UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences
Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

Changes in countermovement jump performance and the force-time waveform after anterior cruciate ligament reconstruction

by

Cassidy de Franca

A dissertation submitted in partial fulfilment of the requirements for the degree MSc Sports Science (Biomechanics)

Division of Biokinetics and Sport Science
Department of Physiology
Faculty of Health Sciences
University of Pretoria

Supervisor: Dr Helen Bayne
Co-supervisor: Dr Matthew Jordan

2022

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

PLAGIARISM DECLARATION

Full Name: Cassidy de Franca

Student number: 14450161

Degree: MSc Sport Science (Biomechanics)

Title of thesis: **Changes in countermovement jump performance and the force-time waveform after anterior cruciate ligament reconstruction.**

I declare that this thesis/dissertation is my own original work. Where secondary material is used, this has been carefully acknowledged and referenced in accordance with university requirements.

I understand what plagiarism is and am aware of university policy and implications in this regard.

Signature:  Date: 2 December 2022

ACKNOWLEDGEMENTS

I wish to extend my deepest appreciation to the following people and institutions, without whose assistance and support this dissertation would have been impossible:

Dr H. Bayne, my supervisor, Department of Physiology, University of Pretoria, for her commitment, thoughtful honesty, encouragement, patience, and the pool of knowledge she offers so willingly.

Dr M. Jordan, my co-supervisor, Faculty of Kinesiology, Sport Medicine Centre, University of Calgary, for his dedication, expertise, enthusiasm, and helpfulness in supervising this study.

Mrs T. Botha, Department of Statistics, University of Pretoria, for her valuable assistance and advice in the analysis of data for this study.

Division of Biokinetics and Sport Science, Department of Physiology, University of Pretoria, for providing the platform and resources to complete this study.

Sport, Exercise Medicine, and Lifestyle Institute (SEMLI), University of Pretoria, for their support and resources to complete this study.

To my family, Adriano, for your unwavering love, support, encouragement and generous offer of your time and data analyst skills; Grobler's and de Franca's, for your love, support, and willingness to help in multiple ways.

TABLE OF CONTENTS

List of symbols and abbreviations

ACL	Anterior cruciate ligament
ACLR	Anterior cruciate ligament reconstruction
BMI	Body Mass Index
BPTB	Bone-patellar tendon bone – autograft technique
BW	Bodyweight
cm	centimetre
CMJ	Countermovement jump
e.g.	For example
GRF	Ground reaction force
HT	Semitendinosus or gracilis hamstring tendon – autograft technique
i.e.	in other words
IKDC	International Knee Documentation Committee scores
kg	kilogram
kg/m^2	kilograms per metres squared
L	Left
m	metre
MET	Metabolic Equivalent Score
m/s	Metres per second
min	minute
ms	milliseconds
N	Newtons
Non ACLR	Non anterior cruciate ligament reconstructed athlete/limb

Ns	Newton seconds
Ns/kg	Newton seconds per kilogram
R	Right
RFD	Rate of force development
RFD/BW	Rate of force development relative to bodyweight
ROM	Range of motion
RSImod	Modified reactive strength index
RTP	Return to play
s	second
SPM	Statistical parametric mapping
SSC	Stretch shortening cycle
HT	Hamstrings tendon graft
W/kg	Watts per kilogram
%/BW	Percentage relative to bodyweight
^{o}	degrees
^{o}trans	Knee joint angle at the transition between braking and propulsive jump phases
>	More than
<	Less than
~	Approximately

List of figures

List of tables

Abstract

Title: Changes in countermovement jump performance and the force-time waveform after anterior cruciate ligament reconstruction

Anterior cruciate ligament (ACL) ruptures pose a substantial injury burden on athletes. Surgery (ACLR) is commonly recommended after ACL rupture. Only a small fraction of athletes return to pre-injury performance levels after ACLR with a high risk of non-contact re-injury. Significant functional impairments and altered movement patterns occur following ACLR which may further increase the risk of future re-injury. Objective return to play protocols are not well established after ACLR with traditional hop tests showing insufficient sensitivity for detecting compensatory movement patterns. The countermovement jump (CMJ) is a common neuromuscular test after ACLR, and bilateral force production is frequently measured on a dual force platform. Athletes with ACLR demonstrate significantly poorer jump performance post ACLR in the CMJ test, specifically within the braking and propulsive phases. However, limitations of these studies include the isolated use of discrete or CMJ phase-specific metrics to measure performance after ACLR instead of assessing the force-time data across the entire jump movement. Between-limb asymmetry indices are also used to quantify differences between involved and uninvolved limbs, but this may lead to a false positive indication of readiness given that ACLR impacts the strength of the uninvolved limb. Pre-injury data, CMJ force-time curve waveform analysis, and a longitudinal study design can help to address these gaps and develop new knowledge surrounding return to play protocols. This study therefore aimed to assess differences in CMJ force production before and after ACLR utilising traditional performance and asymmetry measures and statistical parametric mapping (SPM) analysis throughout an athlete's rehabilitation up to two years post-surgery.

Twenty (age = 21.6 ± 3.8 years) competitive athletes from alpine skiing, freestyle skiing, football, ski jump, and wrestling performed the CMJ as part of routine testing and monitoring before and after ACLR over a five year study period. Dual force plates measured the ground reaction force (GRF), and these force-time data were analysed using the Shiny vertical jump analysis app (https://github.com/mattsams89/shiny-vertical-jump) in RStudio. The difference in time between surgery and testing was calculated and stratified into five time intervals: pre-injury (T0), 24 ± 3 weeks (T1), 36 ± 3 weeks (T2), 48 ± 3 weeks (T3), and between 72 – 100 weeks (T4) after surgery. Traditional measures of jump performance and asymmetry were assessed using paired sample t-tests. SPM analysed differences in the continuous force-time data between the involved and uninvolved limbs at each of the post-surgical time periods and compared the involved limb to itself post-surgically to pre-surgical baseline testing values.

Results showed that, compared to pre-injury baseline values, traditional discrete jump performance outcomes (jump height, contact time, RSImod) were decreased after ACLR, with lower peak force production for the involved limb and greater peak force asymmetry at six months post ACLR. Traditional discrete CMJ phase metrics showed lower impulse production of the involved limb after surgery up until one-year post-ACLR, although this was not statistically significant. There was a significant increase in braking impulse asymmetry at two years post ACLR compared to pre-injury values, favouring the involved limb. Propulsive impulse production was lower for the involved limb versus pre-injury baseline ~ two years after surgery, versus the uninvolved limb up to nine months post-surgery and showed greater asymmetry six months after surgery. SPM analysis confirmed that for the continuous force-time data, the involved limb had a lower unweighting and propulsive impulse production compared to pre-injury baseline values at six months post ACLR and showed a lower propulsive impulse production of the involved limb versus the uninvolved limb at six months and at two years after surgery compared to pre-injury baseline values.

It is hoped that the results from this study contribute to the knowledge surrounding return to play protocols after ACLR and help inform practitioners with new evidence to promote a safer return to sport past traditionally determined return to play timelines.

Key words: Anterior cruciate ligament, countermovement jump, force-time curve, knee injury, statistical parametric mapping.

Chapter 1

1. Introduction

Anterior cruciate ligament (ACL) ruptures cause a significant injury burden for athletes due to their severity and prevalence, particularly for female athletes, amateur sporting groups and within multidirectional team sports.[1-4] ACL ruptures lead to the most days lost to sport participation post-injury compared to other injury types[2,5-6] and after ACL rupture, surgical reconstruction is commonly recommended (ACLR).[4,7-10] Return to play typically takes between six and 12 months, but two-thirds of athletes may not reach their pre-injury performance level within one year after surgery, often with only a fraction of athletes returning to their pre-injury performance levels at all.[11-12] ACLR athletes show altered movement patterns and significant differences between the involved and uninvolved limbs up to two years post-surgery, which may increase the risk of future ACLR non-contact re-injury.[3,13-15,16]

Functional performance is hampered following surgery[3,17-18] and a loss of neuromuscular strength capacity is seen as a decrease in lower limb maximal and explosive strength of the involved limb which may cause increased interlimb asymmetries[14,16,18-21] as well as altered lower limb biomechanics compared to uninjured athletes.[3,22-24] Optimally, athletes aim to restore neuromuscular function and pre-injury performance levels to support a safe return to sport.[14,20] However, effective return to play measures post ACLR are not well established[14,25-27] with the majority of the literature focusing on cross-sectional measures examining knee function with a lack of longitudinal monitoring throughout rehabilitation to guide these return to play measures.[13,28]

The countermovement jump (CMJ) is a coupled eccentric-concentric stretch shortening cycle (SSC) movement and is widely used to evaluate neuromuscular capacities,[29] performance fatigability,[30] the rate of force development (RFD), and importantly reactive strength capacity after ACLR.[14] The CMJ may be performed on dual force plates to measure the ground reaction force (GRF) produced by each limb and has become a commonly used performance and rehabilitation test.[14,29-31] Primarily, jump height is used to quantify CMJ performance, which is determined by the net impulse (area under the force-time curve) produced across the three phases of the CMJ (unweighting, braking and propulsive phases).[31-32] Although discrete variables (single time point measures of performance such as peak force, the ratio of jump height to time to take off and force at zero velocity) and CMJ phase-averaged metrics (phase durations, average phase force production) are the most commonly used metrics, sole use of these metrics may result in the loss of important information regarding vertical force production during the CMJ.

ACLR athletes experience impairment to overall CMJ performance due to reduced muscular strength[14,20,21,33] and neuromuscular function, primarily the stretch shortening cycle.[1,13,17] More specifically, discrete performance variables that decrease after ACLR include: jump height, peak force, peak external mechanical power and force at the lowest point of the CMJ.[1,20,34] Additionally, CMJ phase-specific impairments after ACLR include decreased propulsive impulse and propulsive peak force, braking impulse and braking RFD.[13-14] Lower force production of the involved limb in comparison to the uninvolved limb and greater interlimb asymmetries have also been consistently reported, in particular during the braking and propulsive phases of the CMJ.[3,13-15,28,35-36] These interlimb asymmetries have been shown to remain from four months up to four years post ACLR,[1,13-14,20,28,33-34] despite adherence to rehabilitation programs compared to non-injured athletes.[13]

Interlimb asymmetries after ACLR can be seen as directional shifts throughout the CMJ force-time curve between the involved and uninvolved limb (Figure 1). This emphases the importance of identifying when during the CMJ (unweighting, braking or propulsion) the asymmetry occurs.[14] This suggests that ACLR may cause changes in the shape of the force-time curve, rather than only at discrete points or phase averaged periods, and the CMJ should be analysed in its entirety.[1,14] This may identify compensatory movement strategies used and prominent points in time where interlimb asymmetries or performance deficits exist during the jump,[31]

Recently, it has been suggested to include pre-injury baseline measures as a method of comparison to the involved limb instead of, or at least in addition to, calculating an asymmetry index between limbs using the benchmark of the non-injured contralateral limb.[37-38] This is due to the emergence of strength deficits in the uninvolved limb post ACLR and potentially underestimating the magnitude of loss of functional performance of the involved limb versus actual pre-injury levels of performance.[37-39]

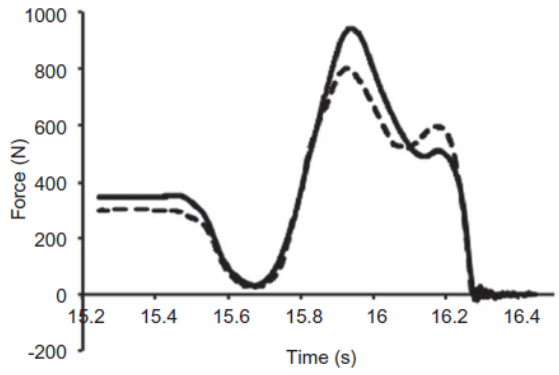

Figure 1: Force-time curve of an ACLR skier's ACLR limb (solid line) and uninjured limb (dashed line) during a CMJ showing a change in the directionality of asymmetry throughout the jump between limbs.[14]

It is recommended to analyse the CMJ after ACLR using a combination of discrete performance (outcome measures) and strategy variables (biomechanical metrics underpinning CMJ performance) in combination with assessment of the shape of the force-time curve. This allows an analysis of entire CMJ waveform, and this combination approach may provide a more complete picture of potential differences in vertical force production. Continuous analysis has been used in become more common in jump analysis, However, no study to date has included statistical analysis of the continuous CMJ force-time waveform in ACLR athletes.

2. Research problem

The CMJ has been largely studied in relation to jump performance cross sectionally involving healthy athletes.[29-31,40-42] Fewer studies have examined neuromuscular function after ACLR using discrete or phase averaged variables[13-14,20,28,33] at single time points after surgery with only two known studies undertaking a cross sectional evaluation of discrete CMJ performance and phase metrics at several key clinical milestones after surgery.[7,13] Sole use of discrete metrics may reduce the depth of information available that analysis of the entire CMJ waveform could offer and overlook important information about the drivers of force production during the CMJ after surgery.[31] Predominantly, the interlimb differences between the involved and uninvolved limbs are calculated from these discrete metrics and reported as a percentage difference (asymmetry index) between limbs or compared to control athletes.[1,7,13-14,20,28,33-34] Often, the involved limb is compared to the uninvolved limb at a specific time point post ACLR and not to pre-injury baseline values.[1,7,13-14,20,28,33-34] This may lead to an overestimation of knee function due to strength deficits that the uninvolved limb also displays post-surgery which impacts asymmetry calculations between limbs at specific time points.[37]

The effect of ACLR on force production during the CMJ has therefore not been applied; i) across the entire CMJ force-time waveform, ii) comparatively to pre-injury baseline values, or iii) longitudinally to determine a more objective assessment of force production capacity after surgery.

3. Aim and objectives

The aim of this study was to investigate changes in CMJ performance, vertical GRF production and interlimb asymmetry in ACLR athletes over ~2 years post ACLR through analysis of the CMJ force-time waveform using statistical parametric mapping.

The objectives of this research study were to:

- Investigate changes in discrete CMJ performance measures and traditional measures of asymmetry from pre-injury to four post-surgery time points (~24 weeks, ~36 weeks, ~48 weeks and 72-100 weeks).
- Investigate changes in the CMJ force-time curve of the involved limb from pre-injury to four post-surgery time points (~24 weeks, ~36 weeks, ~48 weeks and 72-100 weeks) utilising statistical parametric mapping.
- Investigate interlimb differences in the CMJ force-time curve at pre-injury and four post-surgery time points (~24 weeks, ~36 weeks, ~48 weeks and 72-100 weeks) utilising statistical parametric mapping.

4. Structure of the dissertation

The remainder of the dissertation consists of:

- Chapter 2: Review and appraisal of the existing literature surrounding changes in CMJ performance and interlimb asymmetries post ACLR highlighting gaps and pointing to a further area of study.
- Chapter 3: An original research study in manuscript format with introduction, methods, results, and discussion sections.
- Chapter 4: Summary of the study and conclusions drawn from the results, with study limitations and recommendations for future research.

Chapter 2: Literature Review

Introduction

Anterior cruciate ligament injuries

Non-contact anterior cruciate ligament (ACL) rupture occurs frequently in field sports (e.g., football) and slope sports (e.g., alpine skiing), and is a severe traumatic knee injury resulting in a high injury burden.[1-4,43] ACL ruptures account for more than 50% of all knee injuries[2] and the most days lost to sport participation post-injury compared to other injury types.[2,5-6] Return to play times vary across sport types with a mean return to play time of 216 days for professional European soccer players,[8] 258 days in the National Hockey League, 370 days in the National Football League, 418 days in the Major Baseball League and 424 days in the National Basketball League.[9] The ACL injury prevalence in female athletes is 3.5% or 1 in every 29 athletes, and in males is 2% or 1 in every 50 athletes across a variety of sports.[43] Female athletes have an ACL injury incidence rate of 1.5 out of 10 000 athlete-exposures and males of 0.9 out of 10 000 athlete-exposures over 1 season up to 25 years.[43] Surgical reconstruction of a torn ACL is often recommended to restore knee joint stability with approximately 90% of ACL tears undergoing ACLR, which is a common recommendation[4,7,44-45] using either a bone-patellar tendon bone (BPTB) or semitendinosus and gracilis hamstring tendon (HT) autograft technique.[20] Other types of grafts include the quadriceps tendon, allografts and synthetic grafts.[46] Post injury only about 50-60% of athletes return to competitive sport[1] and extensive training and rehabilitation are required after ACLR to restore pre-injury knee function.[1]

Return to the pre-injury level sport is often assumed to take between six and 12 months,[11] however, more recent research shows that the ACLR rehabilitative process may be nonlinear and highly individualised.[12] Studies of professional athletes in pivoting sports such as soccer, hockey, American football, and basketball show rates of return to pre-injury level sport of 78% to 98% within one year post ACLR surgery, however, for amateur athletes, two thirds may not achieve pre-injury level of return to preinjury performance levels within one year.[11,47-54] Additionally, 45% of athletes will not return to their competitive pre-injury performance level at all after an ACL injury.[11-12,45]

Athletes who have ruptured their ACL or undergone ACLR demonstrate significant differences between their injured and uninjured limbs up to two years post ACLR and these altered movement patterns may increase the risk of future non-contact ACL re-injury.[3,13-15,16] There is also an increased risk of developing long-term degenerative knee conditions like osteoarthritis following ACL surgery.[55-56] After ACLR, the injury, graft harvest and period of restricted activity result in reduced neuromuscular capacities.[7] ACLR athletes demonstrate decreased

proprioception,[3] decreased range of motion,[18] decreased maximal lower limb strength (particularly the hamstring and quadriceps muscle groups) and explosive strength (the ability to produce high force in a short period of time) on the ACLR side.[3,17] Compared to individuals without ACL injury, these deficits after surgery often present as increased interlimb asymmetry compared to the contralateral limb,[14,18-21] a loss of functional performance[3,17-18] and altered lower limb biomechanics[3,22-24]. Altered lower limb joint kinematics and kinetics post ACLR compared to pre-injury are seen as increased knee valgus and hip adduction angle (frontal plane movement) compared to baseline values pre-ACLR.[16,57] Altered lower limb joint kinetics include decreased peak internal knee extension moments, decreased peak internal hip flexion moments and decreased peak anterior tibial shear force (sagittal plane movements) during a double leg jump-landing movement.[16,57-58] This decreased sagittal plane loading may be due to decreased quadriceps voluntary activation and strength post-ACLR.[16]

The countermovement jump (CMJ) is a commonly used test in performance testing and return to play assessments.[14,29-31] A majority of research studies examining knee function after ACLR are cross sectional, have relatively small sample sizes (< 20 participants) and examine discrete CMJ performance variables and/or CMJ phase averaged outcomes between ACLR and non ACLR athletes or between injured and uninjured limbs.[13,28] A further limitation of these study designs is that it is not known whether the asymmetry was as a result of surgery or incomplete rehabilitation, a combination of the two, or if it was unrelated and present prior to injury which may have actually contributed to the initial injury itself.[16,57] A comparison of athletes prior to and post injury showed that movement patterns were consistently altered after ACL injury and surgery, despite controlling for graft type, mechanism of injury and rehabilitation program in comparison to remarkably consistent movement patterns pre-injury.[16] This suggests that the cause of altered movement patterns develops after ACL injury and is not present prior to injury. The practical implications of these findings are twofold. First, postinjury movement patterns have been shown to predict future ACL injury in ACLR athletes, which often result from faulty landing, jumping or change of direction mechanics.[59] Known risk factors for ACL injury such as decreased thigh muscle strength, and increased interlimb asymmetries continue following ACLR in spite of rehabilitation efforts and return to normal activities.[14] Second, understanding the force production deficits and risk factors has the potential to optimise rehabilitation programs and provide objective criteria-based testing for return to play after ACL.

Post ACLR, primary rehabilitative objectives are to restore neuromuscular function, establish criteria for a safe return to play and to re-establish pre-injury performance levels.[14,20] The impact of ACL injury on sport performance and athlete health has resulted in

recommendations for ACL injury prevention strategies.[33] However, measures that indicate successful return to play levels after ACLR have not been well established.[14,25-27] To address these gaps, longitudinal athlete monitoring is recommended in order to provide information on individual progression throughout an athlete's rehabilitation process and aid in determining return to play readiness.[12]

Objective measures for criteria-based rehabilitation and return to play

After ACL injury, functional performance tests are recommended to measure an athlete's rehabilitative status,[3,17] guide rehabilitation progression and to assist in decision making for a safer return to play[17] by assessing interlimb asymmetries[3,44,60] and lower limb function.[44,60] These assessment tools often include tests for muscular strength,[3,18-19] running speed,[60] cardiovascular fitness,[60] balance,[60] change of direction ability,[60] hopping[3,18-19,58,60-61] and jumping performance.[14,19,60] Few scientifically supported measures exist to clearly guide return to play after ACLR despite the large injury and re-injury rate.[14] Recent research shows that re-injury rates are reduced by 50% for every month that return to play is delayed up to 9 months post injury[13,62] and that a criterion-based approach in combination with a traditional time-based approach is more favourable to determine return to play readiness.[13,63] For example, de Carlo[63] found that patients who deviated from traditional time-based recommendations and accelerated their progress based on achieving functional milestones gained knee extension range of motion earlier and achieved better outcomes compared to patients who restricted their movement and adhered to time-based criteria. Notably, these patients started weight bearing and gained range of motion (ROM) sooner, increased their muscle strength and demonstrated greater functional capability of the knee in later stages of rehabilitation, leading to clinical support for a criterion or 'movement goal' based approach to ACL rehabilitation.[63]

The combination of single leg hop tests and isokinetic dynamometry for the knee flexors and knee extensors comprise the traditional clinical assessment test battery to determine return to play readiness, with the achievement of 90% limb symmetry compared to the contralateral limb as a threshold of sufficient recovery to recommend a return to play.[58,64] However, single leg hop tests ignore the joint-level biomechanics including the relative contribution of the hip, knee and ankle joints of the affected limb and therefore limit the sensitivity of this test for detecting compensatory biomechanical movement patterns like chronic knee extensor weakness that occurs readily after ACL injury.[13,20,57] Further, isokinetic dynamometry is limited to only measuring strength deficits at a range of fixed speeds (usually an angular velocity of 60 or 180 degrees per second) and a uniplanar joint motion of knee flexion and extension within a set range of motion (e.g. zero to 100 degrees).[20] Consequently, additional dynamic testing methodologies like the CMJ and drop jump test performed on single and dual force

plate systems have been explored to bolster return to play testing. Although isokinetic dynamometry has limitations, it remains a sensitive measure to detect residual deficits after ACL injury.[25] A combination approach of isokinetic dynamometry, CMJ testing and other dynamic lower limb testing may more accurately detect deficits after ACLR compared to the use of a single testing method. The CMJ, performed on dual force platforms, not only provides jump outcome measures but also detects the athlete's bilateral force production capabilities across phases of the jump which allows for more specific analysis of performance or asymmetry differences post injury.[65] Overall, traditional tests that only measure jump performance outcomes like height or distance may provide a false indication of readiness to return to play because they do not examine the biomechanical underpinnings of the performance. The CMJ is a sensitive tool for detecting differences in interlimb force production after ACL injury and may successfully address the limitations posed by traditional test batteries.

The countermovement jump test

The CMJ is a popular assessment of slow SSC movements,[14] practically used to assess athletic performance changes,[30-31] neuromuscular capabilities,[29] and performance fatigability.[30] As jumping is a proximal to distal movement sequence, the CMJ is able to assess knee extensor maximal muscle power, the rate of force development (RFD), and reactive strength capacity after ACLR.[14] The period from movement initiation to take-off in the CMJ is typically divided into three phases (Figure 2) based on the GRF produced during the jump and the associated vertical motion of the centre of mass. The GRF is related to knee kinetics which point to the usefulness for measuring athletes after ACLR. The unweighting phase occurs from initiation of the countermovement until GRF returns to bodyweight, which corresponds with the peak negative centre of mass velocity.[65] The braking phase then begins, as GRF exceeds bodyweight, until the instant the centre of mass velocity reaches 0 m/s.[65] This is the lowest point of the centre of mass. The propulsion phase starts when centre of mass velocity is positive and ends at the instant of ground take-off.[65] The primary performance outcome of the CMJ is jump height, which is determined by the net impulse produced between initiation and take-off.[29]

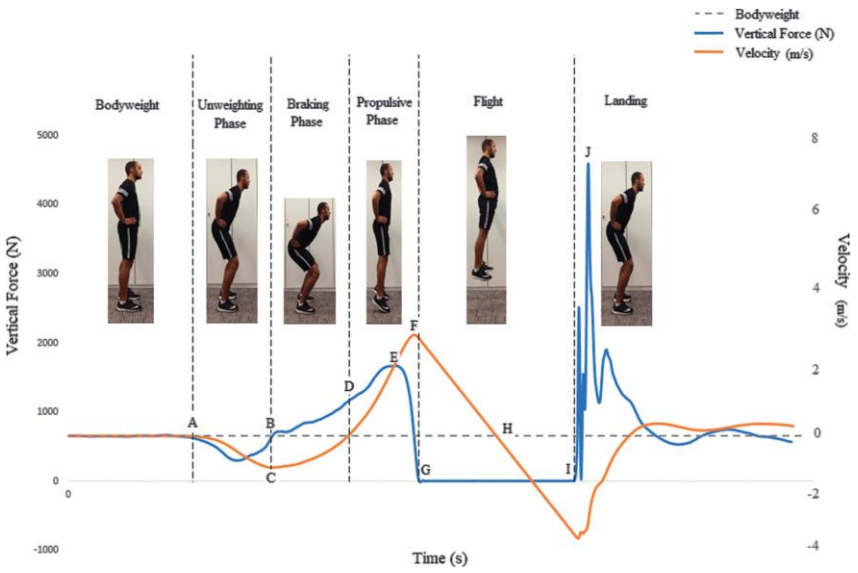

Figure 2: Vertical force-time curve illustrating the six different phases of the CMJ. Adapted from Chavda et al.[30]

Higher jump heights are achieved by increasing the body centre of mass velocity at take-off, which is determined by the kinetic impulse (area under the force-time curve) according to the impulse-momentum relationship. Although the net positive impulse that ultimately determines jump height occurs during the propulsion phase, this outcome is heavily influenced by force production during the preceding phases and the jump strategy of the athlete.[31] Understanding the way in which force is produced or 'how' an athlete jumps may help to inform training and rehabilitation recommendations for practitioners.[29,31] In order to do this, practitioners must understand what constitutes a biomechanically efficient or inefficient jump, and be able to acquire force data to analyse the individual's performance.[31] Variables commonly used to quantify the CMJ have more recently been classified as either jump strategy or performance metrics.[32] Performance metrics are mainly discrete mechanical outcome measures of the CMJ and commonly include jump height, the modified reactive strength index (RSImod: calculated as the ratio between jump height and jump contraction time or time to take-off), and take-off momentum.[66] Jump strategy metrics allow an analysis of jump kinetics that provide a more in-depth analysis of neuromuscular function compared to performance metrics alone,[21,32] and they have been shown to be more sensitive to change compared to performance metrics alone when measuring recovery after injury.[32] Jump strategy metrics underpin CMJ performance, are derived from the CMJ force-time waveform phase durations, and include measures like the time to take-off, contact time, countermovement depth, phase-specific net impulses, average force and power, force at zero velocity, and eccentric RFD in the braking phase of the CMJ.[32,66] A biomechanically efficient jump is associated with a higher velocity in the initial unweighting phase, shorter braking duration, shorter propulsion phase duration, higher jump

height, higher RSImod and greater braking RFD. The timing of peak force is also an important determinant of an optimal CMJ force time curve, with peak force coinciding with the low position of the CMJ being preferred.[29,40,67]

Although discrete variables are the most commonly used metrics in the literature and are useful in quantifying aspects of performance, discrete variables exclude large portions of the force-time curve data,[20,29] and phase-averaged measures[31] and impulse may fail to reveal variations from the norm within that phase of the CMJ.[17] Discrete variables may also reduce the dimensionality of the CMJ waveform and miss important information regarding vertical force production during the CMJ.[31] Visual observation of the entire CMJ force-time curve in the existing literature shows two different shapes during the propulsive phase: a unimodal and bimodal shape (Figure 3).[31,67] The unimodal shape presents a single vertical force peak whereas the bimodal presents two distinct vertical force peaks.[31,67] The description of force-time curve shapes fluctuates across the literature and an optimal force-time curve shape for jump performance is debatable.[67-68] Guess,[31] Kennedy & Drake,[41] and McHugh[40] found that a unimodal shape of the force-time curve represents a biomechanically effective jump. Opposingly, Peng[42] found that a bimodal force-time curve is more biomechanically effective than a unimodal shape. Possible reasons for this inconsistent evidence are that many studies classify modality by visual inspection and include only a small sample of athletes ($n < 50$).[67-68] Perhaps more importantly, though, is that this categorisation approach fails to take into account the timing or relative magnitude of the force peaks, which may omit significant implications for jump performance.[40] This is supported by the findings of McHugh[40] where the optimal CMJ force-time profile, according to a sample of 100 athletes, occurred when peak force aligned with the transition point between the braking and propulsive phases, regardless of the force-time curves modality.[40,67] The authors concluded that an efficient force-time curve is determined by the timing of peak force production, regardless of the shape categorisation of the curve.[40] The literature has examined force-time curve shape cross-sectionally in healthy participants as a measure of CMJ performance[29-31,40-42] and significantly less so in injured participants[1,14-15,20,28,33,35] with only two known studies repeating CMJ testing across key points of ACLR rehabilitation.[7,13] The changes in the shape of the force-time curve as a result of ACLR have not been investigated during the course of rehabilitation following ACLR. CMJ performance may reflect compensatory movement patterns after injury seen during the transition from eccentric to concentric muscle actions, reflecting the SSC capacity of the athlete at the low point of the jump.[15,28,31] The highest rate of change of velocity occurs during this transition and therefore a diminished capacity to produce force at zero velocity may be expected after injury.

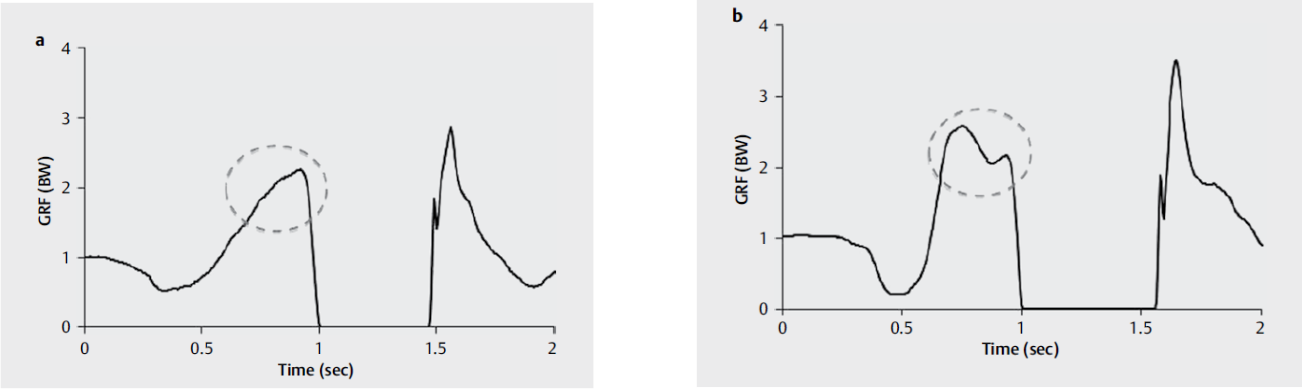

Figure 3: Two types of GRF-time curve modalities – unimodal (left) and bimodal (right). Adapted from Peng et al.[42] *Ground reaction force – GRF; body weight – BW*

Analysing the entire CMJ force-time waveform utilising repeated measures obtained from pre-injury testing and across the post-injury time period including key time points related to the recovery process allows an objective view of force production of the involved and uninvolved limb compared to pre-injury values across an athletes' rehabilitation. Utilising a combination of jump strategy and performance variables within this analysis of the entire CMJ force-time curve provides a robust view of an athlete's movement strategy and neuromuscular capabilities to reliably inform return to play and address limitations posed by traditional tests and analyses that largely rely on single time point analysis.[23-25,35]

CMJ performance and asymmetries in ACLR athletes

ACLR impairs neuromuscular function, including stretch shortening cycle capacity, which impairs vertical jump performance[1,13,17] and reduces the total GRF produced during the CMJ.[3,13-15,28,35-36] Specifically, ACLR negatively impacts the force production of the involved limb, seen as reduced GRF of the involved limb compared to the uninvolved limb (Figure 4).[13] These changes in single limb force production after ACLR translate to greater interlimb asymmetries between the involved and uninvolved limb compared to non-injured athletes .[3,13-15,28,35-36]

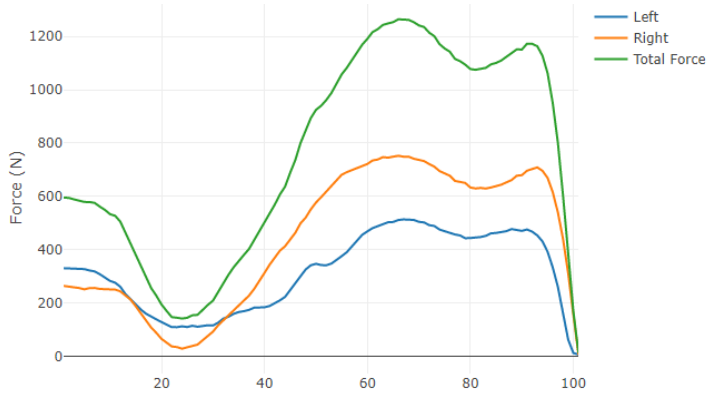

Figure 4: A CMJ time normalised force-time curve illustrating left (blue curve), right (orange curve) and total GRF (green curve) over the entire (100%) jump movement of one subject in this study at 24 ± 3 weeks post ACLR. The left limb is the involved limb. *Countermovement jump - CMJ, Ground reaction force – GRF, anterior cruciate ligament reconstruction - ACLR.*

In terms of jump performance, ACLR athletes show lower values for discrete measures such as jump height, peak force, peak external mechanical power, and force at the lowest point of CMJ compared to controls.[1,20,34] This reduced performance may be due to muscular strength deficits of the quadriceps and hamstrings observed after surgery (Table 1).[14,20,21,33]

Comparing the involved limb of ACLR athletes to the uninvolved limb, the involved limb has been reported to produce lower braking impulse, braking RFD as well as lower propulsive impulse and peak force (Table 1).[13]

CMJ force-time asymmetry testing has commonly been used to evaluate athletes cross sectionally post ACLR across a range of sports (Table 1).[1,3,7,14,17,20,25,27-28,33,35,69-70] ACLR athletes consistently demonstrate increased interlimb asymmetries in the GRF across braking and propulsive phases of the CMJ.[3,13-15,28,35-36] This may be due to asymmetries of the lower limb muscle mass and graft type.[13] In the braking phase, ACLR athletes display elevated asymmetry percentages for RFD,[13,28] peak force,[28] and impulse.[1,13,15] In addition, ACLR athletes display elevated asymmetry percentages in the propulsion phase for peak GRF[13] and impulse[1,7,13-14,20,28,33] (with large effect sizes)[28] which may indicate compensatory movement patterns and force production post ACLR. In terms of timing of rehabilitation, asymmetries were lower the further athletes were away from surgery[1,7,13] but an important finding was that interlimb asymmetries remained significantly larger in athletes more than 9 months post ACLR versus non injured controls, specifically for propulsive impulse and peak force, braking impulse and braking RFD asymmetry.[13] Another observation was that directional shifts in asymmetry occur during the CMJ, from injured limb dominance and greater force production in the beginning and middle of the jump, to uninjured limb dominance and greater force production toward the end of the jump (Figure 1). This highlights the specific phases of the CMJ where

asymmetry was the greatest between limbs for ACLR athletes. This also suggests that the CMJ force-time curve should be analysed in its entirety and not only with discrete variables to provide a more comprehensive perspective of the force production strategy and capabilities post ACLR compared to the sole use of discrete metrics which may mask these changes.[1,14]

These data suggest that athletes with previous injury may demonstrate changes in the shape of the force-time curve related to single limb force production i.e., the involved and uninvolved limbs rather than only changes in the magnitude of the overall force production.[28]

By assessing the entire CMJ waveform it may be possible to identify specific neuromuscular deficits between limbs from a single jump along with differences in the waveform within a limb between jumps at different time points during an athlete's rehabilitation. This may provide additional information on force production strategies and support the design of rehabilitation programs and assist return to play recommendations.[1,13-14,28]

Table 1: Comparisons of CMJ performance and asymmetry variables post anterior cruciate ligament reconstruction

Authors	**ACLR Participants**	**Non-ACLR Participants**	**Time from surgery**	**CMJ performance variables**	**Asymmetry variables** *(ACLR vs non ACLR)*			**Variables with no statistical difference**
					Braking	Propulsive	Other	
Hart et al.[28]	17 male professional soccer player's age: 19 ± 2 years, height 179.9 ± 7.0 cm, mass 76.9 ± 9.6 kg.	17 male professional soccer player's age: 18 ± 2 years, height: 180.0 ± 6.0 cm, body mass 75.8 ± 8.5 kg.	Within 12 months of RTP.	No significant differences between groups for jump height (cm), peak power/BW, flight: contraction time (s), eccentric: concentric force ratio and concentric RFD/BW.	ACLR group = greater interlimb asymmetry % for braking RFD (20.5 ± 10.6%; 10.5 ± 8.2%) , peak force (12.0 ± 7.5; 7.4 ± 4.8%)	ACLR group = greater interlimb asymmetry % for impulse (100ms) (10.9 ± 5.9%; 5.7 ± 4.3%), impulse (7.3 ± 3.6%; 4.1 ± 2.8%), peak force (8.2 ± 4.8%; 3.2 ± 2.3%)	ACLR group = greater interlimb asymmetry % for force at zero velocity (11.9 ± 7.5%; 7.3 ± 5.0%) and eccentric: concentric force ratio (10.9 ± 6.9%; 5.5 ± 5.6%)	Braking impulse (12.6 ± 8.6%; 9.7 ± 6.2%)
Jordan et al.[14]	18 elite alpine skiers. 5 female's age: 23.8 ± 3.3 years, mass:70.3 ± 5.7kg, body fat %: 21.6 ± 2.5.	4 female's age: 21 ± 1.4 years, mass = 66.8 ± 4.5kg, body fat %: 15.3 ± 2.5. 5 male's age: 23.4 ± 2.5 years, mass: 80.7 ± 1.7kg,	Males: 23.5 ± 10.6 months. Females: 28.4 ± 13.5 months			ACLR group had higher mean asymmetry index % for kinetic impulse (6.8% vs 0.5%)		Braking kinetic impulse asymmetry % (5.2% vs 1.0%); braking kinetic impulse, propulsive

	4 male's age, 30.5 ± 2.1 years, mass: 86.6 ± 9.9 kg; body fat %, 14.7 ± 3.1.	body fat % = 13.8 ± 2.2.						kinetic impulse.
Read et al.[13]	Male professional soccer players. Group 1: n = 42, age: 24.3 ± 4.5 years, height: 175.1 ± 10.4cm, mass: 72.9 ± 1.3 kg. Group 2: n = 69, age: 23.7 ± 6.7 years, height: 174.7 ± 8.2 cm, mass: 70.6 ± 10.1 kg. Group 3: n = 55, age: 24.0 ± 5.4 years, height: 174.2 ± 7.4cm, mass: 70.1 ± 12.0 kg.	Group 4: n = 204, age: 24.4 ± 4.7 years, height: 175.7 ± 6.6cm, mass: 71.9 ± 9.4 kg.	Group 1: 19.5 ± 1.9 weeks (SD 13-23) Group 2: 29.1 ± 3.2 weeks (SD 24-35) Group 3: 46.0 ± 67 weeks (SD 36-60)	ACLR groups vs controls had lower values closer to surgery (G1 vs G4): Jump height (26.1 ± 5.5 cm; 34.5 ± 4.0 cm) Peak power (44.2 ± 6.1 W/kg; 50.4 ± 4.9 W/kg)	ACLR groups vs controls had greater asymmetry % (G1 vs G4): Braking impulse (10.4 ± 7.2%; 6.0 ± 4.5%) Braking RFD (17.3 ± 11.6%; 8.6 ± 7.4%) Involved vs uninvolved/ left vs right limbs had lower values closer to surgery (G1 vs G4): Braking impulse (114 ± 32.8 N/s vs 137.4 ± 41.7 N/s; 109.6 ± 25.2 N/s vs 114.3 ± 26.6 N/s) Braking RFD (1370 ± 1109 vs 1889 N/s ± 1488 N/s; 2290 ±	ACLR groups vs controls had greater asymmetry % (G1 vs G4): Impulse (11.3 ± 5.8 N/s ; 2.8 ±1.8 N/s) Peak force (9.3 ± 5.0 N; 3.0 ± 2.1 N) Involved vs uninvolved/ left vs right limbs had lower values closer to surgery (G1 vs G4): Propulsive impulse (178 ± 45.4 N/s vs 226.1 ± 66.4 N/s; 180.7 ± 49.6 N/s vs 207.3 ± 52.5 N/s) Peak force (739 ± 156 N vs 895 ± 212 N; 843 ± 125 vs 855 ± 127)	ACLR groups vs controls had greater asymmetry % (G1 vs G4): Peak landing force (15.8 ± 12.4%; 8.7 ± 6.6%) Involved vs uninvolved/ left vs right limbs had lower values closer to surgery (G1 vs G4): Peak landing force (1482 ± 445 N vs 2044 ± 666 N; 2382 ± 761 N vs 2478 ± 789 N)	

					1030 N/s vs 2272 ± 1084 N/s) Mean force (342 ± 62 N vs 362 ± 72 N; 344 ± 51 N; 360 ± 51 N)			
Baumgart et al.[15]	50 participants split into high /low International Knee Documentation Committee scores (IKDC) High IKDC group: 9 females, 3 males, age: 29 ± 7 years, BMI: 27 ± 4 kg/m^2 Low IKDC group: 3 females, 17 males, age: 32 ± 10 years BMI: 28 ±5 kg/m^2		High IKDC group: 32 ± 7 months. Low IKDC group: 31 ± 7 months	Involved limb vs uninvolved limb of low IKDC group had lower: Peak relative force (1.06 ± 0.15 %/BW vs 1.16 ± 0.19 %/BW) Relative force (deepest point) (0.91 ± 0.13 %/BW vs 1.03 ± 0.16 %/BW)	Involved limb vs uninvolved limb of low IKDC group had lower: Braking impulse (10.4 ± 4.2% vs 17.0 ± 4.1%)	Involved limb vs uninvolved limb of low IKDC group had lower: Propulsive impulse (32.4 ± 4.1% vs 40.2 ± 4.3%)		Jump height (cm) between high and low IKDC groups.

Jordan et al.[33]	12 World ranking skiers: 6 females, age: 24.2 ± 3.1 years, mass: 66.9 ± 8.3kg. 6 males, age: 29.2 ± 2.7, mass: 90.0 ± 7.9kg.	12 Elite level skiers: 6 females age: 22.3 ± 2.5 years, mass: 64.4 ± 5.1kg, 6 males age: 25.5 ± 2.7 years, mass: 83.7 ± 4.9 kg. 12 adolescent level skiers: 6 females age: 17.7 ± 1.0 years, mass: 65.8 ± 6.9 kg. 6 males age: 18.0 ± 0.0 years, mass: 79.5 ± 8.5 kg.	4 ± 2 years		Adolescent skier's vs elite skiers had lower: Net braking impulse (1.33 ± 0.32 Ns/kg; 1.59 ± 0.16 Ns/kg)	ACLR vs non ACLR (elite and adolescent) had greater asymmetry %: Propulsive impulse (approximately 12%; vs 2% and 0%)		Braking phase asymmetry % Jump height Mean power
Miles et al.[20]	44 male multidirectional field sport athletes:	22 male multidirectional field sport athletes age: 23.1 ± 3.4 years, height:	BPTB: 9.4 ± 0.4 months	ACLR vs controls showed lower: jump height (cm) but it was only statistically significant between	BPTB vs HT athletes had greater absolute asymmetry index:	ACLR groups versus controls had greater absolute asymmetry index:	ACLR group (BPTB) versus controls had greater absolute	No diff ACLR groups versus controls for

	22 bone-patellartendon-bone group (BPTB) age: 23.4 ± 4.4 years, height: 181.8 ± 6.4 cm, mass: 85.2 ± 11.5kg. 22 semitendinosus and gracilis hamstring tendon (HT) age: 26.1 ± 4.4 years, height: 179.4 ± 6.1 cm, mass: 79.8 ± 9.4kg.	185.0 ± 6.2 cm, mass: 83.3 ± 5.9kg.	HT: 9.1 ± 0.3 months	BPTB group and controls (28.3 ± 4.1 cm; 32.2 ± 3.7 cm)	Braking impulse BPTB: 20%; HT: 10%. But no difference to controls.	Propulsive Impulse BPTB: 14 ± 6%; HT: 8 ± 6%; Controls: 4 ± 4%	asymmetry index: Landing impulse 21 ± 12%; 12 ± 11%	absolute asymmetry index: Braking impulse (close to statistical significance for BPTB vs controls p = 0.06) Landing impulse (HT vs controls)
Jordan et al.[1]	1 female elite alpine skier, age: 28 years			Involved limb vs pre-injury baseline up to 18 months post ACLR showed lower: Mean power	Involved limb vs pre-injury baseline showed greater asymmetry % up to 18 months post ACLR for: Braking impulse phase	Involved limb vs pre-injury baseline showed higher asymmetry % up to 18 months post ACLR for: Propulsive impulse phase		

Holsgaard-Laarsen et al.[35]	23 male's age: 27.2 ± 7.5 years, BMI: 25.4 ± 3.2 kg/m^2, MET score: 37.7 ± 8.2.	25 male's age: 27.2 ± 5.4 years, BMI: 24.1 ± 1.8 kg/m^2, MET score: 35.2 ± 9.5.	27.7 ± 7 months	ACLR group vs controls had greater asymmetry % for ACLR limb vs non ACLR compared to non-dominant vs dominant limb of controls for ROM (96.1 ± 6.7^o; 102.6 ± 4.6^o) Knee joint angle at eccentric-concentric movement transition (98.6 ± 3.0 $^o_{trans}$; 101.3 ± 2.6 $^o_{trans}$)				
Costley et al.[7]	44 multidirectional field sport male athletes: 22 bone-patellar tendon-bone group (BPTB) age: 23.4 ± 4.4 years, height: 181.8 ± 6.4cm, mass: 85.2 ± 11.5kg		6.2 ± 0.4 months (BPTB: 6.4 ± 0.4 months, HT: 6.1 ± 0.2 months) 9.3 ± 0.4 months (BPTB: 9.4 ± 0.4, HT: 9.1 ± 0.3 months)		BPTB vs HT athletes: greater braking asymmetry	From six to nine months post ACLR: Reduced propulsive impulse asymmetry Reduced braking impulse for ACLR and uninvolved limb BPTB vs HT athletes: greater propulsive asymmetry		From six to nine months post ACLR: Jump height Braking impulse asymmetry Landing impulse asymmetry

	22 hamstrings tendon group (HT) age: 26.1 ± 4.4 years, height: 179.4 ± 6.1cm, mass: 79.8 ±9.4kg							

Abbreviations: ACLR: anterior cruciate ligament reconstruction; non ACLR; limb or athlete that did not undergo anterior cruciate ligament reconstruction; cm: centimetres; kg: kilograms; RFD/BW: rate of force development relative to bodyweight; ms: milliseconds; W/kg: watts per kilogram; N/s: newtons per second; N: newtons; IKDC: international knee documentation committee scores; BMI: body mass index; kg/m^2: kilogram per metres squared; MET: metabolic equivalent score; ROM: range of motion; ^{o}: degrees; ^{o}trans: knee joint angle at the transition between braking and propulsive jump phases; HT: hamstrings tendon graft; BPTB: bone-patellar tendon-bone graft

Statistical parametric mapping in biomechanical analysis

Statistical parametric mapping (SPM) assesses spatiotemporal changes to smoothed continuous data and considers the magnitude and shape of the entire data set for each curve. A test statistic is calculated at every point in the time series after calculating a critical threshold for each test.[71-72] A single statistical test is conducted which compares the test statistic curve to random data (as SPM is based on random field theory) to determine if the test statistic exceeds the determined critical threshold for significance at any point.[71] Graphically, SPM can be applied to CMJ testing to illustrate a test statistic curve throughout the time series with shaded areas on the curve representing the areas of the force- time series curve in which a statistical difference is found, permitting an analysis across the entire force-time waveform of the CMJ (Figure 5).[71]

The practical implication of SPM analysis applied to CMJ testing in the context of return to play testing is an evaluation of the entire jumping motion instead of only single time point measures permitting a more expansive and potentially less biased evaluation of an athlete's neuromuscular capacities. For example, the use of discrete variables may diminish the sensitivity of jump testing protocols and create bias in the analysis and interpretation of the data. SPM or entire cycle analysis may reveal changes in force production and movement patterns due to fatigue or injury even when little change is seen in jump height or impulse.[71-72] Further, movement quality and possible temporal changes in jumping ability is also better assessed over an entire cycle compared to single time point variables in the CMJ.

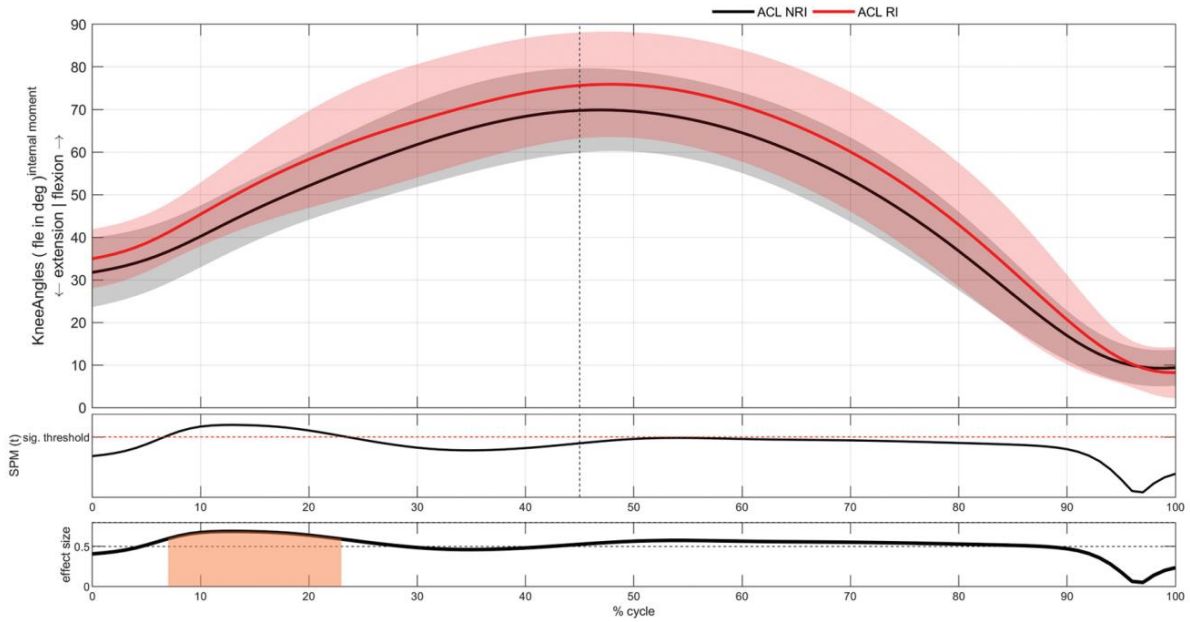

Figure 5: Differences in knee flexion angles of the anterior cruciate ligament reconstructed re-injury group compared to the non-re-injury group in the double leg drop jump test. The re-injury group showed less knee flexion with a medium effect size. Top panel: shows mean and standard deviation clouds. Re-injury group is red. The dotted red line shows the threshold of statistical significance and the orange shaded area shows where the critical threshold (*t*) has been exceeded $p < 0.05$. [73]

SPM has become well established in the analysis of human movement and has been used to analyse muscle activation patterns, GRF, joint kinetics and kinematics in injured and non-injured populations.[71] SPM has also recently and infrequently been used to study biomechanical interlimb asymmetries post ACLR in jumping, landing and change of direction tasks.[71]

Hughes[72] compared SPM analysis of one dimensional force-time curves to previous zero-dimensional (discrete force data) analysis of peak force and subjects completed CMJs and SJs at baseline, 15 minutes, 1, 24 and 48 hours following fatigue. Compared to baseline CMJ values, changes in the force-time curve were evident at multiple time points. The SPM analysis revealed a difference between force-time data at various post-fatigue time points with main effects for time and interaction compared to zero-dimensional discrete data that reported no effect of fatigue on CMJ and SJ peak force. These results highlight the ability of SPM analysis to expose differences in the CMJ force-time curve that were previously masked by exclusively discrete data analysis of the force-time curve, and provide a rationale for applying SPM in the context of post ACLR testing.

King[73] recruited 1045 male athletes and tested injured and non-injured limbs during strength, jumping and planned and unplanned change of direction tasks at 9 months post ACLR and

again at 2 years post-surgery. Athletes were then grouped into two groups: no re-injury and athletes who had reinjured the ACLR side. No differences on the ACLR side were detected between groups in strength and performance measures (isokinetic strength of hamstrings and quadriceps, jump height, or change of direction times) or biomechanical variables. However, for the double leg drop jump, medium effect sizes were detected for knee flexion angle, vertical distance from COM to ankle, and ground contact time with more knee flexion, shorter vertical distance from COM to the ankle and longer ground contact times in the re-injured group. A longer ground contact time indicates more time required on the ground and more lowering of the COM to absorb the landing force and to take-off again. This may point to an increase in the risk of future ACL re-injury due to greater ACL loading during sporting activities. Furthermore, considering the biomechanics of the double-leg drop jump during rehabilitation may aid in informing return to play and reducing the risk of re-injury, despite other performance measures showing no differences between the no re-injury group and re-injured group.

The potential ability of SPM to detect interlimb asymmetries may be superior compared to discrete analysis alone. SPM would enable a more in depth understanding of movement strategies linked to re-injury or lack of recovery after surgery in a variety of clinical applications.[71]

There are two apparent gaps in the existing literature. First, the shape of the force-time curve has been well investigated in relation to jump performance[31,40-41] in cross-sectional studies involving healthy participants.[29-31,40-42] However, this concept has not been applied longitudinally to assess CMJ performance after ACLR throughout rehabilitation.[14] Longitudinal testing is required for comprehensive understanding of complex motor patterns,[71] like the CMJ, in order to make stronger inferences on changes in CMJ performance and interlimb asymmetries post ACLR. Longitudinal data collected from neuromuscular testing can give practitioners information about individual progression, manage the individual variability through sport rehabilitation, better inform return to play decision making[74] and more objectively assess performance at key time points of an athlete's rehabilitation.[21] Second, CMJ performance is predominantly assessed using discrete and phase averaged metrics. However, these do not account for the timing across the entire movement which requires analysis of the waveform data. SPM is a novel analytical technique that addresses this gap by considering the entirety of the CMJ force-time curve and highlights interlimb asymmetries that may be overlooked using discrete time point analysis by taking into account both magnitude and shape of the entire continuous time series.[71]

Chapter 3: Changes in the countermovement jump performance and the force-time waveform after anterior cruciate ligament reconstruction

This chapter is presented as an original research study

Introduction

Anterior cruciate ligament (ACL) rupture is a common and debilitating knee injury for athletes participating mainly in pivoting and landing-type field sports.[10,75] ACL injury accounts for more than 50% of all knee injuries across a variety of sports and causes the most days lost to sport participation compared to other injury types.[1-6,43] Return to play duration varies between sports and has been reported to range from 216 days up to 424 days in soccer,[8] hockey, football, baseball and basketball, in ascending order.[9] Surgical reconstruction (ACLR) is typically recommended following ACL rupture[4,7,20,44-45] with only approximately half of athletes returning to competitive sport and pre-injury performance levels after injury.[1,11-12,45] Return to play is frequently assumed to be between six and 12 months, however, more recent research points out that the return to play process can be described as nonlinear, highly individualised and may take longer than 12 months.[1,11,74] ACLR athletes consistently demonstrate reduced neuromuscular capabilities, significant interlimb differences and compensatory movement patterns up to two years after surgery.[3,13,16]

Neuromuscular impairments after ACLR include loss of lower limb muscle strength, decreased functional performance,[3,17-18] altered lower limb kinematics and kinetics[16,57] and lower force production capacity on the injured side that leads to greater interlimb asymmetries.[14,18-21] Altered knee kinematics after ACLR present as increased knee valgus and hip adduction angle (frontal plane movement). Altered kinetics after ACLR are observed as decreased internal knee extension moments, internal hip flexion moments and anterior tibial shear force (sagittal plane moments) during a double leg jump-landing movement when comparing both kinetics and kinematics to pre-injury.[16,57-58] However, the literature studying these neuromuscular impairments typically examine one point in time after ACLR,[14,20,28,33-34] failing to analyse athletes across the course of rehabilitation.[12] Another limitation of the existing literature is scarce inclusion of pre-injury measures as a comparison.

Primary rehabilitative objectives are to restore pre-injury neuromuscular function and performance levels and ensure a safe return to play.[14,20] However, measures indicating successful return to play post ACLR are not well established.[14,25-27] Post-injury testing of lower limb function and interlimb asymmetry is recommended to evaluate rehabilitative status and

assist in decision making for a safe return to play.[3,17,44,60] Assessments of muscular strength,[3,18-19] running speed,[60] cardiovascular fitness,[60] balance,[60] change of direction ability,[60] hopping[3,18-19,58,60-61] and jumping performance[14,19,60] are common but few scientifically supported measures exist to guide return to play post-ACLR progression despite the high injury and re-injury rate.[14] Common clinic-based functional tests such as single leg hop for distance have shown limited sensitivity to detect compensatory movement patterns after injury that are associated with reinjury.[13,57-58] To overcome these limitations, biomechanical testing is recommended including dual force plate analysis of the vertical countermovement jump (CMJ) to assess the ground reaction force (GRF) generated by each limb.[13,20,65]

The CMJ is a coupled eccentric-concentric movement that has been used to detect neuromuscular ability,[29] performance changes,[30-31] performance fatigability,[30] lower limb maximal muscle power and explosive, and reactive strength capacity after ACLR.[14] The vertical jump height calculated from the net impulse between initiation and take-off is a principal performance outcome of the CMJ[29] but this may be insufficient to guide rehabilitation as it does not consider the jump strategy and potential interlimb compensatory movement patterns.[31] It is therefore recommended that CMJ testing incorporate assessment of both performance metrics and the jump strategy. Performance metrics are predominantly discrete variables that explain the mechanical outcome of the CMJ and include jump height, impulse, external mechanical power, modified reactive strength index (RSImod), and take-off momentum.[66] Strategy metrics describe the change in the centre of mass motion that occurs while executing the jump and include measures such as the CMJ phase durations, the downward displacement, and lower limb stiffness.[32,66] Previous literature has used predominantly discrete force metrics (peak force or force at zero velocity) and phase-specific metrics (phase durations, peak force and impulse) to assess athletes after injury, but these metrics ignore a large portion of the force-time curve data which may reveal important information regarding force production during the CMJ.[17,20,31] It is recommended that practitioners utilise a combination of strategy and performance variables as well as an assessment of interlimb asymmetries to assess CMJ outcomes.[66] This overcomes limitations associated with the use of solely discrete metrics in the analysis of the CMJ which may not thoroughly explain slow stretch shortening cycle (SSC) capabilities post ACLR. Furthermore, research that analyses the CMJ as an entire movement via point-to-point statistical analysis may provide evidence to help practitioners make interlimb comparisons and provide a more thorough assessment of the vertical jump movement strategies post-ACLR.[29-31,65-66]

It has recently been observed that an effective force-time curve is determined by the timing of peak force, regardless of visual categorisation of the CMJ curve shape based on the number

of force peaks during the concentric phase (unimodal or bimodal).[40] Peak force occurring at the lowest point of the centre of mass is proposed to characterise an efficient jump.[40] This reflects the athlete's SSC capabilities to transition from the braking to propulsive phase. Although discrete variables, like peak force, are commonly used in the literature to quantify CMJ performance, they may fail to reveal variations in timing within the CMJ force-time curve. The assessment of continuous force-time data from the CMJ provides information on an athlete's instantaneous force production throughout the entire range of motion of the CMJ, which addresses the limitations of discrete time point analysis. Predominantly, the literature has examined force-time curve shape cross-sectionally in healthy participants as a measure of CMJ performance.[29-31,40-42] The changes as a result of ACLR have not been thoroughly investigated during the course of rehabilitation following ACLR.

Several studies have examined the CMJ to cross-sectionally assess asymmetry post ACLR across various sports.[1,3,14,17,20,25,27-28,33,35,69-70] These studies consistently report greater interlimb asymmetries in the braking and propulsive phases of the CMJ compared to healthy controls, with lower GRF production for the ACLR limb.[3,13-15,28,35-36] These asymmetries may persist up to two years post-surgery despite returning to pre-injury activity levels.[3,13-15] More specifically, in the braking phase, ACLR athletes displayed increased asymmetry values for braking (rate of force development) RFD,[13,28] peak force, [28] and impulse. [1,13,15] In the propulsive phase, ACLR athletes showed greater asymmetry values for propulsive peak force[13] and consistently for lower propulsive impulse for the involved limb.[1,7,13-14,20,28,33] However, these studies examine force production capacity using discrete or phase-specific metrics, not accounting for potential differences or asymmetries in force that may occur throughout the entire CMJ movement and neglect to measure athletes across different stages of rehabilitation.

An alternative approach that analyses the entire GRF trace without removing any data points is statistical parametric mapping (SPM). This method has the potential to provide a more in-depth analysis of variations in force production in specific phases of the CMJ and identify interlimb asymmetries outside of the peak force compared to discrete time point analysis. This knowledge may aid in understanding force production capabilities throughout rehabilitation.[71] While the shape of the force-time curve has mainly been studied in healthy subjects cross sectionally[29-31,40-42] with a focus on jump performance, [31,40-41] it has not been well investigated in injured athletes and longitudinal studies.

Therefore, the aim of the study was to investigate differences in CMJ force production before and after ACLR based on traditional performance and asymmetry measures as well as waveform analysis using SPM. ACL injury is known to cause impairments to the contralateral

limb[37-38], and recently the use of the contralateral limb as a benchmark for return to sport has been questioned[38-39]. This has led others to recommend using a pre-injury baseline as an index of recovery.[37-39] Consequently, we addressed this concern by using two separate comparisons in this study to elucidate the potential for a *false positive* indication of recovery. First, the involved limb was compared to the pre-surgical baseline testing timepoint. Secondly, the involved limb was compared to the uninvolved limb across each of the four post-surgical timepoints. These comparisons were made for discrete jump performance measures and traditional assessments of interlimb asymmetry, including measures derived from a phase-specific analysis, which has become conventional in the literature. Second, these comparisons were made using SPM analysis across the entire force-time waveform.

We hypothesized that CMJ discrete and phase-specific performance metrics would be lower post-surgery due to reduced force production capacity of the involved limb with greater asymmetry indices, that these deficits would be greater the closer the athlete was to surgery, and that they would still exist up to two years post-surgery. Secondly, we hypothesized that SPM analysis would show the timing of force production deficits of the involved limb not detected by the traditional approach within the braking and propulsive phases of the CMJ the closer the athlete was from surgery and that these deficits may also be present up to two years post-surgery.

3.2 Methods

This study utilised a retrospective intra-subject design to assess changes in the involved (injured) limb and an inter-subject cross-sectional design repeated at four discrete time points post ACLR compared to pre-injury baseline values to examine bilateral performance and interlimb asymmetries in athletes throughout ACLR rehabilitation.

3.2.1 Participants

A neuromuscular testing database with five years of longitudinally collected data between 2017 and 2021 was examined. Elite and world class athletes (n=20; male n = 12, female n = 8, age = 21.6 ± 3.8 years) performed the CMJ as part of routine testing and monitoring before and after ACLR, and throughout the post-injury recovery period including after their return to play. Participants competed in alpine skiing (n=7), freestyle skiing (n = 4), ski cross (n = 4), football (n = 2), luge (n = 1), ski jump (n = 1), and wrestling (n = 1). Athletes were included if they had sustained primary ACL injury and subsequently undergone ACLR. The majority of ACLR athletes had undergone semitendinosus grafts (n =17), followed by bone-patellar-tendon-bone grafts (n = 2) and a quadriceps graft (n =1). Athletes who had sustained secondary injury associated with primary ACL injury to other knee structures such as meniscus

injury, articular cartilage, and medial collateral ligament injury (MCL) were also included. Athletes were excluded if they had other active sport injuries such as lumbar spine injury, hip injuries, patellofemoral pain syndrome, muscle strains, leg fractures, and ankle injuries and bilateral injuries. ACL injury was confirmed through medical records and communication with the relevant medical personnel. While not strictly controlled and standardized, participants with ACLR followed an individualised, progressive rehabilitation program administered by qualified practitioners that combined time and outcome measure based rehabilitation milestones. This study was approved by the Conjoint Research Ethics Board at the University of Calgary (REB14-2270 REN6) and the Faculty of Health Sciences Research Ethics Committee of the University of Pretoria (380/2021). Athletes were aware of the benefits and risks associated with the maximal neuromuscular testing and gave written informed consent to participate in the study prior to testing.

3.2.2 Surgery-test date definitions

The difference between the time of the ACLR surgery and time of CMJ testing was calculated and stratified into five surgery-test time intervals that included: the pre-ACLR test (Pre-Surgery Baseline Time 0 – T0) which was the most recent test prior to injury up to a maximum of 6 months before surgery; and post ACLR tests conducted at 24 ± 3 weeks (Post-Surgery Time 1 – T1), 36 ± 3 weeks (Post-Surgery Time 2 – T2), 48 ± 3 weeks (Post-Surgery Time 3 – T3), and between 72 – 100 weeks (Post-Surgery Time 4 – T4) after surgery. The pre-ACLR test period (T0) included participants with pre-injury data prior to ACLR surgery and no previous history of ACL injury up to their ACLR surgery date.

3.2.3 Test procedures

The CMJ was performed as part of routine testing and monitoring, and all athletes were familiar with the testing protocol and regularly performed maximal effort CMJs as a part of training. Certified practitioners conducted testing. Participants performed a standardised 10-minute warm up on a cycle ergometer and light lower body dynamic stretching before the CMJ test. Athletes were instructed to place each foot on the adjacent force plates and remain still to collect a stationary baseline force. Athletes then performed between 5-10 maximal effort CMJs during which they were instructed to maximize their vertical jump height using a self-selected jump whilst keeping their hands firmly planted on their hips. CMJ trials that deviated from the instructed technique were discarded and then repeated. A strong verbal cue was provided before each jump to ensure a maximal effort was given.

3.2.4 Force plate data analysis

A dual force plate system was used to simultaneously measure left and right ground reaction force (GRF), sampling at 1500 Hz (AMTI Accupower) and gathered using commercial software

(Noraxon MR3.14). Data were recorded on a personal computer and the force-time data were exported to csv files. Test dates that aligned with the pre- and post-ACLR time periods and were analysed using the Shiny Vertical Jump Analysis app (https://github.com/mattsams89/shiny-vertical-jump) in RStudio. The raw force-time data was processed during this study, to negate any influence of variation in processing methods that may have been used over the five year period.

The start of the unweighting phase of the CMJ was determined as the initiation of the countermovement until force returned to bodyweight corresponding with the peak downward negative centre of mass velocity. The braking phase was defined from the maximum negative centre of mass velocity, during which the GRF exceeds bodyweight to the instant the centre of mass velocity reached 0 m/s. This marked the start of the propulsion phase (i.e., positive centre of mass velocity) that ended at the instant the athlete's COM has reached zero acceleration and their velocity had peaked just before flight.

The initiation of the CMJ unweighting phase was initially established using two methods. First, after determining body weight (BW) that was averaged over a 1-second quiet standing period the CMJ initiation was identified as the point at which GRF decreased to BW – 5SD.[30,65] The second method employed an algorithm that searched backwards from the BW – 5SD point to check if the inverse (BW + 5SD) occurred within the previous 100 ms. This algorithm worked back until the last point before this inverse threshold was broken in order to find the true initiation of movement (i.e., accounting for the potential of a small rise in the body centre of mass before the initiation of the unweighting phase, termed "preload"). Method one (BW – 5 SD) was used to analyse all of the time normalised force-time waveform data during the unweighting, braking and propulsive phases of the CMJ for the SPM analysis. Method one was considered to be more specific to the downwards motion of the COM and allowed more consistent take-off time durations within and between athletes, therefore, this method was used for analysis of continuous data using SPM. Method two (BW + 5 SD) was used to analyse the discrete variables generated from the raw-force time data as it was determined to be more valid for impulse calculations and the requirement that the initial velocity be equal to zero at the onset of the jump. Next, a visual inspection of all jump trials was done and trials that had clear performance errors or were outliers that displayed large discrepancies in jump height or shape of one trial compared to other trials completed on the same day were excluded. Jump trials were also excluded if minimum force was less than 20 N in the unweighting phase of the jump (i.e., total unweighting occurred). Trials on the same day with larger than 20% discrepancy in peak force production were excluded. Lastly, the jump trial with the best jump height was chosen from the jump trials completed in a given session that met the inclusion

criteria of each of the athlete's relevant surgery-test dates. Take-off was determined at the point where force falls below 20N. Collation of the final datasets comprising all trials and the best trials for the jumps was completed in R studio.

Net impulse was calculated as the resultant impulse after removing the effect of gravity on the mass of the athlete's body, through time-integration of the combined force-time curve (i.e., left + right GRF). The impulse-momentum method was used to calculate take-off velocity, and subsequently jump height. RSImod was calculated as the ratio of jump height to the jump contraction time (time-to-take-off). The net impulse for each limb was calculated separately by time integration of the left and right force-time curves.

An asymmetry index was calculated for net force and impulse and reported as percentages, using the following recommended method for calculating asymmetry during bilateral tasks, in order to maintain the directionality of the asymmetry:

(Uninvolved limb - involved limb)/(Sum of left and right) x 100.[76]

Here, a positive number indicated an uninvolved limb dominance, and a negative number indicated involved limb dominance.

The discrete variables of interest that were included in the analysis were jump height (m), contact time (s), RSImod (AU) and total net peak force (N/kg). Net impulse (N.s/kg) and net peak force (N/kg) for the unweighting, braking and propulsive phases were also analysed for the involved and uninvolved limb, as well as the asymmetry index for impulse and force.

3.2.5. Statistical analysis

Descriptive statistics (mean ± SD) for all discrete performance and comparisons of the discrete CMJ phase variables were performed using paired sample t-tests. The normality of the data were tested used the Shapiro-Wilk test and the Wilcoxon rank p value was used if data was found to be non-normally distributed. Continuous data were analysed using SPM analysis, which calculates a single test statistic for each data point of the CMJ which is compared to a critical threshold. If the test statistic exceeds this threshold, a significant difference ($p < 0.05$) is achieved between data points of the CMJ. These areas of statistical significance are seen as shaded areas in the figures and show the involved limb compared to presurgical baseline testing timepoint and the involved limb compared to the uninvolved limb.

Across the five surgery-test time points, paired time-course comparisons were made against pre-surgery (T0) (i.e., T0 vs. T1, T0 vs. T2, T0 vs. T3, T0 vs. T4) to determine if there was a difference between pre-surgery and other time points. Each of the time point comparisons involved an analysis of (1) traditional discrete CMJ performance metrics including interlimb asymmetry utilising paired t-tests, (2) change in force production of the involved limb using

SPM analysis, and finally (3) a comparison of the involved limb to the uninvolved limb using SPM analysis at each post-surgical time period.

3.3 Results

Table 2: Demographics of athletes

Subject	Sporting code	Age at surgery	Sex	Involved limb	Type of graft	Number of surgery-test dates tested
3	Alpine	27	Male	Right	QUAD	1
10	Alpine	29	Female	Right	STG	5
19	Alpine	20	Male	Left	STG	3
24	Alpine	20	Male	Right	STG	2
33	Alpine	18	Female	Right	STG	2
36	Alpine	18	Female	Right	STG	4
39	Alpine	26	Male	Left	STG	5
46	Football	29	Male	Right	BPTB	1
47	Football	20	Male	Right	STG	2
49	Freestyle	19	Male	Right	STG	3
51	Freestyle	21	Male	Left	STG	3
52	Freestyle	18	Male	Left	STG	2
53	Freestyle	19	Male	Right	STG	3
57	Luge	26	Male	Right	STG	2
64	Ski jump	17	Female	Right	STG	2
66	Skier cross	20	Female	Left	STG	3
67	Skier cross	23	Male	Right	STG	1
69	Skier cross	24	Female	Right	STG	3
70	Skier cross	20	Female	Right	STG	4
77	Wrestling	19	Female	Left	BPTB	4

Abbreviations: QUAD: quadriceps graft; STG: semitendinosus graft; BPTB: bone-patellar-tendon-bone graft.

A comparison of discrete CMJ performance measures and asymmetry

CMJ height was decreased at T3 (0.31 ± 0.04 m) compared to T0 (0.35 ± 0.05 m) ($p = 0.007$) and the jump contraction time increased (T3: 0.85 ± 0.04 s; T0: 0.77 ± 0.05 s) ($p = 0.041$), resulting in a lower RSImod (T3: 0.36 ± 0.05; T0: 0.46 ± 0.07, $p= 0.005$). Peak force decreased at T1 (13.6 ± 2.0 N) compared to T0 (15.0 ± 2.3 N) ($p = 0.009$) (Table 3). No other statistically significant differences were found between the other surgery-test dates for these discrete metrics.

A comparison of vertical force production of the involved limb to itself across surgery-test dates showed that peak force was decreased (16.9%) at T1 (6.4 ± 1.6 N/kg) compared to T0 (7.7 ± 1.4 N/kg) (p = 0.002).

A comparison of asymmetry percentage for CMJ performance between limbs showed a significant increase for peak force from T0 (-1.1 ± 6.1%) to T1 (7.3 ± 11.1%) (p = 0.039) (Table 4). The increased interlimb asymmetry reflected a reduced peak force contribution of the involved limb at T1 compared to the uninvolved limb. No other statistically significant differences were found for the involved limb across surgery-test dates for these discrete metrics.

Comparison between the limbs for peak force found that the involved limb's peak force was lower (10.8%) at T1 compared to the uninvolved limb (involved: 6.6 ± 1.5 N/kg; uninvolved: 7.4 ± 0.6 N/kg, p = 0.021) (Table 5). No other significant differences were seen for these discrete metrics between limbs.

A comparison of CMJ phase-specific impulse production and asymmetry

Analysis of unweighting phase impulse production of the involved limb across surgery-test dates showed smaller (14.3%) unweighting impulse at T2 (-0.66 ± 0.10 N.s/kg) versus pre-injury (-0.77 ± 0.11 N.s/kg) (p = 0.033) and smaller unweighting (11.8%) at T3 (-0.67 ± 0.11 N.s/kg) versus pre-injury (-0.76 ± 0.08 N.s/kg) (p = 0.011). The asymmetry index for unweighting impulse was lower at T1 (-0.7 ± 10.6%) versus pre-injury (-10 ± 10.6%) (p = 0.017) and greater at T2 (7.7 ± 7.7%) versus pre-injury (T0: -0.25 ± 10.0%) (p = 0.035) with a shift in direction of asymmetry favouring the uninvolved limb at T2 (Table 4) which is an unexpected finding. However, there was also pronounced between-subject variation present. These findings are novel, as the unweighting phase has not been examined to date, to the best of the authors' knowledge. Although novel, these findings re-iterate the common outcomes observed post ACLR of lower force production of the involved limb compared to pre-injury baseline values. Unweighting asymmetry percentages varied greatly, presenting as negative, positive and neutral at different surgery-test dates with large between-subject standard deviations. No significant differences were found between other surgery test dates for the unweighting phase.

The asymmetry index in the CMJ braking phase was increased at T4 compared to the pre-surgical baseline (T4: -5.8 ± 11.5%; T0: -0.5 ± 12.7%) (p = 0.013) (Table 4) indicating a greater difference in impulse production between involved and uninvolved limbs at ~2 years after surgery, with the involved limb producing greater impulse. No other significant differences were found in the braking phase when comparing the involved limb to itself across surgery-test dates for these metrics.

Analysis of impulse production during the propulsion phase showed significant changes across all three discrete analyses of: the involved limb to itself, between limbs and the asymmetry index. Comparing the involved limb to itself within the propulsion phase showed a significantly lower (6.6%) impulse at T4 (1.26 ± 0.16 N.s/kg) versus pre-injury (1.35 ± 0.11 N.s/kg) ($p = 0.013$) with no other significant differences for propulsion phase metrics between other surgery – test dates (Table 4). Propulsive impulse production of the involved versus uninvolved limb showed that the involved limb had significantly lower (19.1%) impulse production compared to the uninvolved limb at T1 (involved: 1.27 ± 0.50 N.s/kg ; uninvolved: 1.57 ± 0.50 N.s/kg, $p = 0.003$) and significantly lower (16.7%) impulse production at T2 (involved: 1.15 ± 0.31 N.s/kg ; uninvolved: 1.38 ± 0.25 N.s/kg, $p = 0.027$) (Table 5). Lastly, the asymmetry index between limbs was significantly greater at T1 (12.3 ± 13.3%) compared to the pre-surgical baseline (-0.2 ± 4.8%) ($p = 0.011$) (Table 4)

Force-time waveform comparison of the involved limb to itself across surgery-test dates

Force production of the involved limb during the propulsion phases was significantly lower ($p<0.001$) at T1 (24 ± 3 weeks post ACLR) compared to T0 (pre-injury) between 92% and 99% of the entire CMJ movement (i.e., towards the end of the propulsion phase of the CMJ) (Figure 6 - A). The involved limb showed significantly less ($p<0.001$) unweighting at T1 (24 ± 3 weeks post ACLR) compared to T0 (pre-injury) between 36% and 37% of the entire CMJ movement (i.e., mid-unweighting phase) (Figure 6 – A).

Force-time waveform comparison of the involved vs uninvolved limb at each surgery-test date

A statistically significant difference ($p=0.009$) in propulsive force production between the involved and uninvolved limb was observed at T1 between 72% and 76% (towards the start of the propulsion phase) of the entire CMJ movement (Figure 7 - B). The involved limb displayed a lower force production across the braking and propulsive phase compared to the uninvolved limb on visual observation of the force-time curves, but this was not statistically different (Figure 7 - B). Propulsive force production ($p = 0.040$) was significantly lower for the involved limb compared to the uninvolved limb at T4 between 88% and 89% (towards the end of the propulsion phase) of the entire CMJ movement (Figure 7 - E).

Table 3: Countermovement jump discrete performance metrics across surgery-test dates, compared to baseline

Surgery-test date	n	Surgery – test date	Jump height (m)	Contact time (s)	RSImod (AU)	Peak force (N/kg)
1	10	T0	0.37 ± 0.05	0.84 ± 0.15	0.44 ± 0.08	15.0 ± 2.3
		T1	0.35 ± 0.09	0.89 ± 0.08	0.39 ± 0.09	13.6 ± 2.0*
		p-value	0.084	0.358	0.178	0.009
2	7	T0	0.36 ± 0.05	0.78 ± 0.08	0.47 ± 0.08	15.1 ± 2.2
		T2	0.34 ± 0.06	0.84 ± 0.03	0.40 ± 0.07	15.1 ± 2.5
		p-value	0.105	0.107	0.084	0.937
3	6	T0	0.35 ± 0.05	0.77 ± 0.05	0.46 ± 0.07	14.9 ± 1.7
		T3	0.31 ± 0.04*	0.85 ± 0.04*	0.36 ± 0.05*	14.1 ±1.8
		p-value	0.007	0.041	0.005	0.272
4	5	T0	0.36 ± 0.04	0.84 ± 0.01	0.44 ± 0.07	15.0 ±1.9
		T4	0.35 ± 0.06	0.86 ± 0.06	0.40 ± 0.06	14.8 ±1.4
		p-value	0.625	0.647	0.464	0.788

Values are presented as mean ± standard deviation

*significant difference to T0

Table 4: Countermovment jump involved and uninvolved limb force, impulse and asymmetry indices across surgery-test dates, compared to baseline

						Impulse (N.s/kg)								
			Peak force (N/kg)			Unweighting phase			Braking phase			Propulsion phase		
Surgery-test date	n	Surgery – test date	Involved	Uninvolved	Asymmetry (%)	Involved	Uninvolved	Asymmetry (%)	Involved	Uninvolved	Asymmetry (%)	Involved	Uninvolved	Asymmetry (%)
1	10	T0	7.7 ± 1.4	7.5 ± 1.0	-1.1 ± 6.1	-0.82 ± 0.13	-0.67 ± 0.12	-10.0 ± 10.6	0.74 ± 0.15	0.74 ± 0.09	0.2 ± 10.5	1.34 ± 0.15	1.33 ± 0.11	-0.2 ± 4.8
		T1	6.4 ± 1.6*	7.3 ± 0.7	7.3 ± 11.1*	-0.83 ± 0.41	-0.81 ± 0.40	-0.7 ± 10.6*	0.70 ± 0.26	0.80 ± 0.22	7.9 ± 20.6	1.26 ± 0.54	1.58 ± 0.55	12.3 ± 13.3*
		p-value	0.002	0.494	0.039	0.160	0.375	0.017	0.587	0.695	0.233	0.084	0.037	0.011
2	7	T0	7.6 ± 1.4	7.6 ± 1.0	0.5 ± 7.2	-0.77 ± 0.11	-0.73 ± 0.08	-0.25 ± 10.0	0.74 ± 0.12	0.75 ± 0.07	1.1 ± 9.7	1.31 ± 0.13	1.35 ± 0.10	1.7 ± 5.2
		T2	7.5 ± 1.8	7.6 ± 0.9	1.8 ± 9.7	-0.66 ± 0.10*	-0.77 ± 0.14	7.7 ± 7.7*	0.58 ± 0.50	0.50 ± 0.52	-2.2 ± 12.7	1.16 ± 0.35	1.26 ± 0.26	5.7 ± 10.3
		p-value	0.891	0.934	0.707	0.033	0.391	0.035	0.578	0.109	0.226	0.229	0.372	0.364
3	6	T0	7.4 ± 1.3	7.6 ± 0.5	1.9 ± 6.6	-0.76 ± 0.08	-0.75 ± 0.07	-0.7 ± 2.4	0.73 ± 0.12	0.77 ± 0.09	2.5 ± 10.2	1.28 ± 0.13	1.34 ± 0.10	2.5 ± 5.1
		T3	6.8 ± 1.1	7.3 ± 0.7	3.6 ± 4.0	-0.67 ± 0.11*	-0.77 ± 0.05	7.5 ± 7.4	0.53 ± 0.53	0.46 ± 0.61	1.8 ± 11.6	1.10 ± 0.24	1.19 ± 0.28	4.0 ± 6.0
		p-value	0.316	0.319	0.581	0.011	0.542	0.052	0.438	0.063	0.844	0.074	0.063	0.566
4	5	T0	7.7 ± 1.2	7.4 ± 0.9	-1.8 ± 5.4	-0.79 ± 0.05	-0.66 ± 0.18	-10.1 ± 13.5	0.73 ± 0.15	0.72 ± 0.12	-0.5 ± 12.7	1.35 ± 0.11	1.31 ± 0.08	-1.4 ± 3.6
		T4	7.6 ± 1.2	7.4 ± 0.6	-1.3 ± 8.5	-0.76 ± 0.08	-0.75 ± 0.12	-1.1 ± 7.2	0.80 ± 0.13	0.71 ± 0.11	-5.8 ± 11.5*	1.26 ± 0.16*	1.35 ± 0.07	3.8 ± 5.7
		p-value	0.724	0.940	0.885	0.416	0.056	0.081	0.063	0.701	0.013	0.047	0.389	

Values are presented as mean ± standard deviation

*significant difference to T0

Table 5: Comparison of force and impulse between the involved and uninvolved limb at each surgery-test date

					Impulse (N.s/kg)								
		Peak Force (N/kg)			Unweighting phase			Braking phase			Propulsion phase		
Surgery-test date	n	Involved	Uninvolved	p-value	Involved	Uninvolved	p-value	Involved	Uninvolved	p-value	Involved	Uninvolved	p-value
0	12	7.5 ± 1.3	7.5 ± 0.9	0.755	-0.80 ± 0.12	-0.70 ± 0.13	0.060	0.74 ± 0.14	0.75 ± 0.09	0.722	1.34 ± 0.14	1.35 ± 0.12	0.624
1	12	6.6 ± 1.5	7.4 ± 0.6*	0.021	-0.83 ± 0.38	-0.79 ± 0.36	0.382	0.70 ± 0.24	0.81 ± 0.20	0.124	1.27 ± 0.50	1.57 ± 0.50*	0.003
2	12	7.1 ± 1.5	7.6 ± 0.7	0.143	-0.68 ± 0.14	-0.71 ± 0.13	0.501	0.57 ± 0.39	0.63 ± 0.42	0.424	1.15 ± 0.31	1.38 ± 0.25*	0.027
3	9	6.8 ± 1.0	7.3 ± 0.8	0.052	-0.68 ± 0.11	-0.74 ± 0.05	0.106	0.57 ± 0.43	0.56 ± 0.51	0.761	1.12 ± 0.25	1.27 ± 0.25	0.097
4	10	7.4 ± 1.1	7.1 ± 0.7	0.435	-0.74 ± 0.09	-0.60 ± 0.47	0.922	0.77 ± 0.10	0.70 ± 0.09	0.125	1.31 ± 0.14	1.38 ± 0.11	0.259

Values are presented as mean ± standard deviation

*significant difference between uninvolved and involved limb

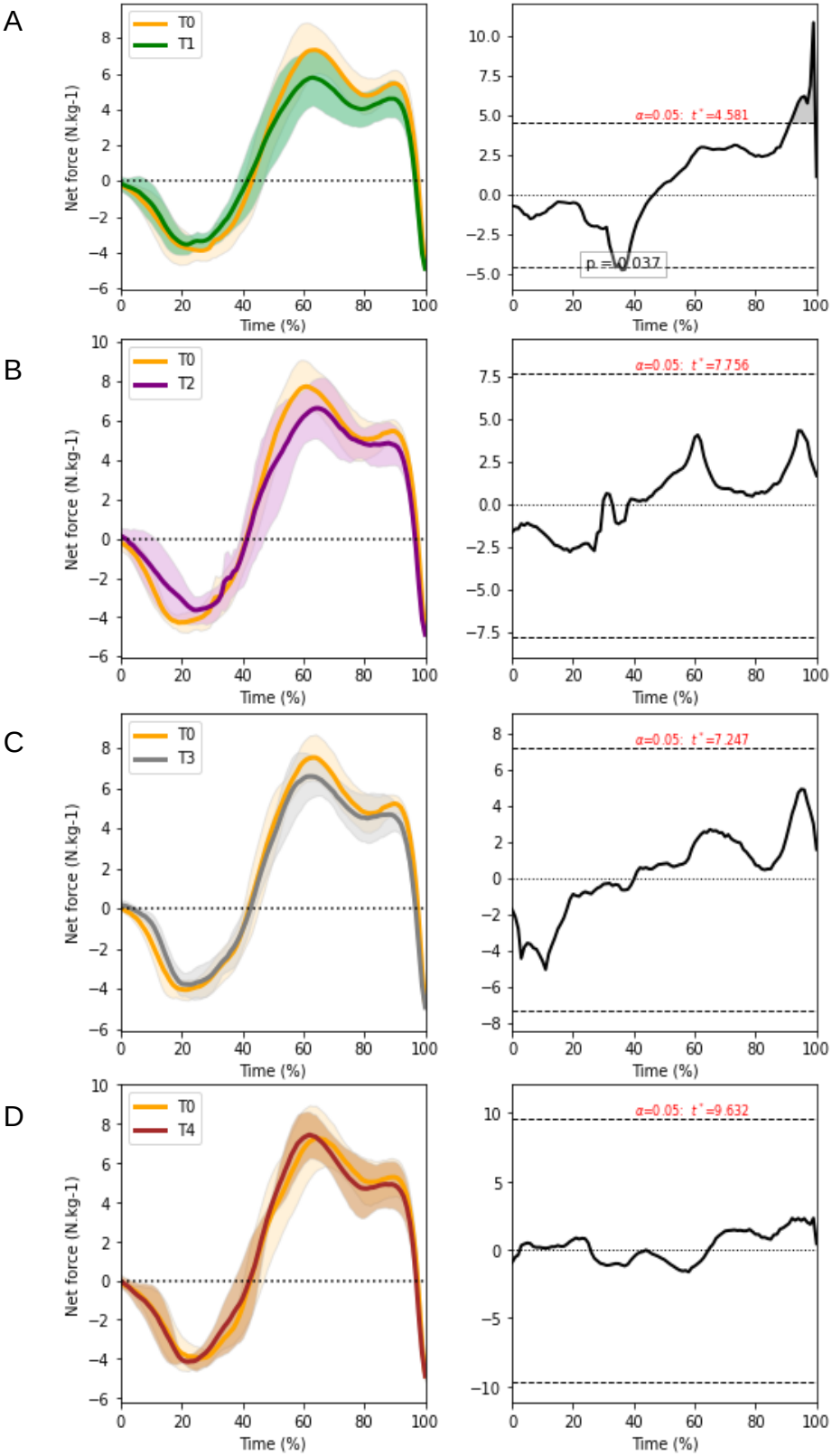

Figure 6: Statistical parametric mapping analysis of the entire countermovement force-time waveform showing group-based changes in force production capacity after anterior cruciate ligament reconstruction of the involved limb compared to itself at: A) T0 vs T1*; B) T0 vs T2; C) T0 vs T3; D) T0 vs T4. Figures on the left indicate the timing as a percentage of the entire of the CMJ movement. Figures on the right indicate where the critical threshold is broken for the statistical parametric mapping test statistic.* Indicates a statistically significant difference (alpha < 0.05) where the critical test threshold (*t*) was exceeded when comparing the involved limb to itself.

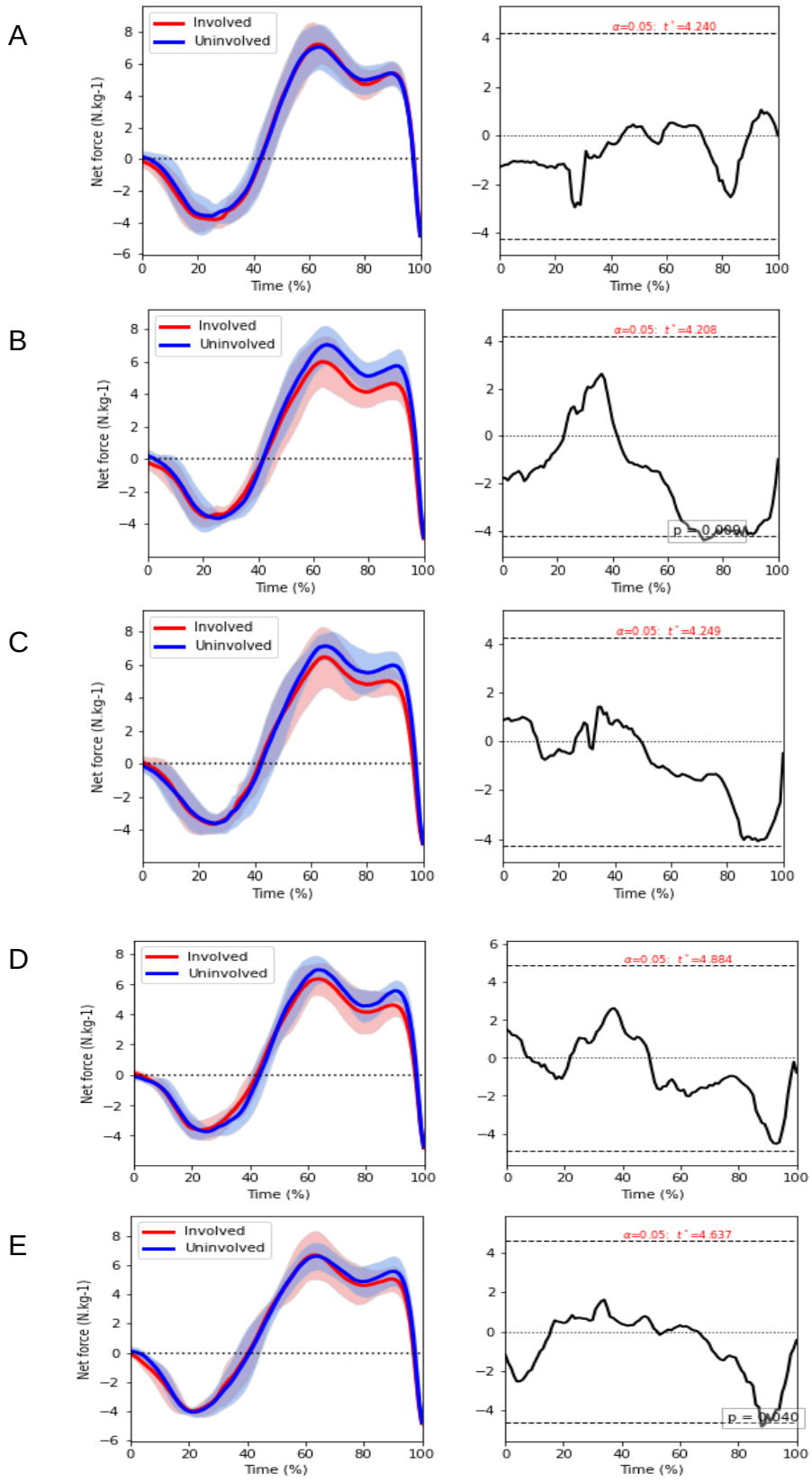

Figure 7: Statistical parametric mapping analysis of the entire countermovement jump force-time waveform showing group-based changes in force production capacity after anterior cruciate ligament reconstruction of the uninvolved and involved limb at: A) T0 B) T1* C) T2 D) T3 E) T4.* Figures on the left indicate the timing as a percentage of the entire of the CMJ movement. Figures on the right indicate where the critical threshold is broken for the statistical parametric mapping test statistic.* Indicates a statistically significant difference (alpha < 0.05) where the critical test threshold (t*) was exceeded between limbs

3.4 Discussion

The aim of this study was to investigate changes in CMJ force production after ACLR using a novel method that involved comparison to pre-injury performance and continuous waveform analysis alongside traditional discrete and phase-specific outcome and asymmetry measures. Comparing each surgery-test date to the pre-injury baseline as ACLR rehabilitation progresses allows a comprehensive analysis of force production capabilities between critical time points across an athlete's rehabilitation. SPM addresses the limitations of utilising discrete and phase-specific performance metrics alone to assess the CMJ performance during ACLR rehabilitation by obtaining point to point information on the timing of force production capacity of the involved limb across the entire movement of the CMJ.[72]

Utilising traditional discrete and phase-specific outcome and asymmetry analyses, the results showed that key CMJ discrete performance metrics were significantly lower compared to pre-injury at approximately six months (T1) and one year post surgery (T3). There were also significantly different asymmetry indices for the unweighting, braking and propulsive phase impulse, generally decreasing the further away athletes were from surgery except for the unweighting phase. The propulsion phase is the only phase that showed significant differences at multiple surgery-test dates for all three types of discrete analyses: at two years post-surgery (T4) versus pre-injury baseline values for the involved limb compared to itself; lower impulse production of the involved limb compared to the uninvolved limb at T2 and T3; and a greater asymmetry index between limbs six months from surgery (T1) compared to pre-injury baseline. The SPM analysis revealed that the involved limb compared to itself had a lower force output towards the end of the propulsion phase soon after surgery (T1) compared to pre-injury (T0). In addition, the involved limb produced lower force than the uninvolved limb at the beginning of the propulsion phase at six months post-surgery (T1) and towards the end of the propulsion phase two years post-surgery (T4).

Overall, outcome measures of jump performance (jump height and RSImod) were only significantly lower than pre-injury performance at approximately one year post surgery (T3) which is an unusual finding. The largest decline in jump performance outcomes would be expected to be observed closer to surgery at T1 and subsequently recover over time..[13,20] Although jump height did continue to decrease from pre-injury up to T3, and RSImod and contact time remained poorer than pre-injury baseline levels no other statistically significant differences occurred between post-surgical time points. These findings may have been affected by the variation in the subjects available for inclusion in the pairwise comparison to pre-injury at each time point. Another explanation may be due to the athlete's elite/world class

level, a quicker recovery of these performance variables could occur nearer to surgery compared to other recreational or less highly trained athletes observed in previous literature.

Significant differences for total net peak force, peak force of the involved limb compared to itself, and peak force asymmetry index were also found six-months post-surgery (T1) versus pre-injury values. The finding of lower peak force production closer to ACL surgery follows the findings of previous literature, which has shown that ACLR athletes compared to non-injured athletes demonstrated lower peak force closer to surgery (<6 months) and improvements 9 months after surgery.[13,15,33] Net peak force and peak force of the involved limb were lower with higher asymmetry at T1, T2 and T3 when comparing both to pre-injury. However, large between-subject variations occurred within the peak force asymmetry index, evidenced by the large standard deviation in relation to the mean value for most asymmetry metrics. This may explain why no other time-points showed statistical significance to pre-injury levels.

Results of phase-specific impulse production metrics in the unweighting phase showed less unweighting of the involved limb compared to itself at approximately nine- and 12-months post-surgery (T2 and T3) versus pre-injury (Table 4). This is unexpected as the greatest change in jump strategy of the involved limb to itself from pre- to post-surgery would be expected to present at the first time point after surgery (T1). Asymmetry indices were greater between limbs at pre-injury versus six (T1) and nine months (T2) post-surgery which is unusual finding as the greatest asymmetry would be expected to be seen after and not prior to injury. Asymmetry indices also showed a shift in direction of asymmetry favouring the uninvolved limb nine months after surgery. Greater asymmetry pre-injury versus post-surgery was not expected, however, the mean asymmetry index between limbs was low with very large between-subject variation. The varying shifts in direction of asymmetry (negative, positive and close to neutral) at different surgery-test dates may indicate that unweighting phase asymmetry is more variable than braking and propulsive phase asymmetry (Table 3). The variation between subjects, based on the standard deviation, generally appears to decline after surgery alongside asymmetry values. It may be that these variations in unweighting phase asymmetry explain characteristics of unloading for both healthy and injured athletes rather than acting as an indication of good or poor performance. Previous literature predominantly excludes analysis of CMJ metrics in the unweighting phase and focuses on investigating discrete and phase-specific metrics of the braking and propulsive phases. Although the total (left and right) net positive impulse applied in the braking phase is equal to the total net negative impulse in the unweighting phase, it may prove worthwhile to assess changes of the involved limb compared to itself after surgery during the unweighting phase.

Significantly greater braking impulse asymmetry was observed at up to two years post ACLR (T4) compared to pre-injury levels favouring the involved limb with a greater (but not statistically significant) braking impulse production of the involved limb compared to pre-injury levels. This is somewhat unexpected as previous literature has demonstrated lower values for braking phase impulse production on the involved limb across rehabilitation from less than six months up to four years after ACLR.[1,13,15,20,33] Generally, braking phase asymmetry is higher the closer the athlete is to surgery, favouring the uninvolved limb, and decreases up to one and a half years post-surgery (T3) with varying shifts in the direction of asymmetry from surgery up to two years post ACLR. Lower braking impulse production and greater asymmetry values may indicate a hampered braking ability post-surgery. A hampered braking force production has been associated with ACL injury and compensation of the uninvolved limb may lead to greater torque placed on the knee.[13] This is because the ability to decelerate the centre of mass requires athletes to reach a point of zero velocity or a momentary pause at the bottom of the CMJ before reversing their centre of mass to propel themselves vertically. Another noteworthy observation for the braking phase is that the asymmetry value was generally low (0 – 8%) with large between-subject standard deviations (10 – 21%) (Table 4). This again highlights that substantial variations exist between individuals in this group-based data set.

Propulsive phase impulse production by the involved limb tended to decrease from pre-injury up to one year after surgery (T3) and was significantly lower up to two years post-surgery (T4) versus its pre-injury baseline (Table 4). Second, compared to the uninvolved limb, the involved limb had significantly lower propulsive impulse production at six months (T1) and nine months (T2) post-surgery (Table 4). Last, the asymmetry index was significantly larger (> 10%) at six months post-surgery (T1) compared to pre-injury baseline measures of asymmetry (Table 4), however, asymmetries would be expected to be present across rehabilitation and not only soon after surgery. Compared to the unweighting and braking phase, the propulsive phase has the highest asymmetry indices closer to surgery, decreasing with time up until ~ two years after surgery (T4). The literature strongly indicates that there is greater interlimb asymmetry for propulsive impulse after ACLR[1,14-15,20,28,33] seen at nine months,[20] one and a half,[1] two[14] and four[33] years after surgery with higher asymmetry values observed closer to surgery.[13] Decreased impulse production of the involved limb in the propulsive phase may reflect chronic deficits of the knee extensors observed after ACLR[14] and a greater reliance on the uninvolved limb in the production of net total impulse to perform a maximal eccentric-concentric movement.[13] Again, results of this study are group-based data and asymmetry percentages show large variation between subjects which may explain the lack of asymmetry across an athletes entire rehabilitation.

SPM analysis revealed that the involved limb had smaller unweighting and diminished propulsion phase force production from pre-injury to approximately six months after surgery (T1) (Figure 6 - A). The finding of less unweighting closer to surgery is a novel finding as existing research excludes analysis of the unweighting phase. Less unweighting of the involved limb after surgery may imply less downward acceleration of the centre of mass and may affect the rate and magnitude of subsequent force production in the braking phase and therefore, SSC function.

Between limb differences in force production for the SPM analysis were also evident in the propulsion phase with the involved limb producing lower force at six months (T1) at the start of the propulsion phase (Figure 7 – B) as well as ~ two years (T4) after surgery later in the propulsion phase compared to pre-injury baseline values (Figure 7 - E). Except for at pre-injury, the uninvolved vs involved limb SPM analyses after surgery were all very near to statistical significance on visual observation of the test statistic approaching its critical threshold (Figure 7 – figures on the right of the SPM waveforms) which could be explored further through effect size analysis. In these instances, the involved limb also showed a lower force production compared to the uninvolved limb on visual observation of the entire force-time curve. Possibly, a larger sample size may have resulted in these analyses reaching statistical significance between limbs. Although not statistically significant, these results may still hold clinical relevance that continuous analysis of the force-time curve through SPM may detect interlimb differences in force production at various critical timepoints during an athlete's rehabilitation from six months up to two years post-surgery with the involved limb producing less force compared to the uninvolved limb. SPM allows these differences between limbs to be analysed at each time point along the force-time curve and not only at certain events during the jump as with discrete metrics. Additionally, examining the force-time curve on an individual basis may be useful for practitioners to better manage individual variation and progression during the rehabilitation process that may be masked with group-based data. The SPM analysis highlights an additional encumbered force production of the involved limb compared to itself closer to surgery (T1) when the knee is in greatest flexion and starting to extend at the start of the propulsive phase that the discrete analysis did not detect. This may imply focusing particularly on the quadriceps muscle group restrengthening during rehabilitation soon after surgery. Deficits that are still present up to two years post-surgery when the knee is near full extension during late propulsive phase may point towards assessing end-range strength or the contribution of other joints, such as the ankle, to vertical propulsion.

No previous literature has reported on changes in the CMJ waveform after ACLR utilising SPM. King et al.[57,73,77-78] did not examine the CMJ but did utilise SPM to analyse other lower limb tests such as change of direction tasks (planned and unplanned) and jumping tasks

(single leg and double leg drop jump, single leg hop for distance, hurdle hop) and reported biomechanical asymmetries in GRF that existed nine months post ACLR. However, greater asymmetry has been shown to be detected in jumping tests compared to change of direction tests nine months after ACLR,[13] therefore the interpretation of these change of direction test results in relation to this study may underestimate the magnitude of asymmetry after ACLR.

The use of SPM analysis therefore confirmed that the involved limb has less unweighting of itself six months after surgery compared to pre-injury baseline values as detected at nine and 12 months after surgery for discrete metrics. SPM analysis also confirmed what was already known regarding group-based differences seen as lower force production of the involved versus uninvolved limb within the propulsive phase and of the involved limb compared to its pre-surgery baseline testing value within the propulsive phase that occur soon after surgery (T1) and are still evident up to ~ two years after surgery (T4). A decreased force production capacity represents decreased knee moments and places a greater demand on the uninvolved limb through compensation which may be due to decreased neuromuscular function, deficits in knee extensor strength, and fear of reinjury.[13,28]

The implication of these findings are four-fold: First, they reiterate recommendations found in recent literature that post ACLR, in the context of return to play, rehabilitation should be an individualised process based on more than one variable[12] and therefore, the traditional rehabilitation time of six to 12 months may not be sufficient to guide rehabilitation. Second, focusing on equal force production early on in the rehabilitative process throughout CMJ phases may aid in determining a more informed return to play.[28] Third, the use of pre-injury baseline performance levels may provide a more appropriate measure of the performance of the involved limb during the course of rehabilitation versus the use of post-surgical interlimb asymmetry indices.[37-38] Lastly, assessing the shape of the force-time waveform as well as assessing the timing of peak force in contrast to relying only on discrete or phase-specific metrics may be a more useful method of assessing unilateral and bilateral force production after ACLR in order to better inform rehabilitative programs and guide return to play across rehabilitation.

Chapter 4: Conclusion

Summary

ACL rupture is a severe injury[1-3,10] that often requires surgical reconstruction to restore knee stability. Many athletes do not return to their pre-injury performance levels[11-12] due to hampered functional performance after surgery which may increase the risk of future ACL re-injury.[3,17-18] As ACLR results in altered movement patterns and significant differences in neuromuscular function between involved and uninvolved limbs up to two years post-surgery,[3,13-15,16] we used the CMJ test (a common assessment that measures bilateral force production using dual force plates) to assess jump performance and asymmetries after ACLR to generate new information to support return to play protocols.[14,29-31] Jump performance has been largely studied cross sectionally within a non-injured population in the existing literature.[29-31,40-42] Fewer studies examine jump performance after ACLR and predominantly have the limitation of using only discrete or CMJ phase-specific (braking or propulsive) metrics to quantify performance, and typically lack pre-injury baseline data.[13-14,20,28,33]

Sole use of discrete metrics at single time points of an athlete's rehabilitation may fail to reveal the magnitude and timing of jump performance deficits, changes in force production or changes in interlimb asymmetry after surgery either within a single limb or between limbs. Practitioners may thus benefit from analysis of the full force-time curve at key clinical milestones after surgery compared to pre-injury baseline values. Therefore, the aim of the study was to investigate changes in CMJ performance, vertical GRF production and interlimb asymmetry in ACLR athletes over ~2 years post ACLR through analysis of the CMJ force-time waveform using statistical parametric mapping.

The results of this study found that, compared to pre-injury baselines values, jump performance outcomes (jump height, contact time, RSImod) were reduced at one year after ACLR, with lower peak force production and greater peak force asymmetry at six months post ACLR.

CMJ phase-specific metrics over the braking phase showed poorer impulse production of the involved limb, decreasing from surgery up until one year post ACLR, although not statistically different. Asymmetry was the greatest the closer the athlete was to surgery up until one year post ACLR, however the direction of asymmetry (negative, positive or neutral) varied at the different surgery-test dates. Braking impulse of the involved limb was greater compared to pre-injury baseline vales at two years post ACLR with a significantly different asymmetry to pre-injury levels, favouring the involved limb.

Performance measures over the propulsive phase compared to pre-injury levels showed significantly lower impulse production of the involved limb compared to itself and greater asymmetry at two years post ACLR, with decreasing force and asymmetry the further the athlete was away from surgery. Between limb comparisons of impulse production found significantly lower impulse production of the involved limb at nine months and one year post ACLR.

These findings indicated reduced jump performance at six months and one year for traditional discrete performance and asymmetry measures. The involved limb demonstrated poorer performance in the braking phase up to one year post ACLR but a relatively higher impulse reflected in a change in the directionality of the asymmetry at two years post ACLR. The propulsion phase showed hampered performance of the involved limb, between limbs and greater asymmetry from six months up to two years post ACLR at various points across rehabilitation for these three measures of performance.

SPM confirmed the findings of previous research using discrete measures of CMJ performance. Compared to pre-injury levels, the involved limb had less unweighting and a lower propulsive force production at six months post ACLR and showed a lower force production of the involved limb versus the uninvolved limb at six months and at two years after surgery. Although group-based analysis was consistent with previous work regarding changes in peak force after surgery, individual assessment of the whole force-time curve may provide additional information for practitioners regarding changes in timing of peak force production throughout the CMJ movement between and within a limb as well as shifts in the direction of asymmetry for individual athletes during rehabilitation (Figure 4).

Limitations

Due to the actuality of the data used, missing values occurred and not all 20 participants formed part of each of the paired comparisons for the SPM analysis of the involved limb compared to itself. Missing values across surgery-test dates resulted in only athletes who had data in a minimum of two of the five time points being analysed which effectively means that each paired statistical test included different participants and different sample sizes. This may increase the volatility of the results due to larger between-subject variations, however, even with a slightly smaller sample size for this specific analysis, there were instances of statistical significance which indicate that the sample was indeed strong enough to detect these differences despite its smaller size. Another limitation was that rehabilitation programs for athletes were not strictly controlled over the course of rehabilitation due to the elite nature and variety of sporting codes of the athletes that formed part of the study which may influence results observed at each surgery-test date. However, all elite athletes did follow a progressive

rehabilitation program, administered by a strength and conditioning professional that was sport specific. Lastly, athletes were not sex and age matched and individual variations at each surgery-test date were not accounted for.

Implications of findings

The aim of the study was to investigate differences in CMJ force production before and after ACLR based on traditional performance and asymmetry measures as well as SPM analysis. Main findings show that performance is hampered after ACLR, reflected in poorer outcomes of traditional CMJ outcome measures, asymmetry as well as continuous analysis of the force-time curve, specifically within the propulsion phase.

Generally, these measures reflect lower force production of the involved limb and greater interlimb asymmetries after surgery compared to pre-injury baseline levels with a reduced unweighting impulse of the involved limb versus itself after surgery, which is a novel finding as this phase is often excluded from analysis. Asymmetries tend to decrease the further the athlete is away from surgery, however the variability of asymmetry values may indicate that these measures are not optimal measures for return to play decision making. However, significant differences in force production of the involved limb compared to itself continue to exist up to two years post-surgery compared to pre-injury baseline values for the propulsion phase of the CMJ reflected in both discrete and SPM analysis, highlighting the complementary nature of a combination analysis. From a practitioner's perspective, inspection of the force-time waveform provides the ability to assess the timing of peak force and its entire shape after surgery which may better inform about neuromuscular deficits in how an athlete produces force across a CMJ.

Furthermore, utilising pre-injury values as a baseline assessment of bilateral force production after ACLR may provide a more appropriate view of functional performance of the involved and uninvolved limb and avoid a *false positive* indication of functional performance deficits compared solely to the uninvolved limb or sole use of asymmetry indices.

Lastly, assessment of bilateral force production after ACLR across key clinical milestones may highlight force production deficits and asymmetries that single time point analysis may underestimate or fail to detect and create a broader picture for practitioners of an athlete's force production capability after surgery.

These considerations may lead to more individualised prescription of rehabilitation programs and return to play protocols and decrease the risk of future non-contact re-injury due to the precise detection of the timing of force production deficits between limbs and of the involved limb that continue to exist past previously anticipated return to play times.

Future research should consider utilising a larger sample size with more stringent adherence for repeated measures to ensure fewer missing values creating a statistically stronger study which would better account for between-subject variations at each repeated measure with age, and sex matched controls.

References

1. Jordan MJ, Morris N, Lane M, Barnert J, MacGregor K, Heard M, et al. Monitoring the return to sport transition after acl injury: An alpine ski racing case study. Front Sports Act Living. 2020; 2:12. doi:10.3389/fspor.2020.00012

2. Joseph AM, Collins CL, Henke NM, Yard EE, Fields SK, Comstock RD. A multisport epidemiologic comparison of anterior cruciate ligament injuries in high school athletics. J Athl Train. 2013; 48(6):810-7. doi:10.4085/1062-6050-48.6.03

3. Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. Clin J Sport Med. 2007; 17(4):258-62. doi:10.1097/JSM.0b013e31804c77ea

4. Moses B, Orchard J, Orchard J. Systematic review: Annual incidence of acl injury and surgery in various populations. Res Sports Med. 2012; 20(3-4):157-79. doi:10.1080/15438627.2012.680633

5. Brown SR, Hume PA, Lorimer AV, Brughelli M, Besier TF. An individualised approach to assess the sidestep manoeuvre in male rugby union athletes. Journal of Science and Medicine in Sport. 2020; 23(11):1086-92. doi:10.1016/j.jsams.2020.03.015

6. Fernández AM MI, García NR, Gutiérrez G, Muñoz ES, Munarriz CT. Lower limb injuries in sport. International Journal of Physical Medicine & Rehabilitation. 2020; 8(5) doi:10.35248/2329-9096.20.08.566

7. Costley JAE, Miles JJ, King E, Daniels KAJ. Vertical jump impulse deficits persist from six to nine months after acl reconstruction. Sports Biomech. 2023; 22(1):123-41. doi:10.1080/14763141.2021.1945137

8. Forsythe B, Lavoie-Gagne OZ, Forlenza EM, Diaz CC, Mascarenhas R. Return-to-play times and player performance after acl reconstruction in elite uefa professional soccer players: A matched-cohort analysis from 1999 to 2019. Orthop J Sports Med. 2021; 9(5):23259671211008892. doi:10.1177/23259671211008892

9. Lu Y, Okoroha KR, Patel BH, Nwachukwu BU, Baker JD, Idarraga AJ, et al. Return to play and performance after shoulder instability in national basketball association athletes. J Shoulder Elbow Surg. 2020; 29(1):50-7. doi:10.1016/j.jse.2019.05.035

10. Montalvo AM, Schneider DK, Webster KE, Yut L, Galloway MT, Heidt RS, Jr., et al. Anterior cruciate ligament injury risk in sport: A systematic review and meta-analysis of injury incidence by sex and sport classification. J Athl Train. 2019; 54(5):472-82. doi:10.4085/1062-6050-407-16

11. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Sports participation 2 years after anterior cruciate ligament reconstruction in athletes who had not returned to sport at 1 year: A prospective follow-up of physical function and psychological factors in 122 athletes. Am J Sports Med. 2015; 43(4):848-56. doi:10.1177/0363546514563282

12. Jordan MJ, Morris N, Barnert J, Lawson D, Aldrich Witt I, Herzog W. Forecasting neuromuscular recovery after anterior cruciate ligament injury: Athlete recovery profiles with generalized additive modeling. J Orthop Res. 2022; doi:10.1002/jor.25302

13. Read PJ, Michael Auliffe S, Wilson MG, Graham-Smith P. Lower limb kinetic asymmetries in professional soccer players with and without anterior cruciate ligament reconstruction: Nine months is not enough time to restore "functional" symmetry or return to performance. Am J Sports Med. 2020; 48(6):1365-73. doi:10.1177/0363546520912218

14. Jordan MJ, Aagaard P, Herzog W. Lower limb asymmetry in mechanical muscle function: A comparison between ski racers with and without acl reconstruction. Scand J Med Sci Sports. 2015; 25(3):e301-9. doi:10.1111/sms.12314

15. Baumgart C, Hoppe MW, Freiwald Jr. Phase-specific ground reaction force analyses of bilateral and unilateral jumps in patients with acl reconstruction. Orthopaedic Journal of Sports Medicine. 2017; 5(6):232596711771091. doi:10.1177/2325967117710912

16. Goerger BM, Marshall SW, Beutler AI, Blackburn JT, Wilckens JH, Padua DA. Anterior cruciate ligament injury alters preinjury lower extremity biomechanics in the injured and uninjured leg: The jump-acl study. Br J Sports Med. 2015; 49(3):188-95. doi:10.1136/bjsports-2013-092982

17. Flanagan EP, Galvin L, Harrison AJ. Force production and reactive strength capabilities after anterior cruciate ligament reconstruction. J Athl Train. 2008; 43(3):249-57. doi:10.4085/1062-6050-43.3.249

18. Lloyd RS, Oliver JL, Kember LS, Myer GD, Read PJ. Individual hop analysis and reactive strength ratios provide better discrimination of acl reconstructed limb deficits than triple hop for distance scores in athletes returning to sport. Knee. 2020; 27(5):1357-64. doi:10.1016/j.knee.2020.07.003

19. Taylor JB, Westbrook AE, Head PL, Glover KM, Paquette MR, Ford KR. The single-leg vertical hop provides unique asymmetry information in individuals after anterior cruciate ligament reconstruction. Clin Biomech (Bristol, Avon). 2020; 80:105107. doi:10.1016/j.clinbiomech.2020.105107

20. Miles JJ, King E, Falvey É C, Daniels KAJ. Patellar and hamstring autografts are associated with different jump task loading asymmetries after acl reconstruction. Scandinavian journal of medicine & science in sports. 2019; 29(8):1212-22. doi:10.1111/sms.13441

21. Read PJ, Pedley JS, Eirug I, Sideris V, Oliver JL. Impaired stretch-shortening cycle function persists despite improvements in reactive strength after anterior cruciate ligament reconstruction. J Strength Cond Res. 2022; 36(5):1238-44. doi:10.1519/jsc.0000000000004208

22. Ernst GP, Saliba E, Diduch DR, Hurwitz SR, Ball DW. Lower extremity compensations following anterior cruciate ligament reconstruction. Phys Ther. 2000; 80(3):251-60.

23. Decker MJ, Torry MR, Noonan TJ, Riviere A, Sterett WI. Landing adaptations after acl reconstruction. Med Sci Sports Exerc. 2002; 34(9):1408-13. doi:10.1097/00005768-200209000-00002

24. Vairo GL, Myers JB, Sell TC, Fu FH, Harner CD, Lephart SM. Neuromuscular and biomechanical landing performance subsequent to ipsilateral semitendinosus and gracilis autograft anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2008; 16(1):2-14. doi:10.1007/s00167-007-0427-4

25. O'Malley E, Richter C, King E, Strike S, Moran K, Franklyn-Miller A, et al. Countermovement jump and isokinetic dynamometry as measures of rehabilitation status after anterior cruciate ligament reconstruction. J Athl Train. 2018; 53(7):687-95. doi:10.4085/1062-6050-480-16

26. Fältström A, Hägglund M, Kvist J. Functional performance among active female soccer players after unilateral primary anterior cruciate ligament reconstruction compared with knee-healthy controls. Am J Sports Med. 2017; 45(2):377-85. doi:10.1177/0363546516667266

27. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: Criteria-based progression through the return-to-sport phase. J Orthop Sports Phys Ther. 2006; 36(6):385-402. doi:10.2519/jospt.2006.2222

28. Hart L, Cohen D, Patterson S, Springham M, Reynolds J, Read P. Previous injury is associated with heightened countermovement jump force-time asymmetries in professional soccer players. Translational Sports Medicine. 2019; 2 doi:10.1002/tsm2.92

29. Krzyszkowski J, Chowning LD, Harry JR. Phase-specific predictors of countermovement jump performance that distinguish good from poor jumpers. J Strength Cond Res. 2020; doi:10.1519/jsc.0000000000003645

30. Chavda S, Bromley T, Jarvis P, Williams S, Bishop C, Turner A, et al. Force-time characteristics of the countermovement jump: Analyzing the curve in excel. Strength and Conditioning Journal. 2017; 40:1. doi:10.1519/SSC.0000000000000353

31. Guess TM, Gray AD, Willis BW, Guess MM, Sherman SL, Chapman DW, et al. Force-time waveform shape reveals countermovement jump strategies of collegiate athletes. Sports (Basel). 2020; 8(12) doi:10.3390/sports8120159

32. Bishop C, Turner A, Jordan M, Harry J, Loturco I, Lake J, et al. A framework to guide practitioners for selecting metrics during the countermovement and drop jump tests. Strength & Conditioning Journal. 2022; 44(4):95-103. doi:10.1519/ssc.0000000000000677

33. Jordan MJ, Aagaard P, Herzog W. A comparison of lower limb stiffness and mechanical muscle function in acl-reconstructed, elite, and adolescent alpine ski racers/ski cross athletes. J Sport Health Sci. 2018; 7(4):416-24. doi:10.1016/j.jshs.2018.09.006

34. Baumgart C, Hoppe MW, Freiwald J. Phase-specific ground reaction force analyses of bilateral and unilateral jumps in patients with acl reconstruction. Orthop J Sports Med. 2017; 5(6):2325967117710912. doi:10.1177/2325967117710912

35. Holsgaard-Larsen A, Jensen C, Mortensen NH, Aagaard P. Concurrent assessments of lower limb loading patterns, mechanical muscle strength and functional performance in acl-patients--a cross-sectional study. Knee. 2014; 21(1):66-73. doi:10.1016/j.knee.2013.06.002

36. Dai B, Butler RJ, Garrett WE, Queen RM. Using ground reaction force to predict knee kinetic asymmetry following anterior cruciate ligament reconstruction. Scandinavian Journal of Medicine & Science in Sports. 2014; 24(6):974-81. doi:10.1111/sms.12118

37. Wellsandt E, Failla MJ, Snyder-Mackler L. Limb symmetry indexes can overestimate knee function after anterior cruciate ligament injury. J Orthop Sports Phys Ther. 2017; 47(5):334-8. doi:10.2519/jospt.2017.7285

38. Pairot de Fontenay B, Argaud S, Blache Y, Monteil K. Contralateral limb deficit seven months after acl-reconstruction: An analysis of single-leg hop tests. Knee. 2015; 22(4):309-12. doi:10.1016/j.knee.2015.04.012

39. Moran TE, Ignozzi AJ, Burnett Z, Bodkin S, Hart JM, Werner BC. Deficits in contralateral limb strength can overestimate limb symmetry index after anterior cruciate ligament reconstruction. Arthrosc Sports Med Rehabil. 2022; 4(5):e1713-e9. doi:10.1016/j.asmr.2022.06.018

40. McHugh M, Hickok M, Cohen J, Virgile A, Connolly D. Is there a biomechanically efficient vertical ground reaction force profile for countermovement jumps? Translational Sports Medicine. 2020; 4 doi:10.1002/tsm2.200

41. Kennedy RA, Drake D. Is a bimodal force-time curve related to countermovement jump performance? Sports (Basel). 2018; 6(2) doi:10.3390/sports6020036

42. Peng HT, Song CY, Chen ZR, Wang IL, Gu CY, Wang LI. Differences between bimodal and unimodal force-time curves during countermovement jump. Int J Sports Med. 2019; 40(10):663-9. doi:10.1055/a-0970-9104

43. Montalvo AM, Schneider DK, Yut L, Webster KE, Beynnon B, Kocher MS, et al. "What's my risk of sustaining an acl injury while playing sports?" A systematic review with meta-analysis. Br J Sports Med. 2019; 53(16):1003-12. doi:10.1136/bjsports-2016-096274

44. Ebert JR, Du Preez L, Furzer B, Edwards P, Joss B. Which hop tests can best identify functional limb asymmetry in patients 9-12 months after anterior cruciate ligament reconstruction employing a hamstrings tendon autograft? Int J Sports Phys Ther. 2021; 16(2):393-403. doi:10.26603/001c.21140

45. Ardern CL, Taylor NF, Feller JA, Webster KE. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: An updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. Br J Sports Med. 2014; 48(21):1543-52. doi:10.1136/bjsports-2013-093398

46. Baawa-Ameyaw J, Plastow R, Begum FA, Kayani B, Jeddy H, Haddad F. Current concepts in graft selection for anterior cruciate ligament reconstruction. EFORT Open Rev. 2021; 6(9):808-15. doi:10.1302/2058-5241.6.210023

47. Busfield BT, Kharrazi FD, Starkey C, Lombardo SJ, Seegmiller J. Performance outcomes of anterior cruciate ligament reconstruction in the national basketball association. Arthroscopy. 2009; 25(8):825-30. doi:10.1016/j.arthro.2009.02.021

48. Carey JL, Huffman GR, Parekh SG, Sennett BJ. Outcomes of anterior cruciate ligament injuries to running backs and wide receivers in the national football league. Am J Sports Med. 2006; 34(12):1911-7. doi:10.1177/0363546506290186

49. Erickson BJ, Harris JD, Cole BJ, Frank RM, Fillingham YA, Ellman MB, et al. Performance and return to sport after anterior cruciate ligament reconstruction in national hockey league players. Orthop J Sports Med. 2014; 2(9):2325967114548831. doi:10.1177/2325967114548831

50. Erickson BJ, Harris JD, Cvetanovich GL, Bach BR, Bush-Joseph CA, Abrams GD, et al. Performance and return to sport after anterior cruciate ligament reconstruction in male major league soccer players. Orthop J Sports Med. 2013; 1(2):2325967113497189. doi:10.1177/2325967113497189

51. Erickson BJ, Harris JD, Heninger JR, Frank R, Bush-Joseph CA, Verma NN, et al. Performance and return-to-sport after acl reconstruction in nfl quarterbacks. Orthopedics. 2014; 37(8):e728-34. doi:10.3928/01477447-20140728-59

52. Harris JD, Erickson BJ, Bach BR, Jr., Abrams GD, Cvetanovich GL, Forsythe B, et al. Return-to-sport and performance after anterior cruciate ligament reconstruction in national basketball association players. Sports Health. 2013; 5(6):562-8. doi:10.1177/1941738113495788

53. Namdari S, Scott K, Milby A, Baldwin K, Lee GC. Athletic performance after acl reconstruction in the women's national basketball association. Phys Sportsmed. 2011; 39(1):36-41. doi:10.3810/psm.2011.02.1860

54. Waldén M, Hägglund M, Magnusson H, Ekstrand J. Anterior cruciate ligament injury in elite football: A prospective three-cohort study. Knee Surg Sports Traumatol Arthrosc. 2011; 19(1):11-9. doi:10.1007/s00167-010-1170-9

55. Cinque ME, Dornan GJ, Chahla J, Moatshe G, LaPrade RF. High rates of osteoarthritis develop after anterior cruciate ligament surgery: An analysis of 4108 patients. Am J Sports Med. 2018; 46(8):2011-9. doi:10.1177/0363546517730072

56. Wang LJ, Zeng N, Yan ZP, Li JT, Ni GX. Post-traumatic osteoarthritis following acl injury. Arthritis Res Ther. 2020; 22(1):57. doi:10.1186/s13075-020-02156-5

57. King E, Richter C, Franklyn-Miller A, Wadey R, Moran R, Strike S. Back to normal symmetry? Biomechanical variables remain more asymmetrical than normal during jump and change-of-direction testing 9 months after anterior cruciate ligament reconstruction. Am J Sports Med. 2019; 47(5):1175-85. doi:10.1177/0363546519830656

58. Kotsifaki A, Korakakis V, Whiteley R, Van Rossom S, Jonkers I. Measuring only hop distance during single leg hop testing is insufficient to detect deficits in knee function after acl reconstruction: A systematic review and meta-analysis. Br J Sports Med. 2020; 54(3):139-53. doi:10.1136/bjsports-2018-099918

59. Boden BP, Dean GS, Feagin JA, Jr., Garrett WE, Jr. Mechanisms of anterior cruciate ligament injury. Orthopedics. 2000; 23(6):573-8. doi:10.3928/0147-7447-20000601-15

60. Hegedus EJ, McDonough SM, Bleakley C, Baxter D, Cook CE. Clinician-friendly lower extremity physical performance tests in athletes: A systematic review of measurement properties and correlation with injury. Part 2--the tests for the hip, thigh, foot and ankle including the star excursion balance test. Br J Sports Med. 2015; 49(10):649-56. doi:10.1136/bjsports-2014-094341

61. Gustavsson A, Neeter C, Thomeé P, Silbernagel KG, Augustsson J, Thomeé R, et al. A test battery for evaluating hop performance in patients with an acl injury and patients who have undergone acl reconstruction. Knee Surg Sports Traumatol Arthrosc. 2006; 14(8):778-88. doi:10.1007/s00167-006-0045-6

62. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after acl reconstruction: The delaware-oslo acl cohort study. Br J Sports Med. 2016; 50(13):804-8. doi:10.1136/bjsports-2016-096031

63. Decarlo MS, Shelbourne KD, McCarroll JR, Rettig AC. Traditional versus accelerated rehabilitation following acl reconstruction: A one-year follow-up. J Orthop Sports Phys Ther. 1992; 15(6):309-16. doi:10.2519/jospt.1992.15.6.309

64. van Melick N, van Cingel RE, Brooijmans F, Neeter C, van Tienen T, Hullegie W, et al. Evidence-based clinical practice update: Practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. Br J Sports Med. 2016; 50(24):1506-15. doi:10.1136/bjsports-2015-095898

65. McMahon JJ, Suchomel TJ, Lake JP, Comfort P. Understanding the key phases of the countermovement jump force-time curve. Strength & Conditioning Journal. 2018; 40(4):96-106.

66. Harry JR, Barker LA, Tinsley GM, Krzyszkowski J, Chowning LD, McMahon JJ, et al. Relationships among countermovement vertical jump performance metrics, strategy variables, and inter-limb asymmetry in females. Sports Biomech. 2021:1-19. doi:10.1080/14763141.2021.1908412

67. Bayne H, Cockcroft J, Robyn A, Louw Q. Objective classification of countermovement jump force-time curve modality: Within athlete-consistency and associations with jump performance. Sports biomechanics. 2021:1-12. doi:10.1080/14763141.2021.1991995

68. Cockcroft J, Robyn A, Louw Q, Bayne H. A large-scale numerical analysis of unimodal and bimodal features in force plate data measured during vertical countermovement jumping. ISBS Proceedings Archive. 2019; 37(1):415.

69. Jordan MJ, Aagaard P, Herzog W. Asymmetry and thigh muscle coactivity in fatigued anterior cruciate ligament-reconstructed elite skiers. Med Sci Sports Exerc. 2017; 49(1):11-20. doi:10.1249/mss.0000000000001076

70. Taberner M, van Dyk N, Allen T, Jain N, Richter C, Drust B, et al. Physical preparation and return to performance of an elite female football player following acl reconstruction: A journey to the fifa women's world cup. BMJ Open Sport & Exercise Medicine. 2020; 6(1):e000843. doi:10.1136/bmjsem-2020-000843

71. Hughes-Oliver CN, Harrison KA, Williams DSB, Queen RM. Statistical parametric mapping as a measure of differences between limbs: Applications to clinical populations. J Appl Biomech. 2019:1-11. doi:10.1123/jab.2018-0392

72. Hughes S, Warmenhoven J, Haff GG, Chapman DW, Nimphius S. Countermovement jump and squat jump force-time curve analysis in control and fatigue conditions. J Strength Cond Res. 2021; doi:10.1519/jsc.0000000000003955

73. King E, Richter C, Daniels KAJ, Franklyn-Miller A, Falvey E, Myer GD, et al. Biomechanical but not strength or performance measures differentiate male athletes who experience acl reinjury on return to level 1 sports. Am J Sports Med. 2021; 49(4):918-27. doi:10.1177/0363546520988018

74. Jordan MJ, Morris N, Nimphius S, Aagaard P, Herzog W. Attenuated lower limb stretch-shorten-cycle capacity in acl injured vs. Non-injured female alpine ski racers: Not just a matter of between-limb asymmetry. Front Sports Act Living. 2022; 4:853701. doi:10.3389/fspor.2022.853701

75. Gokeler A, Dingenen B, Hewett TE. Rehabilitation and return to sport testing after anterior cruciate ligament reconstruction: Where are we in 2022? Arthrosc Sports Med Rehabil. 2022; 4(1):e77-e82. doi:10.1016/j.asmr.2021.10.025

76. Bishop C, Read P, Lake J, Chavda S, Turner A. Inter-limb asymmetries: Understanding how to calculate differences from bilateral and unilateral tests. STRENGTH AND CONDITIONING JOURNAL. 2018; 40 doi:10.1519/SSC.0000000000000371

77. King E, Richter C, Daniels KAJ, Franklyn-Miller A, Falvey E, Myer GD, et al. Can biomechanical testing after anterior cruciate ligament reconstruction identify athletes at risk for subsequent acl injury to the contralateral uninjured limb? Am J Sports Med. 2021; 49(3):609-19. doi:10.1177/0363546520985283

78. King E, Richter C, Franklyn-Miller A, Daniels K, Wadey R, Jackson M, et al. Biomechanical but not timed performance asymmetries persist between limbs 9 months after acl reconstruction during planned and unplanned change of direction. J Biomech. 2018; 81:93-103. doi:10.1016/j.jbiomech.2018.09.021

ANNEXURES

Annexure A: Research ethics committee approval certificate - SEMLI (2021)

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences

Institution: The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.

- FWA 00002567, Approved dd 18 March 2022 and Expires 18 March 2027.
- IORG #: IORG0001762 OMB No. 0990-0278 Approved for use through August 31, 2023.

Faculty of Health Sciences **Research Ethics Committee**

14 July 2022

Approval Certificate
Annual Renewal

Dear Mrs CJ de Franca,

Ethics Reference No.: 380/2021 – Line 1
Title: Changes in the countermovement jump force-time waveform after anterior cruciate ligament reconstruction

The **Annual Renewal** as supported by documents received between 2022-06-21 and 2022-07-13 for your research, was approved by the Faculty of Health Sciences Research Ethics Committee on 2022-07-13 as resolved by its quorate meeting.

Please note the following about your ethics approval:

- Renewal of ethics approval is valid for 1 year, subsequent annual renewal will become due on 2023-07-14.
- Please remember to use your protocol number (380/2021) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, monitor the conduct of your research, or suspend or withdraw ethics approval.

Ethics approval is subject to the following:

- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

On behalf of the FHS REC, Dr R Sommers
MBChB, MMed (Int), MPharmMed, PhD
Deputy Chairperson *of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria*

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes, Second Edition 2015 (Department of Health)

Research Ethics Committee
Room 4-60, Level 4, Tswelopele Building
University of Pretoria, Private Bag x323
Gezina 0031, South Africa
Tel +27 (0)12 356 3084
Email: deepeka.behari@up.ac.za
www.up.ac.za

Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

Annexure B: Renewal - Research ethics committee approval certificate – SEMLI (2022)

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences

Institution: The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.

- FWA 00002567, Approved dd 22 May 2002 and Expires 03/20/2022.
- IORG #: IORG0001762 OMB No. 0990-0279 Approved for use through February 28, 2022 and Expires: 03/04/2023.

Faculty of Health Sciences **Research Ethics Committee**

29 July 2021

Approval Certificate
New Application

Dear Mrs CJ de Franca

Ethics Reference No.: 380/2021
Title: Changes in the countermovement jump force-time waveform after anterior cruciate ligament reconstruction

The **New Application** as supported by documents received between 2021-06-28 and 2021-07-28 for your research, was approved by the Faculty of Health Sciences Research Ethics Committee on 2021-07-28 as resolved by its quorate meeting.

Please note the following about your ethics approval:

- Ethics Approval is valid for 1 year and needs to be renewed annually by 2022-07-29.
- Please remember to use your protocol number (380/2021) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, monitor the conduct of your research, or suspend or withdraw ethics approval.

Ethics approval is subject to the following:

- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

On behalf of the FHS REC, Professor Werdie (CW) Van Staden
MBChB, MMed(Psych), MD, FCPsych(SA), FTCL, UPLM
***Chairperson**: Faculty of Health Sciences Research Ethics Committee*

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes, Second Edition 2015 (Department of Health)

Research Ethics Committee
Room 4-60, Level 4, Tswelopele Building
University of Pretoria, Private Bag x323
Gezina 0031, South Africa
Tel +27 (0)12 356 3084
Email: deepeka.behari@up.ac.za
www.up.ac.za

Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

Annexure C: Amendment - Research ethics committee approval certificate – SEMLI (2022)

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences

Institution: The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.

- FWA 00002567, Approved dd 18 March 2022 and Expires 18 March 2027.
- IORG #: IORG0001762 OMB No. 0990-0278 Approved for use through August 31, 2023.

Faculty of Health Sciences **Research Ethics Committee**

13 October 2022

Approval Certificate
Amendment

Dear Mrs CJ de Franca,

Ethics Reference No.: 380/2021 – Line 3
Title: Changes in countermovement jump performance and the force-time waveform after anterior cruciate ligament reconstruction.

The **Amendment** as supported by documents received between 2022-10-03 and 2022-10-12 for your research, was approved by the Faculty of Health Sciences Research Ethics Committee on 2022-10-12 as resolved by its quorate meeting.

Please note the following about your ethics approval:

- Please remember to use your protocol number (380/2021) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, monitor the conduct of your research, or suspend or withdraw ethics approval.

Ethics approval is subject to the following:

- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

On behalf of the FHS REC, Dr R Sommers
MBChB, MMed (Int), MPharmMed, PhD
Deputy Chairperson *of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria*

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes, Second Edition 2015 (Department of Health).

Research Ethics Committee
Room 4-60, Level 4, Tswelopele Building
University of Pretoria, Private Bag x323
Gezina 0031, South Africa
Tel +27 (0)12 356 3084
Email: deepeka.behari@up.ac.za
www.up.ac.za

Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

Annexure D: Umbrella Study - Research ethics committee approval certificate – SEMLI (2021)

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences

Institution: The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.

- FWA 00002567, Approved dd 22 May 2002 and Expires 03/20/2022.
- IORG #: IORG0001762 OMB No. 0990-0279 Approved for use through February 28, 2022 and Expires: 03/04/2023.

11 February 2021

Approval Certificate
Annual Renewal

Ethics Reference No.: 869/2019
Title: Sport Science Services at the University of Pretoria: An Umbrella Protocol

Dear Dr HL Bayne

The **Annual Renewal** as supported by documents received between 2021-01-18 and 2021-02-10 for your research, was approved by the Faculty of Health Sciences Research Ethics Committee on 2021-02-10 as resolved by its quorate meeting.

Please note the following about your ethics approval:

- Renewal of ethics approval is valid for 1 year, subsequent annual renewal will become due on 2022-02-11.
- Please remember to use your protocol number (869/2019) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, monitor the conduct of your research, or suspend or withdraw ethics approval.

Ethics approval is subject to the following:

- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

Dr R Sommers
MBChB MMed (Int) MPharmMed PhD
Deputy Chairperson of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes, Second Edition 2015 (Department of Health)

Research Ethics Committee
Room 4-60, Level 4, Tswelopele Building
University of Pretoria, Private Bag x323
Gezina 0031, South Africa
Tel +27 (0)12 356 3084
Email: deepeka.behari@up.ac.za
www.up.ac.za

Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

Annexure E: Conjoint Health Research Ethics Board Approval – CSI (2021)

Conjoint Health Research Ethics Board
Research Services Office
2500 University Drive, NW
Calgary AB T2N 1N4
Telephone: (403) 220-2297
chreb@ucalgary.ca

CERTIFICATION OF INSTITUTIONAL ETHICS APPROVAL

Ethics approval for the following research has been renewed by the Conjoint Health Research Ethics Board (CHREB) at the University of Calgary. The CHREB is constituted and operates in compliance with the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* (TCPS 2); Health Canada Food and Drug Regulations Division 5; Part C; ICH Guidance E6: Good Clinical Practice and the provisions and regulations of the Health Information Act, RSA 2000 c H-5.

Ethics ID:	REB14-2270_REN6
Principal Investigator:	Walter Herzog
Co-Investigator(s):	Patricia Katherine Doyle-Baker Matthew Jordan
Student Co-Investigator(s):	
Study Title:	A Retrospective Analysis of the Pattern of Secondary Injury Associated with Primary ACL Injury in Elite Alpine Ski Racers
Sponsor:	Kinesiology - Administration

Effective: 3-Mar-2021 **Expires:** 2-Mar-2022

Restrictions:

This Certification is subject to the following conditions:

1. The research as described in the application is approved.
2. Proposed modifications must be approved prior to implementation.
3. An application for renewal must be made annually.
4. Closure requests must be submitted when the research is complete or terminated.

Approved By: **Date:**

Stacey A. Page, PhD, Chair , CHREB 22-Feb-2021

Note: This correspondence includes an electronic signature (validation and approval via an online system).

Annexure F: Conjoint Health Research Ethics Board Approval – CSI (2020)

Conjoint Health Research Ethics Board
Research Services Office
2500 University Drive, NW
Calgary AB T2N 1N4
Telephone: (403) 220-2297
chreb@ucalgary.ca

CERTIFICATION OF INSTITUTIONAL ETHICS APPROVAL

Ethics approval for the following research has been renewed by the Conjoint Health Research Ethics Board (CHREB) at the University of Calgary. The CHREB is constituted and operates in compliance with the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* (TCPS 2); Health Canada Food and Drug Regulations Division 5; Part C; ICH Guidance E6: Good Clinical Practice and the provisions and regulations of the Health Information Act, RSA 2000 c H-5.

Ethics ID:	REB15-1094_REN6
Principal Investigator:	Walter Herzog
Co-Investigator(s):	Matthew Jordan
Student Co-Investigator(s):	Nicholas Simpson Bryan Yu Nathaniel Morris Drew Lawson
Study Title:	The Long-Term Effects of ACL Injury on Bilateral Limb Asymmetry and Muscle Activation in Elite Alpine Ski Racers
Sponsor:	Canadian Institutes of Health Research

Effective: 21-Jun-2020 **Expires:** 20-Jun-2021

Restrictions:

This Certification is subject to the following conditions:

1. Approval is granted only for the research and purposes described in the application.
2. Any modification to the approved research must be submitted to the CHREB for approval.
3. An annual application for renewal of ethics certification must be submitted and approved by the above expiry date.
4. A closure request must be sent to the CHREB when the research is complete or terminated.

Annexure G: Permission to use data – CSI (2021)

CANADIAN SPORT INSTITUTE CALGARY — INSTITUT CANADIEN DU SPORT

2021-05-09

To whom it may concern,

I am writing this letter in support of Ms. Cassidy de Franca's Master Thesis project and providing written notification that it is permissible for her to use previously collected vertical jump force-time recordings and participant demographic and injury information. These data were collected at the Canadian Sport Institute Calgary as a part of ongoing research approved by the University of Calgary Research Ethics Board. Data will be anonymized to protect participant privacy.

If you have any questions or concerns, please let me know.

Sincerely

Dr. Matt Jordan, PhD
Director, Sport Science, Canadian Sport Institute Calgary
Adjunct Professor, Faculty of Kinesiology, University of Calgary
E: mjordan@ucalgary.ca P: 403-202-6817

Markin MacPhail Centre, #250, 151 Canada Olympic Road SW, Calgary, AB T3B 6B7

SPORT INSTITUTE NETWORK
RÉSEAU DES INSTITUTS DU SPORT

Annexure H: Permission to use facilities, equipment, and data – SEMLI (2021)

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

SEMLI
Sport, Exercise Medicine and Lifestyle Institute

04 May 2021

To whom it may concern:

Permission to use SEMLI's facilities, equipment and associated data

I hereby grant the following student permission to use SEMLI facilities and equipment and associated data for research purposes for their degree.

Student name:	Cassidy de Franca
Student number:	14450161
Degree programme:	MSc Sports Science (Biomechanics)
Working title:	Changes in the countermovement jump force-time waveform after anterior cruciate ligament reconstruction

The project falls under the umbrella protocol (869/2019) entitled "Sport science services at the University of Pretoria: An umbrella protocol", for which Dr Helen Bayne is the principal investigator.

Prof. M Schwellnus
Director: SEMLI
Faculty of Health Sciences
University of Pretoria

Annexure I: Informed consent form – CSI (2021)

UNIVERSITY OF CALGARY
KINESIOLOGY

HUMAN PERFORMANCE LABORATORY

INFORMED CONSENT FORM
University of Calgary
Faculty of Kinesiology
Human Performance Laboratory

Project Title: The Long-Term Effects of ACL Injury on Bilateral Limb Asymmetry and Muscle Activation Patterns in Elite Athletes

Investigators: Walter Herzog, Matthew Jordan, Isabel Aldrich-Witt

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more details about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this form carefully and to understand any accompanying information.

CHREB COVID-19 Risk and Consent Requirements

The COVID pandemic has altered research conduct significantly. The University of Calgary has determined that certain changes must be put in place to reduce risk to participants and staff.

Increased research-attributable risk

By participating in this research project and because in-person interaction is required, you are at an increased risk of exposure, which may include:

- increased time within a research facility
- increased exposure to other people (e.g. participants or other people)

Visiting our facility for a research interaction may increase you risk by:

- risks associated with travel (e.g., public transit)
- time within a research facility
- exposure to other people

Risk mitigation

To help reduce your risk we are doing the following:

- use of PPE for both research staff and research participants (e.g., masks, gloves)
- use of hand sanitizer for both research staff and research participants.
- single use research apparatus where possible
- physical distancing measures
- sanitization of surfaces and multi-use equipment between participants

UNIVERSITY OF CALGARY
KINESIOLOGY

Background

Anterior cruciate ligament (ACL) injury is very common amongst competitive athletes, and despite significant scientific attention and equipment modification injury rates have remained unchanged. Furthermore, after the first ACL injury, elite athletes are at considerable risk for re-injury suggesting that future research be done into the long-term effects of ACL injury.

In other populations it has been shown that over the long-term, ACL injury results in significant bilateral asymmetries during multi-joint movements such as jumping and squatting, and neuromuscular deficits. These asymmetries and deficits are linked to ACL injury and the development of early osteoarthritis.

Cellular and structural changes in muscle influence the ability of muscle to produce force and therefore trying to identify cellular changes after injury may be crucial for determining athlete readiness for return to sport. Research investigating the changes injury and disuse has on structural proteins in muscle in addition to muscle strength capacity post-injury can lead to a better understanding of the muscular impact of ACL injury and rehabilitation protocols aimed at restoring neuromuscular function.

Given the high rates ACL re-injury in athletes, the well-known long-term effects of ACL injury on bilateral asymmetries in other populations, and the presence of bilateral symmetry in healthy competitive athletes it is proposed that research be undertaken to better understand the long-term effects of ACL injury on competitive athletes.

Purpose

The purpose of this research project is to investigate the long-term effects of ACL injury on structural proteins in the lower limb muscles along with bilateral limb physical capacity and asymmetry during isometric knee flexion and extension along with jump testing. It is hoped that the current research project will improve the understanding of the long-term effects of ACL injury on elite alpine ski racers, and lead to better rehabilitation, screening and testing protocols.

Explanation of Subject's Involvement

As a participant in this study with an ACL injury, you are required to attend physical capacity testing sessions of approximately 90 minutes in duration at four different dates around 3 months apart up to a year post surgery. You will perform three maximal effort contractions of knee extension, knee flexion and a series of jump testing on force plates including single leg drop jumps. Both limbs will be assessed. Sometimes you will jump land on one leg and sometimes you will jump and land on both legs. If you are an uninjured participant, you will only be required to do this testing 1-2 times.

In addition to this, if you are an injured athlete that is undergoing anterior ligament reconstruction surgery, you will also be required to undergo biopsies of your

semitendinosus hamstring and vastus lateralis quadricep muscles of both limbs at the time of surgery and at 2-4 time periods after surgery. The first biopsy procedure will occur during surgery and will be performed by your orthopaedic surgeon. The 2nd to 4th biopsies will be performed at months 3-12 post-surgery.

If you are an uninjured athlete, you will only be required to undergo physical capacity testing and biopsy of your semitendinosus hamstring and vastus lateralis quadricep muscles of both limbs once.

Local anesthetic will be injected into the skin just above the muscle biopsy site. Disposable instruments for each biopsy will be used to ensure a sterile environment. Extended field of view ultrasound will be used to identify the semitendinosus (ST) hamstring muscle and guide the biopsy needle as it is a smaller muscle. This will be done by someone skilled in musculoskeletal ultrasound in order to be sure that the muscle sample is indeed from the ST muscle. Biopsy sites include semitendinosus hamstring muscles along with samples from the vastus lateralis quadricep muscles from both limbs.

Risk and Discomforts

The risks involved are minimal. There might be some discomfort or post-test joint or muscle pain of short duration. There is some potential for minor muscle strain.

Biopsy is procedure commonly done for muscle fibre sampling. Some minor discomfort usually occurs during the injection of the anesthetic, but this allows the biopsy procedure to be relatively pain free. Most participants describe a sensation of pressure during the sampling of muscle fibres, but this is usually not painful. There is a very small risk of infection with the biopsy procedure due to the penetration of the skin, as there is with any procedure involving needles. To make sure this risk stays very low, we will ensure that the environment and skin are sterilized, the proper protection is worn, and new disposable needles are used with each participant. Mild to moderate soreness around the biopsy sites is common for a few days after the procedure but shouldn't interfere with daily life or training.

Research Related Injury

In the event that you suffer injury as a result of participating in this research there will be no compensation provided to you by the University of Calgary, the Calgary Health Region or the Researchers. You still have all your legal rights. Nothing said in this consent form alters your right to seek damages.

Benefits to be Expected

If you agree to participate in this study, there may or may not be a direct medical benefit for you. If you have previously suffered an ACL injury, the results of this study may be of benefit to your rehabilitation. Further, this study will assist the researchers in developing a better understanding

of the long-term effects of ACL injury on performance and neuromuscular function in competitive athletes. The results of this investigation will lead to further research to optimize and improve rehabilitation protocols, and to develop better screening and testing protocols for competitive athletes returning from ACL injury.

Do I have to Participate?

Participation in this study is voluntary. You are free to withdraw from the study at any point by informing any of the lead investigators. In no way will your voluntary withdrawal affect you. Furthermore the investigators reserve the right to withdraw from the study should any factor arise that may affect the research question.

Costs for the Participants

There are no costs associated with your participation in this study.

Privacy of Your Records

Information obtained during this research project is confidential. It will not be released without your written consent. The information however, may be used for statistical analysis or scientific purposes with your right to privacy retained. To prevent the invasion of privacy through a digital medium, all computerized data will be saved on a password protected hard drive. All passing of information between computers will be done only with the use of an external hard drive eliminating the need of a network transfer of information. Three years following the final day of data collection all files will be destroyed. Files saved on disk will be erased and hard copy files will be shredded. Identification of subjects through publication will be prevented by the use of the Subject ID Codes.

Freedom of Consent

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the investigators, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time without jeopardizing your health care. If you have further questions concerning matters related to this research, please contact:

Isabel Aldrich-Witt (Ph. 780-288-6444) or
Dr. Matthew Jordan (Ph. 403-714-4655) or
Dr. Walter Herzog (Ph. 403-220-8525)

If you have any questions concerning your rights as a possible participant in this research, please contact the Chair Conjoint Health Research Ethics Board, University of Calgary at 403-220-7990. The University of Calgary Conjoint Health Research Ethics Board has approved this study (REB15-1094).

UNIVERSITY OF CALGARY
KINESIOLOGY

Signatures

Participant	Signature and Date
Investigator Name	Signature and Date
Witness' Name	Signature and Date

A signed copy of this consent form has been given to you to keep for your records and reference.

Annexure J: Informed consent form – CSI (2015)

UNIVERSITY OF CALGARY
KINESIOLOGY

HUMAN PERFORMANCE LABORATORY

INFORMED CONSENT FORM
University of Calgary
Faculty of Kinesiology
Human Performance Laboratory

INFORMED CONSENT FORM

TITLE: A Retrospective Analysis of the Pattern of Secondary Injury Associated with Primary ACL Injury in Elite Alpine Ski Racers

INVESTIGATORS: Walter Herzog, Matthew Jordan

This consent form is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Take the time to read this carefully and to understand any accompanying information. You will receive a copy of this form.

BACKGROUND

Anterior cruciate ligament (ACL) injury is very common amongst elite alpine skiers, and despite significant attention and equipment modification injury rates remain quite high. Furthermore, after the first ACL injury, elite alpine skiers are at risk for a re-injury suggesting that future research be done into injury and re-injury prevention.

In addition to ACL rupture, knee injuries often occur alongside other injuries to knee structures, which can worsen functional outcomes. The type of surgical procedure that is used including the graft type also affects functional outcomes after ACL reconstruction. To date, very little information is known about the pattern of secondary injury associated with ACL injury and the prevalence of different surgical procedures in elite alpine ski racers. Yet, an understanding of these factors is important for ACL injury and re-injury prevention strategies.

WHAT IS THE PURPOSE OF THE STUDY?

The purpose of this research project is to investigate the pattern of secondary injury associated with primary ACL injury and the prevalence of different surgical procedures in an elite alpine skiing population. Additionally, using a physical fitness-testing database, fitness indices prior to injury and at the time point closest to one year post-surgery will be used to evaluate the relationship between secondary knee injuries and the restoration of physical fitness.

UNIVERSITY OF CALGARY
KINESIOLOGY

WHAT WOULD I HAVE TO DO?

As a participant in this study your surgical notes will be obtained from your orthopaedic surgeon and the findings will be coded and evaluated. Additionally, the physical fitness-testing database with the Canadian Sport Institute-Calgary will be accessed to obtain fitness indices before your surgery and at the time point closest to one year after your surgery.

WHAT ARE THE RISKS?

The risks associated with this study are low and the probability of any adverse events is low.

WILL I BENEFIT IF I TAKE PART?

This study will assist us to develop a better understanding of the nature of ACL injury in elite alpine ski racing and the performance effects of these injuries. The results of this investigation will lead to the development of a standardized method for reporting the factors associated with ACL injury, and to improve screening and testing protocols for alpine ski racers returning from ACL injury.

DO I HAVE TO PARTICIPATE?

Participation in this study is voluntary. You are free to withdraw from the study at any point by informing any of the lead investigators. In no way will your voluntary withdrawal affect your care or involvement in Alpine Canada. Furthermore the investigators reserve the right to withdraw you from the study should any factor arise that may affect the research question. If you choose to withdraw from this study at any point, your data will be withdrawn.

WILL I BE PAID FOR PARTICIPATING, OR DO I HAVE TO PAY FOR ANYTHING?

You will not be paid to participate in this study and there will be no financial costs associated with your participation.

WILL MY RECORDS BE KEPT PRIVATE?

Information obtained during this research project is confidential. It will not be released without your written consent. The information however, may be used for statistical analysis or scientific purposes with your right to privacy retained. To prevent the invasion of privacy through a digital medium, all computerized data will be saved on a password protected hard drive. All passing of information between computers will be done only with the use of an external hard drive eliminating the need of a network transfer of information. Five years following the final day of data collection all files will be destroyed. Files saved on disk will be erased and hard copy files will be shredded. Identification of subjects through publication will be prevented by the use of the Subject ID Codes.

UNIVERSITY OF CALGARY
KINESIOLOGY

IF I SUFFER A RESEARCH-RELATED INJURY, WILL I BE COMPENSATED?

In the event that you suffer as a result of participating in this research there will be no compensation provided to you by the University of Calgary, the Alberta Health Services or the Researchers. You still have all your legal rights. Nothing said in this consent form alters your right to seek damages

SIGNATURES

Your signature on this form indicates that you have understood to your satisfaction the information regarding your participation in the research project and agree to participate as a participant. In no way does this waive your legal rights nor release the investigators or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time without jeopardizing your health care. If you have further questions concerning matters related to this research, please contact:

Matthew Jordan (Ph. 403-714-4655) or Dr. Walter Herzog (Ph. 403-220-8525)

If you have any questions concerning your rights as a possible participant in this research, please contact the Chair Conjoint Health Research Ethics Board, University of Calgary at 403-220-7990.

_____	_____
Participant Name	Signature and Date
_____	_____
Investigator Name	Signature and Date
_____	_____
Witness Name	Signature and Date

The University of Calgary Conjoint Health Research Ethics Board has approved this research study.

A copy of this consent form has been given to you to keep for your records and reference.

Annexure K: Declaration of Helsinki

Special Communication

World Medical Association Declaration of Helsinki
Ethical Principles for Medical Research Involving Human Subjects

World Medical Association

Adopted by the 18th WMA General Assembly, Helsinki, Finland, June 1964, and amended by the:
29th WMA General Assembly, Tokyo, Japan, October 1975
35th WMA General Assembly, Venice, Italy, October 1983
41st WMA General Assembly, Hong Kong, September 1989
48th WMA General Assembly, Somerset West, Republic of South Africa, October 1996
52nd WMA General Assembly, Edinburgh, Scotland, October 2000
53rd WMA General Assembly, Washington, DC, USA, October 2002 (Note of Clarification added)
55th WMA General Assembly, Tokyo, Japan, October 2004 (Note of Clarification added)
59th WMA General Assembly, Seoul, Republic of Korea, October 2008
64th WMA General Assembly, Fortaleza, Brazil, October 2013

Preamble

1. The World Medical Association (WMA) has developed the Declaration of Helsinki as a statement of ethical principles for medical research involving human subjects, including research on identifiable human material and data.

   The Declaration is intended to be read as a whole and each of its constituent paragraphs should be applied with consideration of all other relevant paragraphs.

2. Consistent with the mandate of the WMA, the Declaration is addressed primarily to physicians. The WMA encourages others who are involved in medical research involving human subjects to adopt these principles.

General Principles

3. The Declaration of Geneva of the WMA binds the physician with the words, "The health of my patient will be my first consideration," and the International Code of Medical Ethics declares that, "A physician shall act in the patient's best interest when providing medical care."

4. It is the duty of the physician to promote and safeguard the health, well-being and rights of patients, including those who are involved in medical research. The physician's knowledge and conscience are dedicated to the fulfillment of this duty.

5. Medical progress is based on research that ultimately must include studies involving human subjects.

6. The primary purpose of medical research involving human subjects is to understand the causes, development and effects of diseases and improve preventive, diagnostic and therapeutic interventions (methods, procedures and treatments). Even the best proven interventions must be evaluated continually through research for their safety, effectiveness, efficiency, accessibility and quality.

7. Medical research is subject to ethical standards that promote and ensure respect for all human subjects and protect their health and rights.

8. While the primary purpose of medical research is to generate new knowledge, this goal can never take precedence over the rights and interests of individual research subjects.

9. It is the duty of physicians who are involved in medical research to protect the life, health, dignity, integrity, right to self-determination, privacy, and confidentiality of personal information of research subjects. The responsibility for the protection of research subjects must always rest with the physician or other health care professionals and never with the research subjects, even though they have given consent.

10. Physicians must consider the ethical, legal and regulatory norms and standards for research involving human subjects in their own countries as well as applicable international norms and standards. No national or international ethical, legal or regulatory requirement should reduce or eliminate any of the protections for research subjects set forth in this Declaration.

11. Medical research should be conducted in a manner that minimises possible harm to the environment.

12. Medical research involving human subjects must be conducted only by individuals with the appropriate ethics and scientific education, training and qualifications. Research on patients or healthy volunteers requires the supervision of a competent and appropriately qualified physician or other health care professional.

13. Groups that are underrepresented in medical research should be provided appropriate access to participation in research.

14. Physicians who combine medical research with medical care should involve their patients in research only to the extent that this is justified by its potential preventive, diagnostic or therapeutic value and if the physician has good reason to believe that participation in the research study will not adversely affect the health of the patients who serve as research subjects.

15. Appropriate compensation and treatment for subjects who are harmed as a result of participating in research must be ensured.

Risks, Burdens and Benefits

16. In medical practice and in medical research, most interventions involve risks and burdens.

    Medical research involving human subjects may only be conducted if the importance of the objective outweighs the risks and burdens to the research subjects.

17. All medical research involving human subjects must be preceded by careful assessment of predictable risks and burdens to the individuals and groups involved in the research in comparison with foreseeable benefits to them and to other individuals or groups affected by the condition under investigation.

    Measures to minimise the risks must be implemented. The risks must be continuously monitored, assessed and documented by the researcher.

18. Physicians may not be involved in a research study involving human subjects unless they are confident that the risks have been adequately assessed and can be satisfactorily managed.

    When the risks are found to outweigh the potential benefits or when there is conclusive proof of definitive outcomes, physicians must assess whether to continue, modify or immediately stop the study.

Vulnerable Groups and Individuals

19. Some groups and individuals are particularly vulnerable and may have an increased likelihood of being wronged or of incurring additional harm.

    All vulnerable groups and individuals should receive specifically considered protection.

20. Medical research with a vulnerable group is only justified if the research is responsive to the health needs or priorities of this group and the research cannot be carried out in a non-vulnerable group. In addition, this group should stand to benefit from the knowledge, practices or interventions that result from the research.

Scientific Requirements and Research Protocols

21. Medical research involving human subjects must conform to generally accepted scientific principles, be based on a thorough knowledge of the scientific literature, other relevant sources of information, and adequate laboratory and, as appropriate, animal experimentation. The welfare of animals used for research must be respected.

22. The design and performance of each research study involving human subjects must be clearly described and justified in a research protocol.

    The protocol should contain a statement of the ethical considerations involved and should indicate how the principles in this Declaration have been addressed. The protocol should include information regarding funding, sponsors, institutional affiliations, potential conflicts of interest, incentives for subjects and information regarding provisions for treating and/or compensating subjects who are harmed as a consequence of participation in the research study.

    In clinical trials, the protocol must also describe appropriate arrangements for post-trial provisions.

Research Ethics Committees

23. The research protocol must be submitted for consideration, comment, guidance and approval to the concerned research ethics committee before the study begins. This committee must be transparent in its functioning, must be independent of the researcher, the sponsor and any other undue influence and must be duly qualified. It must take into consideration the laws and regulations of the country or countries in which the research is to be performed as well as applicable international norms and standards but these must not be allowed to reduce or eliminate any of the protections for research subjects set forth in this Declaration.

    The committee must have the right to monitor ongoing studies. The researcher must provide monitoring information to the committee, especially information about any serious adverse events. No amendment to the protocol may be made without consideration and approval by the committee. After the end of the study, the researchers must submit a final report to the committee containing a summary of the study's findings and conclusions.

Privacy and Confidentiality

24. Every precaution must be taken to protect the privacy of research subjects and the confidentiality of their personal information.

Informed Consent

25. Participation by individuals capable of giving informed consent as subjects in medical research must be voluntary. Although it

may be appropriate to consult family members or community leaders, no individual capable of giving informed consent may be enrolled in a research study unless he or she freely agrees.

26. In medical research involving human subjects capable of giving informed consent, each potential subject must be adequately informed of the aims, methods, sources of funding, any possible conflicts of interest, institutional affiliations of the researcher, the anticipated benefits and potential risks of the study and the discomfort it may entail, post-study provisions and any other relevant aspects of the study. The potential subject must be informed of the right to refuse to participate in the study or to withdraw consent to participate at any time without reprisal. Special attention should be given to the specific information needs of individual potential subjects as well as to the methods used to deliver the information.

    After ensuring that the potential subject has understood the information, the physician or another appropriately qualified individual must then seek the potential subject's freely-given informed consent, preferably in writing. If the consent cannot be expressed in writing, the non-written consent must be formally documented and witnessed.

    All medical research subjects should be given the option of being informed about the general outcome and results of the study.

27. When seeking informed consent for participation in a research study the physician must be particularly cautious if the potential subject is in a dependent relationship with the physician or may consent under duress. In such situations the informed consent must be sought by an appropriately qualified individual who is completely independent of this relationship.

28. For a potential research subject who is incapable of giving informed consent, the physician must seek informed consent from the legally authorised representative. These individuals must not be included in a research study that has no likelihood of benefit for them unless it is intended to promote the health of the group represented by the potential subject, the research cannot instead be performed with persons capable of providing informed consent, and the research entails only minimal risk and minimal burden.

29. When a potential research subject who is deemed incapable of giving informed consent is able to give assent to decisions about participation in research, the physician must seek that assent in addition to the consent of the legally authorised representative. The potential subject's dissent should be respected.

30. Research involving subjects who are physically or mentally incapable of giving consent, for example, unconscious patients, may be done only if the physical or mental condition that prevents giving informed consent is a necessary characteristic of the research group. In such circumstances the physician must seek informed consent from the legally authorised representative. If no such representative is available and if the research cannot be delayed, the study may proceed without informed consent provided that the specific reasons for involving subjects with a condition that renders them unable to give informed consent have been stated in the research protocol and the study has been approved by a research ethics committee. Consent to remain in the research must be obtained as soon as possible from the subject or a legally authorised representative.

31. The physician must fully inform the patient which aspects of their care are related to the research. The refusal of a patient to participate in a study or the patient's decision to withdraw from the study must never adversely affect the patient-physician relationship.

32. For medical research using identifiable human material or data, such as research on material or data contained in biobanks or similar repositories, physicians must seek informed consent for its collection, storage and/or reuse. There may be exceptional situations where consent would be impossible or impracticable to obtain for such research. In such situations the research may be done only after consideration and approval of a research ethics committee.

Use of Placebo

33. The benefits, risks, burdens and effectiveness of a new intervention must be tested against those of the best proven intervention(s), except in the following circumstances:

    Where no proven intervention exists, the use of placebo, or no intervention, is acceptable; or

    Where for compelling and scientifically sound methodological reasons the use of any intervention less effective than the best proven one, the use of placebo, or no intervention is necessary to determine the efficacy or safety of an intervention

    and the patients who receive any intervention less effective than the best proven one, placebo, or no intervention will not be subject to additional risks of serious or irreversible harm as a result of not receiving the best proven intervention.

    Extreme care must be taken to avoid abuse of this option.

Post-Trial Provisions

34. In advance of a clinical trial, sponsors, researchers and host country governments should make provisions for post-trial access for all participants who still need an intervention identified as beneficial in the trial. This information must also be disclosed to participants during the informed consent process.

Research Registration and Publication and Dissemination of Results

35. Every research study involving human subjects must be registered in a publicly accessible database before recruitment of the first subject.

36. Researchers, authors, sponsors, editors and publishers all have ethical obligations with regard to the publication and dissemination of the results of research. Researchers have a duty to make publicly available the results of their research on human subjects and are accountable for the completeness and accuracy of their reports. All parties should adhere to accepted guidelines for ethical reporting. Negative and inconclusive as well as positive results must be published or otherwise made publicly available. Sources of funding, institutional affiliations and conflicts of interest must be declared in the publication. Reports of research not in accordance with the principles of this Declaration should not be accepted for publication.

Unproven Interventions in Clinical Practice

37. In the treatment of an individual patient, where proven interventions do not exist or other known interventions have been ineffective, the physician, after seeking expert advice, with informed consent from the patient or a legally authorised representative, may use an unproven intervention if in the physician's judgement it offers hope of saving life, re-establishing health or alleviating suffering. This intervention should subsequently be made the object of research, designed to evaluate its safety and efficacy. In all cases, new information must be recorded and, where appropriate, made publicly available.

ARTICLE INFORMATION

Corresponding Author: World Medical Association, 13, ch. du Levant, CIB - Bâtiment A, 01210 Ferney-Voltaire, France; wma@wma.net.

Published Online: October 19, 2013. doi:10.1001/jama.2013.281053.

Online-Only Content: Audio podcast is available at www.jama.com.

Annexure L: Data management policy – UP

UNIVERSITY OF PRETORIA
Office of the Vice-Principal: Research and Postgraduate Education

RESEARCH DATA MANAGEMENT POLICY

Document type: Policy
Policy Category: Academic

Document number: S 4417/17

CONTENTS

1. INTRODUCTION

Data and research records are an essential part of all research projects. With advances in information technology and digital science over the last decade, the wider research context has changed rapidly, the amount of data being generated has increased dramatically, and there is a need to ensure that research data is managed so as to be accessible and secure.

Concerns related to intellectual property rights, data authenticity, and ownership of data, have highlighted the need to ensure the maintenance, storage and preservation of the data on which research publications, theses, reports, patents and other forms of published material are based. These data must be stored in a secure environment, in tamper-free form (as far as possible), and with sufficient detail (as metadata). Metadata will enable all stakeholders (principal investigators, independent bodies of experts, the broader research community, funding agencies and the public) to address questions relating to accuracy and

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

authenticity, and will also support the publication and re-use of the data generated from research activities.

In light of the changes referred to above, there have been developments with regard to the requirements of national and international funders, academic publishers and other related organisations, requiring research data to be managed in a systematic and transparent way. In the South African context, agencies including the National Research Foundation (NRF) require that data supporting publications be deposited in an accredited open access (OA) data repository with a registered Digital Object Identifier (DOI) for citation and referencing purposes from March 2015 onwards.[1]

The rationale for this policy revision is that these changes and requirements must be addressed in order to ensure the accessibility and security of the University's research data, and to ensure that it managed in a systematic manner.

2. ORGANISATIONAL SCOPE

This policy applies to all University staff, students and affiliates involved in conducting research under the auspices of the University of Pretoria.

This policy supersedes the UP Policy for the Preservation and Retention of Research Data (Rt 306/07).

3. PURPOSE

The purpose of this policy is to govern the management of research data at the University of Pretoria and to ensure that all research data generated at the University of Pretoria are managed and curated effectively and efficiently in order to support the University's positioning as an international research-intensive university.

4. POLICY STATEMENT

4.1 The data generated through research conducted at the University of Pretoria are recognised as an important asset. These data sets belong to the University (see section 5 in this policy document), unless intellectual property rights are superseded by specific terms of a funding agreement, or another agreement, or University policy.[2]

4.2 Research data must be managed in a manner that will be beneficial to researchers, the University and society as a whole[3]. Effective research data management will foster international research collaboration, contribute to increased research impact, enhance research practices, and improve and enhance research publication.

[1] Statement on Open Access to Research Publications from the National Research Foundation (NRF)-Funded Research (2015), available at: http://www.nrf.ac.za/media-room/news/statement-open-access-research- publications-national-research-foundation-nrf-funded
[2] In accordance with the University of Pretoria Intellectual Property Policy and Contract Research and Consulting Policy.
[3] In accordance with the principles of Distributive justice and Accountability of the Code of Ethics for Scholarly Activities.

4.3 All research conducted at the University must comply with this Policy, to ensure:

- that research data are managed, stored and preserved through their entire data lifecycle according to subject/discipline-specific standards;
- that data management plans (DMPs) (see 2.1 in the Research Data Management Procedure) are provided when required, in accordance with funder requirements and/or faculty or departmental guidelines;
- that data generated by means of public funding are made available in a timely and responsible manner without infringing on intellectual property, legal or ethical obligations;
- that legal, ethical and commercial restrictions on release of certain research data (embargoed/closed data) will be considered in accordance with the Code of Ethics for Scholarly Activities, the Policy and Procedures for Responsible Research, the University of Pretoria Intellectual Property Policy, and the Protection of Personal Information Act;
- that metadata are provided in a manner that will allow for research data to be discoverable, thereby enabling the broader researcher community to evaluate the research and allowing for the re-use of the available data;
- that where required, published results include links or references to the supporting data;
- that training is available to all researchers and students in support of sustainable and responsible research data management (see section 7 in the Research Data Management Procedure); and
- the establishment of data repositories at the University for the purposes of depositing data in a secure environment for the purposes of maintenance, preservation, publication and/or re-use.

4.4 The management of research data will be implemented in order to:

- protect intellectual property;
- reduce the risk that important research data may be lost or become inaccessible
- due to changes in storage formats, damage or theft;
- assist in the resolution of any disputes concerning the reproducibility of research results, accusations of falsification of data and all other issues in which the authenticity of data is questioned;
- protect the rights of staff and students regarding access to data;
- make data accessible for re-use in further research;
- address funding bodies' and publishers' requirements for the proper management of research data as part of project or publication agreements;
- facilitate research cooperation; and
- ensure that data can be used as research outputs.

4.5 Research data sets are required to be stored for a minimum of ten (10) years after the completion of the original project but if intellectual property is involved, or if there are particular statutory or contractual requirements, a longer period may be required. In some cases, and in particular where research involving human subjects is concerned, funding bodies may require that all raw data be kept indefinitely (see Section 4 in the Research Data Management Procedure).

4.6 A report on the management of research data should be provided annually by faculties to the Vice-Principal: Research and Postgraduate Studies.

5. OWNERSHIP[4]

All primary research materials and data created, collected and/or generated by students, employees and affiliates of the University belong to the University and must be stored throughout the entire life cycle of a research project, in line with a project Data Management Plan.

6. ACCESS TO / SHARING OF RESEARCH DATA AND METADATA

Data (normally processed data; see Definitions section) and accompanying metadata will be published and managed in an institutional Research Data Management System, an accredited open data repository, or an accredited or trusted discipline-specific repository, where available (in accordance with funder and/or publisher requirements (see section 6 in the Research Data Management Procedure). In some instances, access to data should and will be embargoed or restricted due to ethical or legal reasons.

7. EXCEPTIONS

This policy does not cover institutional information, research administration data (which includes information on grant applications, contractual agreements, publication counts and research outputs) as governed by the Information and Governance Framework.

8. DEFINITIONS AND ABBREVIATIONS

Data Lifecycle	The process through which data flow from creation, to processing, analysis, preservation, distribution/sharing and re-use (UK Data Archive).
Data Management Plan (DMP)	A document outlining how the research data collected or generated, will be handled during a research project and after it is completed. Such a plan describes what data will be collected or generated, and what methodology and standards will be used, as well as whether and how these data will be shared and/or made open, and further how they will be curated and preserved (Guidelines on Open Access to Scientific Publications and Research Data in Horizon 2020, 2013).

[4] Ownership and custodianship of data are governed according to the University of Pretoria Information Governance Framework Policy and supporting Matrix.

Data Preservation	Actions taken to ensure that a digital collection remains usable, regardless of the future changes in technology. Without the appropriate preservation methods in place, a digital collection can easily become inaccessible and useless in just a few years (JISC Guide: An introduction to digital preservation, 2014).
Data Repository	A central secure place, or digital warehouse, where data together with their metadata are stored and maintained. A repository can be a place where multiple databases or files are located with access through the Internet.
Digital Object Identifier (DOI)	A serial code used to uniquely and persistently identify digital objects.
Embargoed data (closed data)	Data to which access is restricted for legal, ethical, privacy and confidentiality and/or commercial purposes.
Metadata	Structured information about the attributes of a dataset that enables the data to be identified, retrieved and managed over time (University of Sydney RDM Policy, 2014).
Open Access (OA)	Open access (OA) is free, immediate, permanent, full-text, online access, for any user, web-wide, to digital scientific and scholarly material, primarily research articles published in peer-reviewed journals. OA means that any individual user, anywhere, who has access to the Internet, may link, read, download, store, print-off, use, and data-mine the digital content of that article. An OA article usually has limited copyright and licensing restrictions. Open access is consistent with both peer-review and copyright law. The legal basis for open access is the consent of the copyright owner
Open Data	Data that can be freely used, re-used and redistributed by anyone, subject only, at most, to the requirement to attribute and share alike (Open Data Handbook, 2015).

Research Data (RD)	Factual records (numerical scores, textual records, images and sounds) used as primary sources for scientific research, and that are commonly accepted in the scientific community as necessary to validate research findings. A research data set constitutes a systematic, partial representation of the subject being investigated (OECD Principles and Guidelines for Access to Research Data from Public Funding (2007)): Research data may include: •documents (text, Word), spreadsheets •questionnaires, transcripts, codebooks •audiotapes, videotapes •photographs, films •test responses •slides, artefacts, specimens, samples •collection of digital objects acquired and generated during the process of research •data files •database contents (video, audio, text, images) •models, algorithms, scripts •contents of an application (input, output, logfiles for analysis software, simulation software, schemas). •methodologies and workflows.

9. ASSOCIATED DOCUMENTS

This policy is aligned with the following University of Pretoria policies:

- University of Pretoria Intellectual Property Policy
- Contract Research and Consulting Policy
- Code of Ethics for Research
- Policy and Procedures for Responsible Research
- Information Governance Policy Framework
- Information Governance Matrix

This policy is aligned to the following government legislation:

- Promotion of Access to Information Act No. 2 of 2000
- Protection of Personal Information Act No. 4 of 2013.

10. ADDENDUM

Research Data Management Procedure

11. ROLES AND RESPONSIBILITIES

11.1 The Department of Research and Innovation Support (DRIS) together with the RDM team in the Department of Library Services (DLS) will be responsible for University-wide communication of this policy. DRIS will also assist researchers with information on funders' requirements with regard to RDM.

11.2 The Department of Library Services will provide consultation and training services for researchers on research data management, e.g. on compiling research data management plans, metadata standards, reference support for finding and citing of data sets, and data publishing, etc.

11.3 The Department of Information Technology Services (ITS) will take responsibility for information technology related issues with regard to RDM, e.g. storage, redundancy etc.

11.4 Faculty administration, Deans and Deputy Deans for research, academic staff, students and supervisors, and all University affiliates have a responsibility towards the curation and management of raw and processed data for all research projects conducted at the University (see Research Data Management Procedure). Deans of Faculties and Heads of Departments should ensure that all relevant role-players in their departments are aware of, and adhere to, the University's Research Data Management policy.

12. POLICY LIFE CYCLE

This policy should be reviewed every three years. The Research Data Management Procedure will be revised as and when needed.

13. DOCUMENT METADATA

Document number:	
Document version:	*Replacing the Policy for the Preservation and Retention of Research Data (Rt 306/07).*
Document approval authority:	*Senate*
Document approval date:	*28 September 2017*
Document owner:	*Vice-Principal: Research and Postgraduate Education*
Document author(s):	*Directors, DRI, DLS, ITS*
Date:	*28 September 2017*
Visibility: Display on staff intranet Display on student intranet Display on public web	 √ √

Annexure M: Letter of statistical support

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Denkleiers • Leading Minds • Dikgopolo tša Dihlalefi

DEPARTMENT OF STATISTICS

LETTER OF STATISTICAL SUPPORT

Date: 11th May 2021

This letter is to confirm that ***Cassidy de Franca,*** studying at the University of Pretoria, discussed the project with the title ***"Changes in the countermovement jump force-time waveform after anterior cruciate ligament reconstruction"*** with me.

We hereby confirm that we are aware of the project and also undertake to assist with the statistical analysis of the data generated from the project. The aim of the study is to investigate longitudinal changes in the CMJ force-time curve during rehabilitation following ACLR.

The study will consist of 30 competitive athletes that participated in routine performance testing after ACLR between 2014 and 2021. These participants will be tested across 5 different time points. An additional group of 30 athletes who are free of any knee injury, knee surgery or chronic lower limb pain for at least 12 months, will be recruited as a control group.

The data analysis will consist of descriptive statistics such as mean, median, standard deviations, frequencies, proportions etc. to describe the results and graphical representation can be made were applicable to assist in visualizing aspects of the data.

The main analysis will include statistical parametric mapping to investigate the force-time curves in order to identify areas within the time series in which significant differences occurred. Inferential statistics will also include investigations to determine differences between injured vs uninjured athletes, compare involved vs uninvolved limbs in the unweighting, braking and propulsive phases of the CMJ and the effect of time and the different groups on the discrete time variables will be investigated. These tests might include the independent t-test, the paired t-tests and the two-way ANOVA tests, or their non-parametric alternatives based on the data. All significance tests will be performed at a 5% level of significance.

A power analysis showed that for parametric tests like the paired t-test with a medium to large effect size of 0.7, using G*Power 3.1.9.2, at an alpha level of 5% and a power of 80%, it can be seen that a sample size of 19 would be required per group. The effect size was determined from previous studies such as (1) which found differences for similar investigations to be significantly different.

Tanita Bo[illegible]
Department of Statistics
Internal Statistical Consultation Service
tanita.cronje@up.ac.za

References:

[1] Hart, L.M., Cohen, D.D., Patterson, S.D., Springham, M., Reynolds, J. and Read, P., 2019. Previous injury is associated with heightened countermovement jump force-time asymmetries in professional soccer players. *Translational Sports Medicine*, *2*(5), pp.256-262.