Hold for 5 seconds.
Slowly relax and lower pelvis to the original position.

GOAL: 30 repetitions, 3 times a day

OTHER – BALANCE AND ICE

10

SINGLE LEG STANCE

Stand on one leg without support and look forward. Try to maintain your balance for 30 seconds on the affected leg.

*If you can perform 5 repetitions easily with your eyes open, you can progress up to having your eyes closed.

GOAL: 5 repetitions with progression to eyes open and closed, 3 times a day

11

ICE WITH KNEE IN EXTENSION

After completing all your exercises, place an ice pack on top of the affected knee. You may also place an additional ice pack over your shin area if it is sore.
Ensure that the knee is as straight as possible.

*It is important to make sure a towel or pillow is not placed underneath the knee.

GOAL: 15 minutes, 3 times a day, after exercises

OTHER – ADDITIONAL EXERCISES

12

STATIONARY BIKE, ELLIPTICAL

Set the seat height so that your knee is almost straight when the pedal is at the bottom. You may add some resistance to the bike to your tolerance.

GOAL: 10-20 minutes

Curriculum Vitae

Name: Sheila S. Gagnon (née Kocay)

Post-secondary Education and Degrees:

University of Manitoba
Winnipeg, Manitoba, Canada
2001 - 2006 B.Kin.

University of Jyväskylä
Jyväskylä, Finland
2008 - 2010 M.Sc.

University of Western Ontario
London, Ontario, Canada
2010 – 2020* Ph.D.
* Maternity leaves: 2012-2013; 2014-2015; 2016; Leave of Absence 2018-2019

Honours and Awards:

Health and Rehabilitation Sciences Graduate Student Travel Award, Western University
2014, 2016, 2017

Faculty of Health Sciences Student Conference Travel Award
Western University
2016, 2017

Ontario Graduate Scholarship
2013 – 2014

Society of Graduate Students' Bursary
Western University
2014

Joint Motion Program (JuMP) Trainee: CIHR Strategic Training Program in Musculoskeletal Health and Research Leadership
2010 – 2017 (no funding during maternity leaves)

Western Graduate Research Scholarship
2010 – 2017 (no funding during maternity leaves)

US Army Research Institute of Environmental Medicine
Certificate of Appreciation
2009

University of Manitoba Bisons Soccer Canadian Inter-University Sport Athletic Award
2005 – 2006

CIS Academic All-Canadian, University of Manitoba Bisons Soccer)
2005 – 2006

Faculty of Kinesiology and Recreation Management Dean’s Honour List, University of Manitoba
2003 – 2004, 2005 – 2006

University of Manitoba Bisons Hockey CIS Athletic Award
2002 – 2003

University of Manitoba Employee’s Scholarship
2001 - 2006

Related Work Experience

Sessional Instructor
School of Human Kinetics, Laurentian University
PHED 2116 Biomechanics (2020)
PHED 2506 Physiology I (2020)
EDPH 1506 Anatomie et kinésiologie I (2016 – 2017, 2020)
PHED 1506 Anatomy and Kinesiology I (2018)
PHED 1507 Anatomy and Kinesiology II (2019)
EDPH 2507 Physiologie II (2017)
EDPH 1006 Science de l’exercice (2016 – 2017)
2016 – present

Laboratory Technologist
School of Human Kinetics, Laurentian University
2017 – 2018

Biomechanics Researcher and Research Assistant
Wolf Orthopaedic Biomechanics Laboratory, Western University
2010 – 2020*

Instructor and Lab Demo, Western University
MSK 9100 Musculoskeletal Health Research
2013 – 2014

Teaching Assistant
School of Physical Therapy, Western University
PT 9707 Functional Anatomy
PT 9535 Rehabilitation II
2011

Exercise and Thermophysiology Research Assistant
Finnish Institute of Occupational Health, Oulu, Finland
2010 – 2011

Student Researcher, Assistant Project Leader, Editor
Department of Biology of Physical Activity, University of Jyväskylä, Finland
2009 – 2010

Editor
Faculty of Kinesiology and Recreation Management, University of Manitoba
2009

Exercise and Environmental Physiology Research Assistant
Laboratory for Exercise and Environmental Medicine, University of Manitoba
2006

Lab Instructor and Demonstrator
Faculty of Kinesiology and Recreation Management, University of Manitoba
PHED 3430 Exercise Physiology
PHED 2320 Human Anatomy
PHED 2310 Kinesiology
2005 – 2008

Head Strength and Conditioning Coach
CIS Bison Sports: Bison Women’s Soccer
2007 - 2008

Certified Fitness Consultant and Personal Trainer
Bison Sport and Active Living, University of Manitoba
2005 – 2008

Teaching Assistant
Faculty of Kinesiology and Recreation Management, University of Manitoba
PHED 1500 Foundations of Physical Education and Exercise Science
PHED 1200 Physical Activity, Health and Wellness
2005 – 2008

Research Output Overview:

Peer-reviewed journal articles	12	Peer-reviewed published abstracts	8
Conference proceedings	26	Published books	2
Theses	1	Invited talks	4

Publications:

1. Nindl BC, Ahtiainen J, **Gagnon SS**, Taipale RT, Pierce JR, Martin BJ, Beckner ME, Lehti M, Häkkinen K, Kyröläinen K. (2020). Microdialysis-assessed exercised muscle reveals localized and differential IGFBP responses to unilateral stretch shortening cycle exercise. *Frontiers in Endocrinology: Translational Endocrinology,* doi: 10.3389/ fendo.2020.00315

2. Taipale RS, **Gagnon SS**, Ahtiainen JP, Häkkinen K, Kyröläinen H, Nindl BC. (2019). Active recovery shows favourable IGF-I and IGF binding protein response following heavy resistance exercise compared to passive recovery. *Growth Hormone & IGF-I Research.* 48-49:45-52. doi: 10.1016/j.ghir.2019.09.001

3. **Gagnon SS**, Nindl BC, Vaara JP, Santtila M, Häkkinen K, Kyröläinen H. (2018). Basal endogenous steroid hormones, sex hormone-binding globulin, physical fitness and health risk factors in young adult men. *Frontiers in Physiology.* 9(1005):1-12. doi: 10.3389/fphys.2018.01005

4. Taipale RS, Kyröläinen H, **Gagnon SS**, Nindl BC, Ahtiainen J, Häkkinen K. (2017). Active and passive recovery influence responses of luteinizing hormone and testosterone to a fatiguing strength loading. *European Journal of Applied Physiology.* doi: 10.1007/s00421-017-3753-3

5. Koskinen SOA, Kyröläinen H, Flink R, Selänne HP, **Gagnon SS**, Ahtiainen JP, Nindl BC, Lehti M. (2017). Human skeletal muscle type I fibre distribution and response of stress sensing proteins along the titin molecule after submaximal exhaustive exercise. *Histochemistry and Cell Biology.* doi: 10.1007/200418-017-1595-z

6. **Gagnon SS**, Birmingham TB, Chesworth BM, Bryant DM, Werstine M, Giffin JR. (2017). Development of a clinician-rated drop vertical jump scale for patients undergoing rehabilitation after ACL reconstruction: A Delphi approach. *Journal of Orthopaedic and Sports Physical Therapy.* 47(8):557-564. doi:10.2519/jospt.2017.7183

7. Gagnon DD, Peltonen JE, Rintamäki H, **Gagnon SS**, Herzig KH, Kyröläinen H. (2017). Cold ambient temperature and whole-body cooling on skeletal muscle oxygenation during exercise. *Journal of Sports Sciences.* doi: 10.1080/02640414.2016.1245436

8. Gagnon DD, **Gagnon SS**, Rintamäki H, Törmäkangas T, Puukka K, Herzig KH, Kyröläinen H. (2014). The effects of cold exposure on leukocytes, hormones, and cytokines during acute exercise in humans. *PLoS ONE.* 9(10): e110774

9. Gagnon DD, Rintamäki H, **Gagnon SS**, Oksa J, Porvari K, Cheung SS, Herzig KH, Kyröläinen H. (2014). Low-intensity shivering does not affect fuel selection during short term submaximal exercise in the cold. *Applied Physiology, Nutrition and Metabolism.* 39: 282-291 doi: 10.1139/apnm-2013-0061

10. Gagnon DD, Rintamäki H, **Gagnon SS**, Cheung SS, Herzig KH, Porvari K, Kyröläinen H. (2013). Cold exposure enhances fat utilization but not non-esterified fatty acids, glycerol or catecholamines availability during submaximal walking and running. *Frontiers in Exercise Physiology.* doi: 10.3389/fphys.2013.00099

11. Vaara JP, Kyröläinen H, Niemi J, Ohrankämmen O, Häkkinen A, **Kocay S**, Häkkinen K (2012). Associations of maximal strength and muscular endurance test scores with cardiorespiratory fitness and body composition. *Journal of Strength and Conditioning Research.* 26(8): 2078-2086

12. Pretorius T, Cahill F, **Kocay S**, Giesbrecht GG (2008). Shivering heat production and core cooling during head-in and head-out immersion in 17 degrees C water. *Aviation Space and Environmental Medicine.* 79(5): 495-499

In Preparation:

1. **Gagnon SS**, Birmingham TB, Leitch KM, Dickey J, Bryant DM, Giffin RJ. Test-retest reliability and longitudinal validity of drop vertical jump biomechanics during rehabilitation after ACL reconstruction. *JOSPT*

2. **Gagnon SS**, Birmingham TB, Bryant DM, Leitch KM, Alcock G, Werstine M, Litchfield R, Willits K, Getgood A, Giffin JR. A randomized trial of a staged home-based and in-clinic rehabilitation programs after anterior cruciate ligament reconstruction: biomechanical and functional outcomes. *AJSM*

Published Abstracts:

1. **Gagnon SS**, Birmingham TB, Remtulla A, Bryant D, Giffin JR. (2017). Reliability of frontal and sagittal plane knee kinematics and kinetics during jump landing after ACL reconstruction. *Canadian Society for Exercise Physiology Back to the Beginnings,* Supplement p62.

2. **Gagnon SS**, Birmingham TB, Chesworth BM, Bryant D, Giffin JR (2016). Development of a clinician rated drop vertical jump scale for patients undergoing rehabilitation after ACL reconstruction. *Medicine and Science in Sports and Exercise,* 48:5 Supplement.

3. Nindl BC, Ahtiainen J, **Gagnon SS**, Taipale RS, Pierce JR, Lehti M, Häkkinen K, Kyröläinen H (2016). Microdialysis-assessed exercised muscle reveals localized and differential IGFBP responses to unilateral stretch-shortening exercise until exhaustion. *Medicine and Science in Sports and Exercise,* 48 Supplement.

4. Kyröläinen H, Lehti M, Ahtiainen J, **Gagnon SS**, Nindl BC (2016). MHC isoforms are associated with acute neuromuscular performance changes induced by prolonged jumping exercise. *Medicine and Science in Sports and Exercise,* 48: Supplement.

5. Gagnon DD, Herzig K-H, Rintamäki H, **Gagnon SS**, Kyröläinen H (2014). Immuno-modulation of combined cold exposure and exercise on leukocyte, endocrine and cytokines responses in humans. *Acta Physiologica* 211 (Suppl 696), p 99.

6. Gagnon DD, Kyröläinen H, **Gagnon SS**, Herzig K-H, Rintamäki H, Peltonen J. (2014). Pre-exercise whole-body cooling decreases blood volume and oxygenated hemoglobin content in skeletal muscle during submaximal exercise. *FASEB* 28 (Suppl 1) 1106.7.

7. Gagnon DD, Herzig K-H, Rintamäki H, **Gagnon SS**, Kyröläinen H. (2012). Acute neuro-endocrines responses during combined treadmill exercise and cold stress. *Acta Physiologica* 206 (suppl 691), p 86.

8. **Kocay S**, Nindl BC, Vaara J, Kyröläinen H (2011). Relationship of endogenous steroid hormones and SHBG to body composition, cardiovascular health and physical fitness. *Medicine and Science in Sports and Exercise.* 43(5): 103-104.

Published Books:

1. **Gagnon SS** (2017). Clinician rated drop vertical jump scale: Instruction booklet. *Journal of Orthopaedic & Sports Physical Therapy,* 47(8):C24-C32 Supplement.

2. **Kocay S**, Perrault T, Turcotte K, Ready AE (2008). KIN 3470 Exercise Physiology Laboratory Manual. Faculty of Kinesiology and Recreation Management, University of Manitoba Bookstore, Canada.

Published Theses:

1. **Gagnon SS** (2010). Circulating endogenous steroid hormones, physical performance, body composition, and health outcomes in men. University Library of Jyväskylä, Master’s Thesis.

Presentations at Professional Meetings:

1. **Gagnon SS**, Birmingham TB, Remtulla A, Bryant D, Giffin JR. (2017). Test-retest reliability of peak frontal and sagittal plane knee kinematics and kinetics during jump landing after ACL reconstruction. *Poster Presentation at Canadian Society for*

Exercise Physiology's 50th Annual General Meeting in Winnipeg, MB, Canada. October 25 – 28

2. **Gagnon SS**, Birmingham TB, Chesworth BM, Bryant D, Giffin JR (2016) Development of a clinician rated drop vertical jump scale for patients undergoing rehabilitation after ACL reconstruction. *Podium Presentation at American College of Sports Medicine 63rd Annual Meeting and 7th World Congress on Exercise is Medicine and World Congress on the Basic Science of Energy Balance in Boston, MA, USA June 4*

3. Nindl BC, Ahtiainen J, **Gagnon SS**, Taipale RS, Pierce JR, Lehti M, Häkkinen K, Kyröläinen H (2016) Microdialysis-assessed exercised muscle reveals localized and differential IGFBP responses to unilateral stretch-shortening exercise until exhaustion. *Debated Poster Presentation at American College of Sports Medicine 63rd Annual Meeting and 7th World Congress on Exercise is Medicine and World Congress on the Basic Science of Energy Balance in Boston, MA, USA May 31 – June 4*

4. Kyröläinen H, Lehti M, Ahtiainen J, **Gagnon SS**, Nindl BC (2016) MHC isoforms are associated with acute neuromuscular performance changes induced by prolonged jumping exercise. *Poster Presentation at American College of Sports Medicine 63rd Annual Meeting and 7th World Congress on Exercise is Medicine and World Congress on the Basic Science of Energy Balance in Boston, MA, USA May 31 – June 4*

5. **Gagnon SS**, Birmingham TB, Remtulla A, Bryant D, Giffin JR (2015) Test-retest reliability of frontal plane knee kinematics and kinetics during jump landing in patients after ACL reconstruction.
    i. *Poster Presentation at International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine, Lyon, France, June*
    ii. *Poster Presentation at Faculty of Health Sciences Research Day, University of Western Ontario, London, Ontario, March 25 (2014)*

6. **Gagnon SS**, Birmingham TB, Chesworth BM, Bryant D, Giffin JR (2014) A Delphi study to establish consensus on the content and scoring of a clinician rated jump landing scale for patients undergoing rehabilitation after ACL reconstruction. *Poster Presentation*
    i. *Poster Presentation at Faculty of Health Sciences Research Day, University of Western Ontario, London, Ontario, March 25*
    ii. *Podium Presentation at the 16th Research Colloquium in Rehabilitation, School of Physical and Occupational Therapy, McGill University, May 2 *Accepted for podium presentation but I had to decline due to maternity leave*
7. **Gagnon SS**, Birmingham TB, Remtulla A, Bryant D, Giffin JR (2014). Test-retest reliability of frontal plane knee kinematics and kinetics during jump landing in patients after ACL reconstruction: preliminary findings. *Poster Presentation at 3D Analysis of Human Movement Conference, Lausanne, Switzerland, July *Accepted for poster presentation but I had to decline due to maternity leave*

8. Gagnon DD, Herzig K-H, Rintamäki H, **Gagnon SS**, Kyröläinen H (2014) Immunomodulation of combined cold exposure and exercise on leukocyte, endocrine and cytokine responses in humans.
    i. *Poster (Debated) at the 2014 Scandinavian Physiological Society Annual Meeting, Stockholm, Sweden, August 21-24*
    ii. *Poster at the 15th International Symposium: Exercise Physiology, Jyväskylä, Finland, November 19-21*
    iii. *Poster at the 12tth of the campus Kontinkangas at The University of Oulu, Oulu, Finland, February 17 (2015)*

9. Gagnon DD, Peltonen J, **Gagnon SS**, Rintamäki H, Herzig K-H, Kyröläinen H (2014). The effects of ambient temperature and whole-body cooling on skeletal muscle oxygenation during aerobic exercise. *Poster Presentation at the International 22nd Puijo Symposium, Kupio, Finland, June 24-28*

10. Gagnon DD, Kyröläinen H, **Gagnon SS**, Herzig K-H, Rintamäki H, Peltonen J (2014). Pre-exercise whole-body cooling decreases blood volume and oxygenated hemoglobin content in skeletal muscle during submaximal exercise. *Poster Presentation at 2014 Experimental Biology, San Diego, CA, USA, April 26-30*

11. Gagnon DD, **Gagnon SS**, Rintamäki H, Karhu T, Kyröläinen H, Herzig K-H (2013). Effects of acute exercise on cytokine and immuno-endocrine responses at different ambient temperatures. *Poster Presentation (Debated) at the 18th Annual Congress of the ECSS, Barcelona, Spain, June 27*

12. Gagnon DD, Kyröläinen H, **Gagnon SS**, Herzig K-H, Rintamäki H (2013). Whole-body cooling modulates skeletal muscle oxygenation during aerobic exercise. *Poster Presentation at the International Union of Physiological Societies, Birmingham, UK, July 27*

13. Gagnon DD, Herzig K-H, Rintamäki H, **Gagnon SS**, Kyröläinen H (2012). Acute neuro-endocrine responses during combined treadmill exercise and cold stress. *Podium Presentation at the Annual Scandinavian Physiology Society Meeting, Helsinki, Finland, August 25*

14. Gagnon DD, Rintamäki H, **Gagnon SS**, Herzig K-H, Kyröläinen H (2012). Effects of cold exposure on energy metabolism during submaximal exercise. *Poster Presentation (Debated) at the 7th Annual Congress of the ECSS, Bruges, Belgium, July 5*

15. Gagnon DD, Kyröläinen H, Herzig K-H, **Gagnon SS**, Rintamäki H (2012). Effects of low-intensity shivering on energy metabolism during exercise in the cold. *Podium Presentation at the 17th Annual Congress of the ECSS, Bruges, Belgium, July 5*

16. Vaara JP, Kyröläinen H, Niemi J, Ohrankämmen O, Häkkinen A, **Kocay S**, Häkkinen K (2012). Maksimivoiman- ja lihasketävyystestien sekä kehon koostomuksen ja hapenottokyvyn yhteydet. "Associations of maximal strength and muscular endurance

test scores with cardiorespiratory fitness and body composition." *Poster Presentation at Kuntotestauspäivät, Metropolia Ammattikorkeakoulu, Helsinki, Finland, March 21*

17. Remtulla A, **Gagnon SS**, Giffin JR, Bryant D, Birmingham TB, Werstine M, Alcock G (2012). Does usual rehab result in better outcomes than staged rehab post ACL surgery?
    i. *Podium Presentation at Western Research Forum, University of Western Ontario, London, Ontario, March*
    ii. *Poster at Health and Rehabilitation Sciences Graduate Research Forum, University of Western Ontario, London, Ontario, February*
    iii. *Poster at Aging, Rehabilitation and Geriatric Care / Faculty of Health Sciences Symposium, Parkwood Hospital, London, Ontario, February*

18. Remtulla A, **Gagnon SS**, Giffin JR, Bryant D, Birmingham TB, Werstine M, Alcock G (2011). A comparison between usual and staged rehabilitation programs post ACL reconstruction. *Podium Presentation at the 28th Western Homecoming Sport Medicine Symposium: "Musculoskeletal Care of the Mature Athlete", London, Ontario, September 30*

19. **Kocay S**, Nindl BC, Vaara J, Kyröläinen H (2011). Relationship of endogenous steroid hormones and SHBG to body composition, cardiovascular health and physical fitness. *Podium Presentation at the American College of Sports Medicine 58th Annual Meeting and 2nd World Congress on Exercise is Medicine, Denver, Colorado, USA, June 1*

20. **Kocay S**, Birmingham TB, Bryant D, Werstine M, Giffin JR (2011). Reliability and sensitivity to change of 3D motion analysis tests of jumping after anterior cruciate ligament reconstruction: a proposal. *Poster Presentation at the CIHR Joint Motion Training Program in Musculoskeletal Health Research and Leadership: 2nd Annual Retreat, London, Ontario, May 13 & 14*

Invited Talks:

1. **Gagnon SS.** Guest lecturer for EDPH1006 Science de l'exercice. September 7, 2017.

2. **Gagnon SS.** Guest lecturer for PHED2507 Physiology II lectures about the digestive system. March 13 and 16, 2017.

3. **Gagnon SS**, Remtulla A, Birmingham TB, Giffin JR, Alcock G, Werstine M, Bryant D (2013). A randomized trial of different rehabilitation strategies after ACL reconstruction: Clinical and biomechanical outcomes. Podium Presentation at the Fowler Kennedy 30th Annual Homecoming Sport Medicine Symposium, London, Ontario

4. **Kocay S** (2011). Motion analysis techniques in rehabilitation sciences: Implications for knee osteoarthritis. Podium Presentation at Canadian Arthritis Network's Canadian Arthritis Research Exchange Seminar (CAN Cares), London, Ontario