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Neuromuscular Function and Performance in Alpine Ski Racers with Anterior Cruciate Ligament Reconstruction: A Return to Sport Framework

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Neuromuscular Function and Performance in Alpine Ski Racers with Anterior Cruciate Ligament Reconstruction: A Return to Sport Framework

by

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A THESIS
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Abstract

The primary aim of this study was to evaluate the effects of ACL injury on neuromuscular function in elite alpine ski racers, and to monitor skiers throughout the return to sport transition. In Chapter 2 a narrative review of the literature was performed on ACL injury, ACL re-injury, and return to sport after ACL injury in ski racing.

In Chapter 3, a new test of inter-limb functional asymmetry was used to evaluate alpine ski racers with/without ACL reconstruction (ACLR). Despite a full return to competition, ACLR ski racers demonstrated elevated inter-limb functional asymmetries that were correlated with lower limb muscle mass asymmetry.

In Chapter 4, hamstring/quadriceps strength ratios were measured in ski racers with/without ACLR. ACLR ski racers displayed significant hamstring/quadriceps strength deficits in the ACLR limb compared to the contralateral limb and the limb average of non-injured skiers.

In Chapter 5, the functional lower-limb asymmetry test introduced in Chapter 3 was used to evaluate the acute effects of a fatiguing jump protocol on asymmetry and hamstring/quadriceps muscle activity in ski racers with/without ACLR. The ACLR skiers displayed systematic inter-limb functional asymmetries. ACLR skiers displayed reduced quadriceps muscle activity at takeoff in the surgical limb. Both the ACLR group and non-injured controls became quadriceps dominant with fatigue. Quadriceps muscle activity increased while hamstring muscle activity decreased. Notably, this was found in the pre-landing phase.

In Chapter 6, primary ACLR operative reports from 28 skiers were analyzed to evaluate the associated pathology including multi-ligament injury, meniscal tears and chondral lesions. Operative reports from future surgeries were analyzed to evaluate the injury progression. At the time of primary ACLR, there was a higher proportion of chondral lesions in the lateral compartment compared to the medial compartment, and complex meniscal tears compared to one-dimensional tears. At the time point of future surgery, a
significant proportion of skiers showed a worsening of chondral lesions, including half of the skiers
presenting with Grade 3 or Grade 4 lesions. Functional asymmetry was also evaluated at various time
points following primary ACLR. Nearly two years were required for functional asymmetry indices to reach
values comparable to those of non-injured ski racers.
Preface

The following five chapters are based on scientific manuscripts:


The references for Chapter 1 (Background) and Chapter 7 (Conclusions and Future Directions) are presented at the end of the document (pages 160-166).

This PhD dissertation is based on a collection of stand-alone manuscripts. The author of this thesis was the main contributor to the conception, design, data acquisition, data analysis, interpretation, and writing of all chapters. The final manuscripts were edited with the help of the co-authors and all articles were written under the supervision of Dr. Walter Herzog.
Acknowledgements

I want to thank my supervisory committee, especially Drs. Herzog and Aagaard for their support, guidance, and encouragement. This experience was truly life changing and I owe an immense amount of gratitude to both of you.

This thesis would not have been possible without the financial support from Alberta Innovates Health Solutions, the University of Calgary, and the Killam Laureates. I want to acknowledge the support I received from the Canadian Sport Institute Calgary, Own the Podium, and Alpine Canada. I also want to deeply thank the Alpine Canada athletes who recognized the importance of this work and supported the research vision.

Finally, I want to acknowledge all the love and support I received from my family and friends. Your ongoing encouragement helped me to persevere and to reach my full potential.
Dedication

To my family – thank you for your love and support.
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<tr>
<td>ACL</td>
<td>anterior cruciate ligament</td>
</tr>
<tr>
<td>ACLR</td>
<td>anterior cruciate ligament reconstruction/reconstructed</td>
</tr>
<tr>
<td>Allo</td>
<td>allograft</td>
</tr>
<tr>
<td>Allo/Auto</td>
<td>allograft/autograft hybrid</td>
</tr>
<tr>
<td>BCM</td>
<td>body centre of mass</td>
</tr>
<tr>
<td>BPTB</td>
<td>bone patellar tendon bone autograft</td>
</tr>
<tr>
<td>CMJ</td>
<td>countermovement jump</td>
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<tr>
<td>DXA</td>
<td>dual x-ray absorptiometry</td>
</tr>
<tr>
<td>EMG</td>
<td>electromyography</td>
</tr>
<tr>
<td>FIS</td>
<td>International Ski Federation</td>
</tr>
<tr>
<td>Fz</td>
<td>vertical ground reaction force</td>
</tr>
<tr>
<td>H&lt;sub&gt;BCM&lt;/sub&gt;</td>
<td>vertical jump height of the body centre of mass</td>
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<td>H/Q Ratio</td>
<td>hamstring/quadriceps strength ratio</td>
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<tr>
<td>ISS</td>
<td>injury surveillance system</td>
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<tr>
<td>Jump-test</td>
<td>80-second repeated squat jump test</td>
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<tr>
<td>MCL</td>
<td>medial collateral ligament</td>
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<td>MRI</td>
<td>magnetic resonance imaging</td>
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<tr>
<td>MVC</td>
<td>maximum voluntary contraction</td>
</tr>
<tr>
<td>OA</td>
<td>osteoarthritis</td>
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<tr>
<td>PCL</td>
<td>posterior cruciate ligament</td>
</tr>
<tr>
<td>Quad-Ham</td>
<td>quadriceps-hamstrings co-activity difference</td>
</tr>
<tr>
<td>Quad</td>
<td>quadriceps tendon autograft</td>
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RFD  rate of force development
rms  root mean square
RTD  rate of torque development
SJ   squat jump
STG  semitendinosus/gracillis tendon autograft
TOV  takeoff velocity
VL-ST vastus lateralis-semitendinosus co-activity difference
Chapter 1: Background

1.1 ACL Injury and ACL Re-Injury in Sport

Non-contact anterior cruciate ligament (ACL) injuries occur frequently in sports that involve high velocity cutting and pivoting movements (16, 30, 60), and in alpine skiing (26, 60, 68, 71). The ACL is an important intraarticular mechanical knee stabilizer that resists anterior tibial translation and tibial rotation relative to the femur (15, 30). The ACL also contains an abundance of proprioceptive sensory organs, local reflex loops with the surrounding musculature, and it works synergistically with the thigh muscles to stabilize the knee joint (8, 22, 25, 30, 43, 66). Thus, suffering from ACL injury is not only painful but also debilitating (30). Following ACL injury, surgical reconstruction (ACLR) is often recommended to restore knee joint stability, especially when the patient’s goal is to return to a high-risk sport for ACL injury, and a sport where optimal knee joint function is essential for success (30). Despite surgical reconstruction, it is estimated that only 55% of athletes make a full return to competitive sport after ACL injury (4). Additionally, young athletes are at increased risk for developing early onset knee joint osteoarthritis (OA) consequent to ACL injury (63).

The impact of ACL injury on athlete health and performance has led to increased research efforts to identify modifiable (trainable) neuromuscular risk factors for ACL injury, and to evaluate the efficacy of injury prevention training programs to reduce the incidence of ACL injuries (1, 2, 17, 18, 34, 42, 47, 49, 55, 67, 69, 73, 74, 75, 76). Injury prevention training programs have been implemented in a variety of sports and have been found to be effective in reducing ACL injuries (2, 49, 55, 67, 69, 75). Interventions have focused on neuromuscular risk factors for ACL injury including inter-limb functional asymmetries such as valgus knee loading (34), balance and proprioception (49, 55), hamstring/quadriceps strength (47, 73), and
hamstring/quadriceps muscle activity especially muscle pre-activity prior to movements with a change of direction (74, 75, 76). Additionally, the hamstring muscle group acts synergistically with the ACL to resist anteriorly directed shear forces on the tibia (8, 33, 43, 46, 66), and at more extended knee joint angles the quadriceps muscle may by itself generate sufficient shear force on the tibia to cause ACL injury (22, 33). The importance of the hamstring muscle for knee joint stabilization can be observed in ACL deficient patients who generate significantly greater hamstring muscle activity during isokinetic knee extension compared to non-injured subjects (3). These observations highlight the importance of the active restraint system (i.e. muscular system) for protecting the passive restraint system (i.e. ligamentous tissues) and the knee joint itself.

Following ACL injury and ACLR, more than two years may be required for knee joint and lower limb function to normalize (50, 56, 57). The recovery process involves biological adaptation of the ACL graft tissue (ligamentization) (21) and recovery of the associated knee structures, such as the subchondral bone, articular cartilage, and menisci (19, 50). In fact, the associated pathology with ACL injury (e.g. multi-ligament tears, meniscal tears, chondral lesions) is an important determinant for long term patient outcome after ACLR (53), and injuries such as meniscal tears are known to accelerate the progression of knee joint OA (63). ACLR patients must also compensate for the persistent loss in sensory and proprioceptive function that occurs with the disruption of the native ACL (41). ACLR subjects display persistent neuromuscular deficits in the ACLR limb such as elevated inter-limb functional asymmetry in squatting, jumping, and landing compared to non-injured controls (20, 39, 56, 58). Quadriceps and hamstring muscle strength are also impaired by the ACL injury per se and by the surgical procedure, particularly when the patient’s own tissues are harvested to reconstruct the ACL (36, 37). Following ACLR with a patellar tendon or hamstring tendon autograft (i.e. harvested from
the patient), quadriceps and hamstring strength deficits are observed in the surgical limb both in comparison to the contralateral limb and to the limbs of non-injured controls (36, 37, 39). The ability to restore quadriceps strength in the surgical limb is also positively related to functional outcomes after ACLR (54).

ACLR athletes are at six-times greater risk for recurrent ACL injury compared to their non-injured counterparts in the two-year period following surgical repair (57). Thus, neuromuscular assessments including tests of inter-limb functional asymmetry in the vertical jump takeoff and landing phases, hamstring strength, quadriceps strength, and proprioception are recommended throughout early phase rehabilitation and the return to sport transition to ensure ACLR athletes are fit to return to high risk activity (35, 48). Not only should functional assessments focus on the ability to tolerate high force events such as landing from a jump but also evaluate fatigue-resistance or the ability to endure repeated muscular efforts (24, 35, 48). A load versus frequency of loading continuum or an “envelope of function” may help to underpin neuromuscular testing protocols and ensure assessments are task-specific (24) (Figure 1.1).

Similar to risk factor testing prior to the first ACL injury, inter-limb functional asymmetries and postural stability measures are strong predictors of a second ACL injury in young athletes (58).

Sport related injury prevention can be described as a four-step process that includes epidemiological study, description of injury etiology, implementation of injury prevention interventions followed by a re-evaluation of the injury incidence (70). Epidemiological studies indicate that ACL injury risk is dependent on the sport, performance level, and sex (16, 60). Additionally, injury etiology is multi-factorial involving both intrinsic risk factors (i.e. factors internal to the athlete) and extrinsic risk factors (i.e. factors external to the athlete) (45). It seems
important that ACL injury prevention and ACL re-injury prevention measures are carried out in a sport-specific manner (45, 70).

### 1.2 ACL Injury in Alpine Ski Racing

While neuromuscular screening for ACL injury/re-injury risk factors and injury prevention training programs have been well investigated for field and court sports, there is less scientific evidence in other high risk sports for ACL injury such as alpine skiing. Epidemiological and etiological studies on ACL injuries in alpine skiing were conducted in recreational skiers (26, 52), professional skiers (71), and competitive collegiate alpine skiers (68). Injury data from Olympic Winter Games competition indicate that alpine ski racing is among the sports with the highest risk for injury (65). Recently, injury prevention efforts have focused on the epidemiology of injuries in elite alpine ski racing through systematic injury surveillance (12, 27, 28, 29). Multi-season injury surveillance determined the knee to be the most commonly injured body part amongst elite alpine ski racers, where ACL injury was the most frequent diagnosis reported (12, 27, 28). Half of all knee injuries were severe resulting in more than 28 days lost from sport (12, 27). In contrast to field/court sport athletes, female elite alpine ski racers have an equal risk for ACL injury compared to their male counterparts (12). However, an increased risk for ACL injury is found in younger female ski racers compared to males (62). A 25-year retrospective study also found a relationship between performance level and the prevalence of ACL injuries with a greater percentage of elite alpine ski racers sustaining ACL injury compared to lower ranked ski racers (61). Etiological investigations reveal three primary ACL injury mechanisms that are unique from field/court sport injury mechanisms. Injury mechanisms include factors intrinsic to the athlete and extrinsic factors such as high force transmission to the knee joint from the ski equipment and the environment (10, 11, 13). The
injury occurs rapidly (< 60 ms) and involves tibial rotation/anterior shear forces that load the ACL (10, 11, 13). Additionally, the knee musculature, notably an aggressive eccentric quadriceps contraction, is also implicated in alpine-ski-racing-related ACL injury (5, 7, 22, 44).

To date, only a single study has evaluated modifiable neuromuscular risk factors for ACL injury in alpine ski racers (62). However, this study included only younger alpine ski racers and did not examine elite alpine ski racers (62). Fitness parameters were not predictive of ACL injury and a trunk muscle strength imbalance was the only significant predictor of ACL injury in this group of younger alpine ski racers (62). To improve ACL injury risk detection in alpine ski racing, the development of ski-specific neuromuscular testing is recommended (62, 64).

Not only is increased scientific attention required for primary (first) ACL injury prevention in alpine ski racers but also ACL re-injury prevention. The prevalence of ACL re-injury in alpine ski racers is high (bilateral ACL ruptures = 30%; ipsilateral ACL re-injuries = 19%) (61). While ACLR elite alpine ski racers may have longer and more successful careers than their non-injured counterparts (32), the impact of ACL injury, ACL re-injury, and the progression in associated injuries such as meniscal tears and chondral lesions on neuromuscular function and long term skier health are largely unknown. Ensuring ACLR alpine ski racers are fit to return to training and competition is important for skier health and safety given the high risk for serious injury in alpine ski racing (27, 65). To this end, sport-specific functional neuromuscular testing is critical (24, 48) as there may be a tendency for practitioners to rely solely on subjective measures of function or time since surgery to clear athletes for sport participation following ACLR (6). Additionally, there appears to be ski-specific ACL injury patterns to associated knee structures (e.g. multi-ligament tears, meniscal tears, and chondral lesions) (31, 59), and data on the injury pattern in elite alpine ski racers is more than twenty
years old (23). Given the high-energy ACL injury mechanisms in ski racing (11) and that the associated pathology is an important determinant affecting prognosis following ACLR (50, 53), an improved understanding of the injury pattern associated with primary ACL tears in elite alpine ski racers is also important for optimizing outcome after ACL injury.

Based on the current scientific literature and expert opinion, sport-specific neuromuscular testing for ACL injury prevention, ACL re-injury prevention, and monitoring ACLR athletes throughout return to sport is important (6, 24, 34, 34, 48, 58, 74). The physical demands of alpine ski racing include bilateral high force eccentric loading of the lower limbs (14, 38). Elite alpine ski racers are also thought to have appreciable levels of fitness including lower body strength and inter-limb strength symmetry (51). Inter-limb strength symmetry is deemed important for ski racers due to the requirement to perform bidirectional high force turns (14, 51). Additionally, signs of hamstring/quadriceps strength imbalance may be related to ACL injuries in elite alpine ski racers (40). Fatigue is also implicated in alpine ski racing injuries as they typically occur in the final sections of the race, presumably when fatigue factors increase injury susceptibility (9). Based on these characteristics and the recommendations proposed by Dye (24), a model of knee function may help guide the development of functional neuromuscular assessments for ACL injury prevention (Figure 1.1A) and return to sport monitoring after ACLR (Figure 1.1B).
Figure 1.1: (A) A model of knee load exposure (envelope of function) specific to alpine ski racing. The magnitude of loading is plotted on the y-axis with the upper limit representing the requirement for high force eccentric loading. Frequency of loading is plotted on the x-axis with the upper limit representing the repeated execution of eccentric/concentric muscle actions that occurs over the duration of a race. The dashed line represents the effects of fatigue on the functional capacity of the athlete whereby muscle force is diminished across the load vs. frequency of loading continuum. (B) The effects of ACL injury on the envelope of function. Following ACL injury, the surgical limb displays functional deficits including diminished capacity to endure repeated muscular efforts and to withstand single event high force loading. The dashed line represents the post-injury functional status and the need to restore function to the pre-injury level (solid line).

In summary, despite the high incidence of ACL injury/re-injury in alpine ski racing, little is known about the effects of ACL injury on neuromuscular performance and function in elite alpine ski racers. Further, there is limited scientific data on trainable neuromuscular risk factors for ACL injury/re-injury in elite alpine ski racers, and there are currently no scientifically supported guidelines for the return to sport transition following ACLR. ACL injury in elite alpine ski racing involves unique mechanisms and factors that require specialized attention including no sex-differences, an age/performance effect, and a relationship between fatigue and injury. Furthermore, of central concern is ensuring ACLR athletes are physically prepared to
return to sport after injury given the high physical demands of elite alpine ski racing including the requirement for controlling bidirectional high-force turns and the potential for persistent neuromuscular deficits following ACLR.

1.3 Purpose

Critical steps towards evaluating the effects of ACL injury on neuromuscular function/performance in elite skiers, the development of effective neuromuscular assessments for ACL injury/re-injury prevention, and return to sport monitoring include: (i) development of ski-specific functional tests that assess an envelope of neuromuscular function, and that are practical for the daily training environment of alpine skiers; (ii) characterization of functional asymmetry and hamstring/quadriceps muscle strength in uninjured and ACLR ski racers; (iii) characterization of the associated pathology with primary ACL injury in elite alpine ski racers, and the time course recovery in functional outcome measures after ACL injury.

The primary purpose of this PhD thesis was to evaluate the effects of ACL injury on neuromuscular function and performance in elite alpine ski racers. Specific research objectives related to this purpose were to:

(i) Develop ski-specific neuromuscular and functional tests for detecting deficits related to ACL injury, ACL re-injury, and neuromuscular monitoring throughout the return to sport transition

(ii) Evaluate functional inter-limb asymmetries, hamstring strength and quadriceps strength in elite alpine ski racers with ACLR compared to uninjured ski racers

(iii) Evaluate the acute effects of fatigue on functional inter-limb asymmetries and hamstring/quadriceps muscle activity including muscle pre-activity prior to landing in elite alpine ski racers with/without ACLR
(iv) Characterize the associated pathology (i.e. multi-ligament tears, chondral lesions, and meniscal tears) with primary ACL tears in elite alpine ski racers, the progression in these injuries over time and the functional recovery after primary ACLR.

Secondary aims that fell outside the scope of this thesis were to employ the neuromuscular tests in a prospective manner in an elite alpine ski racing population including skiers with/without ACLR, and to monitor neuromuscular function following surgery in ACLR elite skiers throughout the return to sport transition. While prospective research requires considerable time and resource that extended beyond the scope of this thesis, it is of critical importance. Thus, the development and implementation of novel functional neuromuscular tests presented in this thesis alongside existing protocols provides a framework for ongoing and future longitudinal research efforts to reduce ACL injuries in alpine ski racing and improve outcome for alpine ski racers after ACLR.

1.4 Abstract for Chapter Two: Review of the Literature

Alpine ski racers are at high risk for ACL injury/re-injury. Available research has addressed the epidemiology of ACL injury in elite alpine ski racers, examined the injury mechanisms and evaluated various equipment-related injury prevention interventions. The association between physical fitness factors and ACL injury have also been evaluated, and ski-specific assessments have been proposed to ensure ACLR ski racers are fit to return to sport. The purpose of the present review was to: (i) provide an overview of the current understanding on the epidemiology, injury mechanisms, risk factors and prevention methods for ACL injury/re-injury in alpine ski racing; (ii) provide perspectives on future research directions for ACL injury/re-injury prevention.
1.5 Abstract for Chapter Three: Lower Limb Asymmetry in Mechanical Muscle Function – A Comparison Between Ski Racers with and without ACL Reconstruction

Due to a high incidence of ACL re-injury in alpine ski racers, this study aimed to assess functional asymmetry in the countermovement jump (CMJ), squat jump (SJ), and leg muscle mass asymmetry in elite ski racers with and without ACLR. Elite alpine skiers with ACLR (n = 9; 26.2 ± 11.8 months post-op) and uninjured skiers (n = 9) participated in neuromuscular screening. Vertical ground reaction forces during the CMJ and SJ were assessed using dual force plate methodology to obtain phase-specific bilateral asymmetry indices in kinetic impulse. Dual x-ray absorptiometry scanning was used to assess asymmetry in lower body muscle mass. Compared with controls, ACLR skiers had increased asymmetry in muscle mass (P < 0.001), the CMJ concentric phase (P < 0.05), and the late takeoff phase of the SJ (P < 0.05). Positive associations were observed between muscle mass and functional asymmetry in the CMJ concentric phase (r = 0.57, P < 0.01) as well as in the SJ late takeoff phase (r = 0.66, P < 0.01). Future research is required to evaluate the efficacy of the proposed assessments of vertical jump functional asymmetry as a part of a multifaceted approach for improving outcome following ACLR in elite ski racers.

1.6 Abstract for Chapter 4: Rapid Hamstring/Quadriceps Strength in ACL Reconstructed Elite Alpine Racers

Due to the importance of hamstring and quadriceps strength for ACL injury prevention, and the high incidence of ACL injury in ski racing, hamstring/quadriceps maximal strength and explosive strength were assessed in ski racers with and without ACLR. Uninjured (n=13 males; n=8 females) and ACLR (n=3 males; n=5 females; 25.0±11.3 months post-op) elite ski racers performed maximal voluntary isometric hamstring and quadriceps contractions to obtain maximal torque (MVC) and rate of torque development (RTD) at 0-50, 0-100, 0-150 and 0-200
MVC and RTD (per kg body mass) were calculated for the uninjured group to compare between sexes, and to compare the control group with the ACLR limb and unaffected limb of the ACLR skiers. Hamstring/quadriceps MVC and RTD strength ratios (H/Q Ratio) were also compared. The ACLR limb demonstrated significant hamstring and quadriceps deficits compared to the contralateral limb for MVC and late-phase RTD (P<0.05). Uninjured male skiers also displayed a limb difference for hamstring MVC and RTD at 150 ms (P<0.05). Quadriceps MVC and RTD deficits were observed in the affected limb of ACLR skiers, which led to an inflated H/Q Ratio (50 ms) compared to uninjured controls (P<0.05). Compared to male skiers, females displayed greater relative hamstring RTD (50 ms) and an elevated H/Q RTD Ratio (50 ms) suggesting enhanced ACL protection (P<0.05). Due to the strength demands of ski racing, our results suggest the importance of including hamstring and quadriceps strength assessments in the physical evaluation of uninjured skiers. Further, hamstring and quadriceps strength should be assessed over a long term period following surgery to identify chronic strength deficits in ACLR ski racers.

1.7 Abstract for Chapter 5: Asymmetry and Thigh Muscle Co-Activity in Fatigued ACL Reconstructed Elite Skiers
The acute effects of fatigue on functional inter-limb asymmetry and quadriceps vs. hamstring muscle activity levels including preparatory co-activation during squat jump takeoff and landing were evaluated in elite alpine ski racers with/without ACLR. Twenty-two elite ski racers (ACLR: n=11; Control: n=11) performed an 80-second repeated squat jump test (jump-test) on a dual force plate system with simultaneous electromyography (EMG) recordings in vastus lateralis, vastus medialis, semitendinosus and biceps femoris. Asymmetry indices and jump height were calculated from the ground reaction force. Normalized EMG amplitudes were obtained at takeoff, in the 25 ms interval prior to landing, and post-landing for the ACLR limb
(Affected Limb), contralateral limb and limbs of the control subjects (Control Limb). Vertical jump height decreased with fatigue for both groups, and ACLR skiers demonstrated elevated asymmetry in the late takeoff phase vs. the early takeoff and landing phases \([P<0.0001]\). No fatigue-induced changes in asymmetry were found. The Affected Limb of ACLR skiers showed lower normalized quadriceps EMG activity at takeoff, pre-landing and post-landing along with increased hamstring activity pre-landing and post-landing compared to the Contralateral Limb and Control Limb \([P<0.001]\). The Affected Limb, Contralateral Limb and Control Limb all demonstrated increased quadriceps and decreased hamstring activity with fatigue \([P<0.001]\). Functional asymmetry indices were not changed with fatigue and the Affected Limb of ACLR skiers who successfully returned to sport demonstrated more hamstring dominant landings compared to the Contralateral Limb and uninjured control limbs. Skiers with/without ACLR demonstrated more quadriceps dominant landings with fatigue.

1.8 Abstract for Chapter 6: Associated Pathology and Lower-Limb Asymmetries in Elite Ski Racers with ACL Tears

The purposes of the studies presented in Chapter 6 were to evaluate the associated pathology (multi-ligament, meniscal tears, chondral lesions) at the time of primary ACLR, the prevalence of ACL re-injury, the time course of injury progression, and recovery assessed by functional asymmetry indices, in ACLR elite alpine ski racers. Primary ACLR operative reports \((n=28)\) and operative reports following primary ACLR \((n=20)\) were obtained from elite alpine ski racers \((n=32)\) to evaluate the associated pathology and injury progression. Seventeen of the 32 skiers also performed vertical jump functional asymmetry testing between 138 and 4444 days following primary ACLR. Statistical modeling was used to evaluate the effects of time post-ACLR on recovery of functional inter-limb asymmetry. A greater proportion of knees \((82\%; \ 23/28)\) had associated injury compared to isolated ACL tears. Fifty-four percent of the ACL injured knees
had chondral lesions of which 73% were sustained in the lateral knee compartment. ACL revision surgery was required for 28% of knees, and 7/32 subjects (22%) sustained contralateral ACL tears following the primary ACLR. At the time of ACL revision or future meniscal/chondral surgery, 40% of the meniscal tears and 80% of the chondral lesions had worsened since the time of primary ACLR. Time following primary ACLR explained between 26% and 54% of the variance in inter-limb functional asymmetry indices. Nearly two years were required for functional symmetry to reach levels comparable to that of elite skiers without ACLR. Elite skiers suffered traumatic knee injuries and recovery following injury and ACLR is slow. Time from the initial surgery explained a significant amount of the variance in the recovery of functional inter-limb asymmetry.
Chapter 2: Review of the Literature

2.1 Introduction

An ACL tear is the most common knee injury suffered by elite alpine ski racers (1) and a significant proportion of skiers sustain an ACL re-injury (65). This is particularly concerning as ACL injury in young adulthood increases the risk of developing symptomatic knee joint osteoarthritis (OA) later in life (68). Additionally, elite alpine ski racers are at high risk for suffering traumatic injury compared to other winter sport athletes (25, 72). This places increased importance on ACL injury prevention and ensuring ACL injured skiers are fit to return to sport given the potential for persistent neuromuscular deficits consequent to ACL injury (40).

Injury prevention is described by van Mechelen (82) as a four-stage model. First, the injury incidence is established. Second, injury mechanisms and etiology are described. Injury prevention strategies are then introduced followed by a return to step 1 to evaluate the effects on injury incidence. The causation of sport related injury is multi-factorial (51). Risk factors are classified as intrinsic to the athlete (e.g. fitness, age, gender) and extrinsic to the athlete (e.g. environmental factors, equipment factors). Of importance is identifying potential modifiable intrinsic risk factors that can be mitigated through physical intervention (training) programs (5). Intrinsic modifiable risk factors related to ACL injury include knee control particularly with respect to valgus loading (1, 39, 54), hamstring/quadriceps muscle strength (53) and quadriceps vs. hamstring co-activity (89). Neuromuscular injury prevention training programs have proved successful for reducing the incidence of ACL injuries in other high risk sports (2, 17, 18, 54, 78, 81, 90).

Following ACL reconstruction, two years may be required for full recovery of hamstring/quadriceps strength and knee function to pre-injury values (55). Further, young
athletes with previous ACL reconstruction are at a significantly elevated risk of ACL re-injury compared to their non-injured counterparts (61). This highlights the importance of identifying modifiable risk factors not only for primary ACL injury prevention but also for secondary ACL re-injury prevention (40).

Recently, a comprehensive narrative review was conducted on injury prevention in elite alpine ski racing (77). The aim of the present review was to undertake a literature review specifically focused on ACL injuries in alpine ski racing given it is the most common injury type. The specific objectives were to: (i) provide an overview of what is known about ACL injuries related to the epidemiology, etiology, injury prevention and re-injury prevention in elite alpine ski racing; (ii) provide perspectives for future research in these areas.

2.2 Methodology

Given the exploratory nature of the scientific research on ACL injuries and re-injuries in elite alpine ski racing, we employed a similar methodological approach to Spörri and co-authors (77). Specifically, a non-systematic narrative review was conducted including a literature search in three scholarly databases (PubMed, SPORTDiscus, MEDLINE) using search terms: “alpine skiing AND ACL” and “alpine skiing AND knee injury” to identify relevant scientific articles published between 1991 and the time of this literature review. Figure 2.1 provides an overview of the data retrieval/analysis for identifying relevant scientific articles of interest.
Figure 2.1: Flow diagram for identifying articles of interest in the present review.

2.3 Epidemiology of ACL Injuries

Initial studies on the prevalence of ACL injuries amongst alpine ski racers and professional skiers have been limited to retrospective research designs on single teams and organizations (65, 80, 83). Stevenson et al. (80) conducted a retrospective review on the prevalence of ACL injuries in 404 collegiate alpine ski racers. ACL tears accounted for nearly 50% of all knee injuries, hence representing the major type of knee joint injury in this group of ski racers (80). A total of 13% of study participants reported an ACL injury with a significantly greater number of ACL injuries occurring in female skiers (22%) compared to males (7%). Twenty-two percent of skiers required a subsequent ACL revision surgery (80). In contrast, a
study evaluating the prevalence of ACL injuries in a large group (n=7155) of professional ski patrols found no difference in ACL injury rates between males and females (83).

Pujol and co-authors (65) retrospectively analyzed a database of 347 French alpine ski racers and found no difference in ACL injury rates between males and females as well. However, female skiers were younger (21±3.9 years) than males (23±3.9 years) when ACL injury was sustained. Twenty-eight percent of skiers sustained at least one ACL injury, 19% sustained a second ACL injury to the same knee, and 30% of these skiers sustained contralateral ACL injury (65). Additionally, the prevalence of ACL injury was highest amongst skiers with a top-30 world ranking compared to lower ranked skiers.

The need for improved injury surveillance led the International Ski Federation (FIS) to implement a systematic Injury Surveillance System (ISS) starting in 2006 (24, 25, 26). Injuries were recorded during FIS World Cup competitions using yearly retrospective interviews with athletes, coaches and medical staff members from ten countries (24). The absolute injury rate in training and competition was expressed as the number of injuries per 100 athletes per season. Relative injury rates were determined for the number of injuries occurring only during World Cup and World Championship competition, and were expressed as the number of injuries per 1000 runs. The knee was the most commonly injured body part (35.6% of all injuries) and 54% of knee injuries resulted in more than 28 days lost from sport (24, 25). ACL injury was the most frequent and specific diagnosis representing 14% of all injuries (24). The absolute injury rate was 5 ACL injuries per 100 athletes per season and the relative knee injury rate was 3.2 per 1000 runs. Like the findings of Pujol and co-authors (65), the relative injury rate was not different between elite male and female ski racers. However, there was an increased risk of knee injury in
Downhill (Relative Risk: Downhill = 1.84) compared to the other events (i.e. Relative Risk: Slalom = 1.43; Giant Slalom = 0.90, Super Giant Slalom = 1.05).

The consistent observation of no sex-differences in ACL injury rates amongst elite alpine ski racers is unique as it is well established that female athletes are typically at increased risk for ACL injury compared to male athletes in other high risk sports (15, 64). A six-year study using the FIS ISS comparing injury rates between male and female elite alpine ski racers reported no sex-differences in the absolute ACL injury rates (Males: 5.5 ACL injuries/100 athletes/season; Females 5.4 ACL injuries/100 athletes/season) or relative ACL injury rates (Males: 1.7 ACL injuries/1000 runs; Females: 1.2 ACL injuries/1000 runs) (12). Consistent with previous reports, the highest risk for knee injuries was in the speed events compared to the technical events (12, 24).

However, sex-differences in ACL injury rates appear to exist in young ski racers (66, 79). A 10-year study evaluating risk factors for ACL injuries in young ski racers between 14 and 19 years of age found females to be at increased risk for ACL injury compared to males (Female-Male Risk Ratio: 2.3) (66). Female skiers 19 years of age were at the highest risk for ACL injury followed by female skiers 17 years of age. Additionally, while knee injuries are the most common injury type amongst elite alpine ski racers, there are mixed findings with respect to adolescent skiers (66). A two-year study including 104 young ski racers reported ACL tears to be the third most common injury preceded by lower back pain and non-traumatic knee pain (42). Conversely, a five-year study including 431 Swedish adolescent alpine ski racers reported knee injuries to be the most common injury type (85).
2.4 ACL Injury Mechanisms

The ACL has a complex morphology and is composed of spiraling fibre bundles (i.e. anteromedial bundle and posterolateral bundle) (14). The strain distribution varies between and within these bundles depending upon the direction of the externally applied force and the knee flexion angle (14). The ACL mainly resists anteriorly directed shear and internal rotation forces applied on the tibia relative to the femur (14, 35, 37). Additionally, internally developed forces from the quadriceps muscles may strain the ACL in the distal range of motion close to full knee extension (4, 19, 38). The hamstring muscles act as ACL synergists by producing a posteriorly directed shear moment on the tibia (8, 38). This highlights the importance of hamstring quadriceps co-activity for dynamic knee joint stabilization (8, 73). Both the equipment and physical demands of alpine skiing may expose the knee joint to high levels of external loading that can strain the ACL causing injury (23, 35, 43, 49, 50, 56). Based on observations in five Canadian elite alpine ski racers, McConkey (50) proposed an ACL injury mechanism involving combined anterior shear loading on the knee from the passive external force imparted on the tibia from the ski boot (i.e. boot induced anterior drawer) and an active internal shear force from a strong quadriceps muscle contraction that occurred as the skier attempted to recover from a back weighted, unbalanced jump landing (50).

Tibial internal rotation forces are implicated in most ski-specific ACL injury mechanisms (23). Hame and co-authors (35) attempted to replicate ski-specific ACL injury mechanisms and evaluated the effects of internal/external tibial torque at four knee joint flexion angles on ACL strain in 37 cadaveric knee specimens. ACL strain was greatest at 0° of knee flexion and in forced hyperflexion in combination with tibial internal rotation torque. With regard to the amount of ACL strain during alpine skiing, the knee flexion angle appears to be of particular
importance (37, 67). Specifically, at deeper angles of knee flexion, the knee joint geometry and lines of action for the quadriceps and hamstring muscles lend towards decreased anterior shear forces and less ACL strain (37, 38, 67). Landing back weighted following a jump may not *per se* be sufficient to load the ACL (37, 67). However, an asymmetrical ski jump landing alongside a strong eccentric quadriceps contraction may generate a sufficiently large knee joint moment and high resulting anterior directed shear forces on the tibia to cause ACL injury (27, 37, 67). The trunk inclination angle in jump landings is also of importance for minimizing ACL strain (36). This highlights the importance of technique and tactics in a failed landing alongside an imbalance in the active muscle forces as potential contributors to non-contact ACL tears in alpine skiing (27, 67). In fact, trunk orientation along with ankle, knee and hip joint angles accounted for 88% of the variance in peak ACL force (36). Additionally, equipment factors including ski bindings (43, 49, 56, 71) and use of a stiffer ski boot are thought to increase anterior shear forces on the tibia during jump landings (21).

A rare and accidental recording of a single skier who suffered an ACL injury while participating in a study evaluating muscle activity patterns and kinematics of alpine ski jump landings provides an indication of the kinematic and muscle activity changes associated with an acute non-contact ACL injury in alpine skiing (7). The quadriceps vs. hamstring muscle activity, and kinematic changes preceding/following the clapping period (i.e. time point when the tails of the skis contacted the snow to the time point when the full length of the skis were in contact with the snow) were measured. Additional parameters included the clap angle or the angle of the skis relative to the slope of the hill at the initial point of contact, and the duration of the clap period. Compared to the non-injured study participants, the subject suffering an ACL tear landed in a slightly more backward position, had a shorter clap period duration (40 ms vs. 95 ms for the
reference group), a smaller clap angle (3° vs. 31° for the reference group), demonstrated a lesser spatial change in the centre of mass throughout the clap period and displayed relatively less hamstring muscle activity in the injured limb compared to the non-injured limb during the post-clap period (7). It was speculated that the smaller clap angle and clap period duration resulted in greater angular acceleration of the ski boot, and thus a greater anteriorly directed shear force on the tibia (7). Additionally, the short time-course required for adequate protective activation of the hamstring/quadriceps muscles prompted an analysis of rapid force capacity (rate of force development: RFD) strength ratios (H/Q Ratio) for other athletes at risk for ACL injury (8).

In other high-risk sports for ACL injury, ACL injury mechanisms have been identified through video analysis (47, 48). Using a similar approach, Bere and co-authors (11) analyzed video recordings from 20 elite alpine ski racers who sustained ACL injuries during competition. All but one of the ACL injuries occurred during skiing. Three main non-contact ACL injury mechanisms were identified by Bere and coworkers (11). The slip-catch mechanism occurred most frequently (50% of cases) and happened while skiing (typically during a turn) (11). Pressure and snow contact was lost on the outer ski. Upon regaining contact with the snow, the ski caught causing a combination of rapid knee joint flexion, tibial internal rotation, and knee valgus. The second injury mechanism, the dynamic snow plow, occurred in 3/20 (15%) of all ACL injuries (11). In this condition, the skier was caught out of balance in a backward position and an asymmetrical inter-limb weighting. The unweighted ski drifted away from the skier placing the skier in a split position. The ski rolled from the outer edge to the inner edge, caught the snow and forced the knee into valgus and tibial internal rotation. The final injury mechanism, landing back weighted, occurred in 4/20 (20%) of all ACL injuries (11). Here the skier gets out of balance with the body mass moving backward during the landing. The tails of
the skis contacted the snow first with a large clap angle and an extended knee joint angle. The proposed specific injury mechanism was a combination of tibiofemoral compression and anterior shear on the tibia as the skier attempted to recover from the back weighted position (11).

The study performed by Bere and co-authors (11) provides new perspectives on potential ACL injury mechanisms for elite alpine ski racers. Notably, the dynamic snow plow and the slip-catch mechanisms occurred in 13/20 (65%) cases during downhill skiing (11), and involved a combination of rapid knee joint flexion, tibial internal rotation, and knee valgus loading in a short time frame (60 ms) (13). These injury mechanisms are similar to the phantom foot mechanism that typically is observed in recreational alpine skiers (23). Tibial internal rotation appears to be a key loading factor in non-contact alpine skiing ACL injuries (35, 48) and tibial rotation forces may be increased with skis that have a small turning radius (i.e. more aggressive self-steering skis) (31, 45, 46, 69, 75, 76).

2.5 ACL Injury Risk Factors

2.5.1 Athlete Risk Factors

Risk factors intrinsic to the athlete are either modifiable (e.g. physical fitness) or non-modifiable (e.g. governed by genetics, sex, body type) (56). Potential ACL injury risk factors include sex, age, limb dominance, and phase of the menstrual cycle (15, 52). While female athletes are at higher risk for sustaining non-contact ACL injury across many sports (15), there are no sex-differences found in elite alpine ski racing competitors (12, 24). Of particular importance for ACL injury prevention is identifying modifiable risk factors that can be mitigated through injury prevention training programs (1, 2, 17, 18, 54, 78, 90, 91) such as knee control and postural balance control (54), hamstring/quadriceps strength (53), knee valgus/abduction
loading (39), and quadriceps vs. hamstring dominance in movements with a change of direction (89, 91).

The scientific data available on athlete related risk factors for ACL injury in elite alpine ski racing is limited. A strong eccentric quadriceps contraction may contribute to anterior shear forces on the tibia and ACL strain during jump landings (50). As hamstring/quadriceps muscle co-contraction is important for dynamic knee joint stabilization (8, 19, 73), a low hamstring/quadriceps strength ratio was identified as a potential ACL injury risk factor for alpine ski racers (43, 52, 57, 87). Additionally, given the short time course of ACL injury in elite alpine ski racing (13), the rapid force producing capability (RFD) of the hamstring/quadriceps muscles may be important as well (88). While non-injured elite alpine ski racers may display marked bilateral hamstring/quadriceps strength symmetry (58), there are no studies to date linking a diminished hamstring/quadriceps strength ratio with increased risk of ACL injury. However, elite alpine ski racers who suffered an ACL injury produced peak hamstring torques at a more extended knee joint angle compared to their non-injured counterparts (43). Further, diminished hamstring strength and increased quadriceps strength are both associated with non-contact ACL injury in female athletes (53), and female elite handball players who displayed a higher quadriceps vs. hamstring muscle co-activity difference (i.e. quadriceps dominance) were at increased risk of ACL injury (89). Functional asymmetries including increased knee abduction moments and valgus loading have also been associated with elevated ACL injury risk in female athletes (39). There are no prospective studies showing a relationship between increased functional asymmetry and increased risk of ACL injury in elite alpine ski racers. However, adolescent alpine ski racers injured their left limb more frequently than their right
limb. Whether this was related to limb dominance of strength asymmetry could not be determined (85).

A 10-year prospective study evaluated the relationship between physical fitness and ACL injury risk in young competitive ski racers and found that trunk (core) strength was a significant predictor of ACL injury (66). Specifically, skiers who suffered from ACL injury demonstrated diminished core strength compared to non-injured skiers along with a suboptimal trunk flexion to trunk extension strength ratio. However, none of the additional fitness parameters obtained were associated with ACL injury risk (66). Similar findings were reported in Swiss elite alpine ski racers where no differences in physical fitness parameters could be observed between skiers who suffered an ACL injury and non-injured skiers (70).

Despite the lack of empirical data supporting a link between physical fitness and ACL injury risk, expert stakeholders identify physical factors in the top five of potential risk factors for alpine skiing injuries (76). Skier fatigue was also identified as a highly ranked injury risk factor (76), and alpine ski racing injuries typically occur in the final sections of the race presumably when fatigue factors presumably are more present (9). To account for this aspect of temporal build-up of fatigue, a fatiguing ski-specific jump test protocol to evaluate potential ACL related neuromuscular risk factors, such as increased functional inter-limb asymmetry and potentially harmful shifts in quadriceps vs. hamstring co-activity may be warranted.

Skier technique and tactics may also be identified as potential athlete related risk factors for injury in ski racing (10, 76). Video analysis on the events leading to ACL injury in 20 skiers found that skiers were often out of balance and made tactical errors (10, 11). Additionally, ACL injuries involving the landing back weighted mechanism were preceded by poor skier jump technique and tactical errors (10). The ability to make tactical decisions is related to an athlete’s
psychological state, and alpine skiers returning from injury/illness may be prone to poor decision 
making at the return to sport transition (16). The effects of “injury contagion” or the 
consequences of a teammate’s season ending injury on the mental well-being of elite alpine ski 
racers was also investigated due to the possibility that being witness to a serious injury may alter 
an alpine skier’s confidence or tactical decision making ability (59). However, no measurable 
effect was found (59).

Finally, a genetic link appears to exist between adolescent alpine ski racers who suffer 
ACL injury and their parents (86). A study evaluating the relationship between parents who 
suffered ACL injury in a group of 418 adolescent alpine ski racers found a significantly greater 
proportion of parental ACL injuries in the ACL injured group compared to the non-injured group 
(86). Most likely, this observation reflects that distinct anatomical features are inherited from 
parents to offspring, including various anatomical ACL injury risk factors such as a narrow 
intercondylar notch width, increased tibial plateau tilt angle, increased valgus angles, etc.

2.5.2 Equipment Risk Factors

Equipment variables are perceived as risk factors for injury in ski racing (76). Expert ski 
coaches identified the aggressiveness of the skis and boots, and the inability of ski racers to 
control their equipment as a key contributor to ACL injury (10). The ski side cut radius, ski 
length, ski bindings, and the stiffness of ski boots are all important equipment factors that are 
thought to be related to knee injury risk in ski racing (10, 31, 43, 45, 46, 49, 50, 56, 69, 71, 75, 
77). As the ski side cut radius decreases, the self-steering effect of skis increases rendering them 
less controllable in an injury situation (10, 45, 46, 75). Increasing the side cut radius of giant 
slalom skis by 33% reduced skier kinetic energy by 5% (46). Longer skis provide more stability
at high speeds (76), which is important as skier speed is also positively associated with increased injury risk (24, 30).

In fact, skier speed and the interaction between speed and jumps in the speed events were related to injury risk (30). Increasing ski length, decreasing ski width, and reducing the standing height (distance between ski base to binding plate cover) decreased skier kinetic energy during the steep sections of an alpine skiing course in expert alpine ski racers, which may be important for reducing skier speed and thus minimizing injury risk (31). To reduce injuries, FIS changed the regulations for ski side cut radius for the 2012-2013 season. Side cut radius and ski length were increased for all disciplines except for slalom (33). While upper body injuries decreased, no statistically significant reduction in ACL injuries was found (33).

The ACL injury mechanism related to landing back weighted is thought to include anterior shear loading on the tibia resulting from the ski boot and a strong coupled eccentric-concentric quadriceps contraction as the skier recovers from the back weighted position (11, 50). Not only did a stiffer ski boot result in greater ACL loading during simulated ski landings but so did increased quadriceps muscle force (21). A combination of intrinsic contractile and anatomical factors as well as extrinsic factors from a stiff ski boot probably altogether make a complex contribution to ACL injury related to landing back weighted (7, 21). However, it was noted that reducing ski boot stiffness may compromise alpine ski racing performance (21).

Finally, the ski bindings may contribute to ACL injury risk (10, 11, 56). The ski bindings serve two purposes, namely to release the ski if loading could potentially cause lower limb injury and to retain a rigid coupling between the boot and the ski (11). In 100% of slip-catch ACL injuries (i.e. valgus/internal rotation mechanism) the ski either failed to release or released after the injury was sustained (11). The ability for ski bindings to differentiate between potentially
injurious forces and normal forces encountered in ski racing may prove to be a significant challenge for ski binding design (10, 11). Nevertheless, current research efforts are directed towards improved ski-binding-boot systems to reduce adverse injurious loading on the ACL (71).

2.5.3 Environmental Risk Factors

Environmental factors including changing snow conditions, the course speed, and course settings are highly ranked amongst expert stakeholders as contributors to injury risk (76). Further, expert alpine ski racing coaches highly ranked snow and course conditions as contributors to ACL injury in 20 cases including inconsistent and bumpy conditions, excessively challenging course sections that generate high speeds or compressions, poor visibility or flat light, and aggressive snow conditions (i.e. hard dry snow that increases the risk of catching and edge) (10). Skier speed resulting from the course design, jumps, and high force turns have also been linked with injury risk (25, 30). It may be possible to reduce skier speed by altering the course design (e.g. reducing gate distance) (30, 31) although a substantial change in course design may be required for a meaningful reduction in skier speed (74). The effect of reducing skier speed on ACL injury risk remains unknown.

2.6 ACL Injury Prevention

In other sports with a high risk for ACL injury, injury prevention training programs have proved effective for reducing ACL injuries (2, 17, 18, 54, 78, 81). Specific neuromuscular training programs focused on improving awareness of higher risk lower limb biomechanics and knee control were implemented as an adjunct to normal training (54), and as a warm up prior to training and competition (17, 18). Additionally, injury prevention programs may improve balance (17), and diminish/remove the presence of specific neuromuscular and biomechanical
risk factors related to ACL injury (90). The effectiveness of such programs is heavily dependent on athlete compliance and consistency in performing the injury prevention training program (54, 78). Notably, based on the current data, neuromuscular injury prevention programs can reduce the relative risk of non-contact ACL injuries by more than 70% in high risk athlete populations (81).

In addition, various equipment modifications have been introduced in alpine ski racing to reduce injuries, yet no change in lower body injury rates was found (33). More research is required into modifications in equipment and slope course design to reduce the risk for ACL injury in alpine ski racing (77) as ski bindings, boot stiffness, and steering ability (turn radius) of skis all contribute to ACL loading (21, 27, 31, 35, 46, 71, 75, 76, 77). Skier tactical and technical errors also contribute to ACL injury risk (10, 11). Interestingly, implementing an educational approach caused knee ligament injuries to decrease by 62% in ski patrols who were shown videos of knee injury occurrences to increase awareness of technical and tactical contributors to injury situations (23). The effectiveness of such an approach has not been tested in alpine ski racers, but as tactical and technical errors are known to contribute to ACL injuries (10, 11) such an approach may be warranted.

Skier fitness (76) and fatigue-resistance (9, 76) are thought to be important factors for injury prevention. However, no link seems to exist between physical fitness variables and ACL injury risk (66, 70) except for trunk strength in young ski racers (66). It seems important for ACL injury prevention and screening programs to have a high degree of specificity to the ACL injury mechanisms in ski racing (11). Yet, this specific aspect is lacking in most standard alpine skiing fitness testing (70). Based on the current data on ACL injury mechanisms in ski racers, possible factors include assessment of trunk control (10, 36), knee/hip control (i.e. tibial internal
rotation, knee valgus and hip internal rotation) (10, 11, 13), functional lower-limb asymmetry and hamstring/quadriceps muscle strength and RFD ratios.

2.7 Return to Sport After ACL Injury

Only 55% of ACL injured athletes manage to return to pre-injury performance levels after ACL reconstruction (3). Similar findings exist amongst professional football players where only 65% return to top-level sport participation following ACL injury (84). More concerning, ACL injury and the associated pathology including meniscal and chondral lesions are known to accelerate the progression of knee joint OA in young adults (68).

It is important to evaluate/test ACL reconstructed athletes to ensure if they are fit to return to sport (40). An ACL reconstructed athlete may be at six-fold elevated risk for re-injury compared to their non-injured counterparts and even two years post-injury may show increased vulnerability toward re-injury (61). ACL graft tissue healing, graft ligamentization, sensory re-innervation, meniscal/chondral tissue healing, recovery in muscle strength, restoration of functional lower-limb symmetry and neuromuscular control contribute to this period of increased vulnerability after ACL injury (55).

Nineteen percent of ACL reconstructed skiers suffered a re-injury to the same knee while 31% demonstrated bilateral ACL rupture (65). This finding and the high-risk nature of alpine ski racing (24, 25, 72) highlights the importance of functional assessments to determine a safe ski-specific return to sport following ACL injury. This is important as often there is an overreliance on a timeline based approach to return to sport, despite that more objective functional measures are recommended (6). In other high risk sports, functional testing post-ACL reconstruction including measures of asymmetry, postural balance and hip/knee muscle control are highly predictive of ACL re-injury (62). Assessments of functional asymmetry, hamstring/quadriceps
muscle strength ratios based on maximum voluntary contraction (MVC) torque as well as RFD, quadriceps vs. hamstrings muscle co-activity, and fatigue-resistance of these neuromuscular factors may be of value in an elite alpine ski racing population. Additionally, rehabilitation programs following ACL reconstruction should be ski-specific and account for the unique physical and technical demands of alpine ski racing (44). The skier’s psychological readiness for return to sport is also important (16, 58) as ski racers may be prone to poor decision making at the transition from rehabilitation to on snow training (16). The consequences of returning to alpine ski racing with these deficits and alterations in neuromuscular activity patterns are unknown. To date there are no links between these deficits and risk for ACL re-injury.

Ski-specific ACL injury patterns have been demonstrated previously including increased prevalence of multi-ligament injuries (32) especially to the medial collateral ligament (MCL) (20, 32, 41, 63). Nevertheless, surgical repair of ACL tears and the associated knee joint injuries, respectively, is generally believed to lead to successful outcome for alpine ski racers (22, 41, 60). Perhaps somewhat unexpectedly, ACL injured ski racers have longer and more successful ski careers compared to those without ACL injury (34, 65), and elite alpine ski racers may in fact improve their pre-injury performance level following ACL rupture (34). However, the ability to improve the pre-injury performance level is a function of skier age and mainly seen in young alpine racers (34).

2.8 Limitations

Recent research efforts have described the prevalence and mechanisms of ACL injury in elite alpine ski racing. However, ACL injury rates remain unchanged, and there is limited scientific literature on ACL injury/re-injury prevention in ski racers. This prevented a quantitative analysis of the scientific data on ACL injury/re-injury prevention in elite alpine ski
racing. The possibility for bias and subjectivity in the article selection exists. This concern was addressed by providing a detailed account of article selection flow in the present study (cf. Figure 2.1).

2.9 Conclusions and Future Perspectives on ACL Injury/Re-Injury Prevention

Presently, the epidemiology and mechanisms of ACL injury are well described for elite alpine ski racers. However, only two distinct risk factors for ACL injury have been identified, namely: (i) reduced trunk flexion/extension strength in young ski racers (66); and (ii) a genetic link in adolescent skiers (86). Apart from these factors, no other risk factors for ACL injury have been identified for elite alpine ski racers. Consequently, physical fitness testing may not be specific enough to the ACL injury mechanisms in play, and this may contribute to the poor relationship previously reported between physical fitness parameters and ACL injury risk.

Development of more specific and sensitive tests might include assessments of trunk/hip/knee control during landing movements, functional asymmetry testing, hamstring/quadriceps muscle strength testing, and potentially on-snow neuromuscular assessments. As specific neuromuscular injury prevention training programs have proved effective for reducing ACL injuries in other high-risk sports, this should also be considered for alpine ski racers. Future research on the reduction of adverse knee joint loading through ski-boot-binding system design and course design features also seems highly important. Based on the available evidence, it also appears that ACL injury prevention efforts could differ depending upon the skier performance level including years of racing, ski racing discipline, and sex. Thus, an important consideration might be to devise specific ACL injury prevention screening and programming according to each subgroup. Developing ski-specific neuromuscular screening tests and prevention programs for ACL injury alongside prospectively designed studies to evaluate their effectiveness should be pursued.
Finally, ACL re-injury prevention is of equal importance as primary ACL injury prevention for alpine ski racers. Given the high-risk nature of alpine ski racing, neuromuscular function should be adequately restored following ACL injury to ensure skiers are fit to ski. Currently, there are no accepted protocols for returning alpine ski racers back to snow after ACL injury. Protocols should include appropriate testing methods, functional standards for return to snow, and suitable progressions towards unrestricted alpine ski racing in the most challenging conditions. Psychological readiness for risk taking should also be evaluated prior to unrestricted return to alpine ski racing. Currently, there are no scientific studies showing a relationship between physical, functional or psychological deficits and risk for ACL re-injury in alpine ski racers. Prospectively designed research studies should be conducted to further explore these possibilities.
2.10 References


Chapter 3: Lower Limb Asymmetry in Mechanical Muscle Function – A Comparison Between Ski Racers with and without ACL Reconstruction

3.1 Introduction

Elite alpine ski racing (i.e., FIS World Cup, World Championship, and Olympic level racing) occurs at high speeds and in an unpredictable environment with repeated bidirectional turning composed of forceful concentric but predominantly eccentric movements that elicit near maximal levels of lower body muscle activation (3, 5, 18). To contend with these physical demands, competitive alpine ski racers are characterized by having a high degree of bilateral thigh muscle strength symmetry (25) along with a high degree of force symmetry in multi-joint closed kinetic chain movements (31).

Due to the intense nature of alpine ski racing, there is a high risk for lower body injury, especially the knee joint (4, 13). Knee injuries account for nearly one third of the injuries sustained by elite ski racers and half of these injuries result in a significant time loss from sport (> 28 days) (4, 13). Anterior cruciate ligament (ACL) injury is the most common type of knee injury (4, 13) and ski racers are at high risk for ACL re-injury (32, 35). ACL injury in elite alpine ski racing is distinct from field sports due to the existence of three different injury mechanisms that occur in a highly unpredictable and changing environment (3). Additionally, recently conducted studies indicate there are no sex-related differences in ACL injury rates in elite ski racers, which has been attributed to the exclusion of sex-related factors commonly found in field sports due to the high force injury mechanisms (4, 13).

Despite the high ACL injury rates and the uniqueness of non-contact ACL injuries in ski racing, only a single longitudinal study has focused on identifying modifiable (trainable) risk factors for ACL injury (33). Furthermore, in consideration of the high ACL re-injury rate (32, 35), very little is known about the neuromuscular function of elite ski racers with a history of
ACL injury and ACL reconstruction (ACLR), and there are no scientifically supported standards or criteria guiding the return to sport period following ACL injury. This is important as following an ACLR the primary objectives are to restore neuromuscular function with rehabilitation exercise (29), ensure athlete safety for return to sport, and re-establish pre-injury performance levels (24). However, known risk factors for ACL injury, such as deficits in thigh muscle strength and increased bilateral limb asymmetry during multi-joint lower body movements, often persist in non-athlete populations following ACL injury and ACLR despite rehabilitation and return to normal activities (2, 8, 19, 23, 27, 30, 34, 38).

Following ACLR, the rehabilitative process is divided into the early phase and late phase of rehabilitation, with the latter phase including the transition to return to sport (24). At the return to sport phase, objective and sport-specific neuromuscular screening including functional testing is important to ensure athlete readiness and safety, and that pre-injury functional ability is restored (24). Evaluating subjects even up to 2 years post ACLR is important due to the potential for prolonged deficits in function (8, 11, 30). Due to the high ACL re-injury rates in elite ski racing and the large physical demands, return to sport (i.e., return to snow) screening is important for ski racers following ACLR. Neuromuscular testing and functional tests should also be easily administered within a high performance sport environment. In this context, assessing bilateral limb asymmetry in multi-joint movements has been proposed as an effective approach to objectively differentiate between normal and pathological movement behaviors (15, 19) and to assess progress in rehabilitation (15, 20). Functional asymmetry testing has also been used to differentiate between ACL-deficient individuals who return to high level physical activity vs those who do not (12), and within a framework of return to sport functional screening for ACLR athletes (24).
To assess ACLR skiers, it is important that functional neuromuscular testing be multifaceted and reflects the demands of ski racing, which includes repeated bilateral eccentric/concentric movements (5, 18). In addition, such tests should reflect deficits that are commonly found in ACLR subjects, including reduced hamstrings and quadriceps strength/power (17). By assessing lower limb asymmetry over specific phases of the vertical jump (phase-specific) using a dual force plate system, knee extensor power and the ability to perform eccentric/concentric movements can be assessed (7, 21, 37). Through analysis of the vertical ground reaction force in the countermovement jump (CMJ), the eccentric and concentric movement phases can be identified, and functional asymmetry can be calculated over these distinct phases (7, 21, 37). Furthermore, as jumping involves a proximal to distal sequence of joint torques, deficits in knee extensor power can be identified by examining the vertical ground reaction force in the mid- to late phase of the squat jump (SJ) where the knee extensors are involved to a larger extent (6). Using this phase-specific approach, the magnitude of the vertical ground reaction force can be obtained by calculating the kinetic impulse or the area under the force–time curve (CMJ and SJ phase-specific kinetic impulse), which permits characterization of the functional asymmetry over a greater portion of the force–time curve than discreet time point analysis with values such as the instant of peak vertical ground reaction force.

The purpose of this study was to quantify bilateral lower limb functional asymmetry using the CMJ and SJ phase-specific kinetic impulse asymmetry index in uninjured and ACLR elite ski racers and asymmetry in lower limb muscle mass measured with dual x-ray absorptiometry (DXA) scanning. We hypothesized that ACLR ski racers would display significantly greater CMJ and SJ phase-specific kinetic impulse AIs compared with uninjured ski racers (8, 30). It was also expected that ACLR ski racers would demonstrate greater asymmetry
in leg muscle mass, which may be associated with the degree of functional asymmetry measured during the CMJs and SJs.

3.2 Methods

3.2.1 Subjects

Eighteen actively competing elite alpine ski racers from the Canadian Alpine Ski Team, including five World Cup medalists, were recruited during an annual fitness testing session at the start of the off-snow training period. Due to the challenges for subject recruitment in an elite athlete population, only nine actively competing elite ski racers suffering primary ACL injury/ACLR (males: \( n = 4 \); females: \( n = 5 \)) and nine uninjured ski racers (males: \( n = 5 \), females: \( n = 4 \)) could be recruited, and a comparison between sexes was not made. The pattern of secondary injury associated with the primary ACL injury was consistent with reports from alpine skiing populations and included meniscus injury, medial collateral ligament (MCL) injury, and articular cartilage injury (14, 28). Subject characteristics (mean ± SD) are provided in Table 3.1. All subjects had medical clearance for ski training and racing. Individuals who were being treated for lumbar spine injury and/or unrelated lower limb injury, such as patellofemoral knee pain and recent leg fractures, were excluded from the study. Ski racers with primary ACL injury who also sustained secondary injury to other knee ligaments, articular cartilage injury, and meniscus injury were included in this study. Inclusion criteria for both subject groups included that the subjects were qualified for and competed in FIS World Cup competition for the subsequent competitive season following testing. The Conjoint Faculties Research Ethics Board at the University of Calgary approved the experimental protocol and all subjects gave written informed consent to participate in this study.
3.2.2 Test Procedures

The functional asymmetry assessment was undertaken as a part of routine annual preseason testing at the start of the off-snow training period. However, DXA scanning and the CMJ and SJ phase-specific kinetic impulse asymmetry index were newly introduced tests; therefore, we were unable to obtain pre-injury data. All subjects were highly familiar with the testing procedures and regularly performed maximal effort CMJs and SJs as a part of their off-snow training routines. After giving informed consent, body composition was assessed by DXA scanning. Following DXA scanning, subjects performed a standardized warm-up including 10 min on a cycle ergometer and light dynamic stretching for the lower body. Dynamic stretching targeted the muscles of the lower limbs (i.e., quadriceps, hamstrings, gluteal muscles, hip flexors, and plantar flexors) and included 10 repetitions of dynamic stretching with a 2-s hold in the stretched position. Subjects then performed 10 maximal CMJs where they were instructed to descend rapidly to a knee joint angle of 90-degree knee flexion and ascend maximally while keeping the hands firmly placed on the hips. Subjects were given a 5-min rest interval, which was followed by 10 maximal SJs. For the SJs, subjects were instructed to descend slowly to a knee joint angle of 90-degree knee flexion and remain stationary for 3 s. After achieving a stationary baseline force, subjects were given verbal instruction to jump. Subjects were instructed to jump maximally on each jump, and as with the CMJs, subjects were required to keep the hands firmly placed on the hips throughout the jump. For both the CMJ and the SJ trials, jumps that deviated from the required technique were discarded and then repeated. All jump variables were calculated as the mean value obtained from 10 jumps.
Table 3.1: Subject Characteristics (Mean ± SD).

<table>
<thead>
<tr>
<th>STATUS</th>
<th>SEX</th>
<th>n</th>
<th>AGE (years)</th>
<th>MASS (kg)</th>
<th>BODY FAT (%)</th>
<th>MONTHS POST-OP</th>
<th>CMJ PEAK POWER (W/kg)</th>
<th>SJ PEAK POWER (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLR</td>
<td>FEMALE</td>
<td>5</td>
<td>23.8±3.3</td>
<td>70.3±5.7</td>
<td>21.6±2.5</td>
<td>28.4±13.5</td>
<td>40.4±5.4</td>
<td>40.4±6.2</td>
</tr>
<tr>
<td></td>
<td>MALE</td>
<td>4</td>
<td>30.5±2.1</td>
<td>86.6±9.9</td>
<td>14.7±3.1</td>
<td>23.5±10.6</td>
<td>49.9±3.9</td>
<td>50.1±3.3</td>
</tr>
<tr>
<td>CONTROL</td>
<td>FEMALE</td>
<td>4</td>
<td>21±1.4</td>
<td>66.8±4.5</td>
<td>15.3±2.5</td>
<td>NA</td>
<td>45.2±3.8</td>
<td>43.5±5.0</td>
</tr>
<tr>
<td></td>
<td>MALE</td>
<td>5</td>
<td>23.4±2.5</td>
<td>80.7±1.7</td>
<td>13.8±2.2</td>
<td>NA</td>
<td>52.7±4.9</td>
<td>52.3±4.3</td>
</tr>
</tbody>
</table>

3.2.3 Force Plate Analysis

Subjects performed the CMJs and SJs on a dual force plate system (Model No: PS 2142; Pasco Canada, Oakville, ON, Canada) that was capable of simultaneously measuring the vertical ground reaction force (Fz) recorded at 500-Hz sampling frequency during the jumps. Data were recorded on a personal computer and then exported and analyzed using a custom-built computer program (Matlab R 2012a; Mathworks, Natick, MA, USA) according to procedures described elsewhere (7, 21, 37). Briefly, the velocity of the body center of mass (BCM) was obtained by time integration of the instantaneous acceleration signal calculated from Fz. From the velocity of the BCM, the eccentric deceleration phase was defined as the time interval from the maximum negative velocity to zero velocity (deepest BCM position), whereas the concentric phase was defined from this instant of zero BCM velocity to the instant of jump takeoff (Figure 3.1). The total kinetic impulses for the right and left limb were then calculated separately for the eccentric
deceleration phase and concentric phase by time integration of the force–time curve over the appropriate periods.

The SJ was divided into two separate phases (Figure 3.1). The early takeoff phase (Phase 1) was defined as the initiation of the jump (i.e., time = 0) to the mid-point of the jump (i.e., time = ½ of the total jump time). The late takeoff phase (Phase 2) was defined as the time interval from the mid-point of the jump (i.e., time = ½ of the total jump time) to instant of toe-off. As with the CMJ, integration of the force–time curve over the appropriate time periods provided the kinetic impulse for the right and left limbs. The use of a phase-specific kinetic impulse calculation was undertaken based on pilot data observations of the force–time tracings of ACLR skiers that revealed directional asymmetries throughout SJs and CMJs, thus providing a rationale for the proposed approach. A typical example is provided in Figure 3.2. For both the SJ and CMJ, instantaneous mechanical muscle power was obtained by multiplying instantaneous vertical ground reaction force (Fz) with the corresponding BCM velocity. Peak power was defined as the maximum power in the concentric jump phase and was normalized relative to body mass.

3.2.4 Body Composition

Thigh lean mass and body fat percentage were determined by DXA scans according to the manufacturer's instructions (Discovery A QDR, Software version 12.6.2, Hologic Inc., Waltham, Massachusetts, USA). The same technician performed the analysis for all the DXA scans.
Figure 3.1: Determination of the vertical jump phases. Left Panel: Countermovement eccentric deceleration phase and concentric phase determined from the velocity of the body centre of mass. Right Panel: Squat jump phase determination including early takeoff phase (Phase 1) (Time = 0 to Time = ½ of the total jump time) and late takeoff phase (Phase 2) (Time = ½ of total jump time to the point of jump toe-off).

Figure 3.2: Force time tracing for an ACLR skier obtained during a countermovement jump demonstrating shift in directionality of asymmetry throughout the jump. The dashed line represents the uninjured limb and the solid line represents the ACLR limb.
3.2.5 Asymmetry Index Calculation

The CMJ and SJ phase-specific kinetic impulse asymmetry index was calculated in order to maintain the directionality of the asymmetry (20). For the control group, the asymmetry index was calculated as:

\[
\text{Asymmetry Index} = \frac{(\text{Left Limb Impulse} - \text{Right Limb Impulse})}{\text{(Maximum of Left and Right Impulse)}} \times 100,
\]

For the ACLR ski racers, the asymmetry index was calculated as:

\[
\text{Asymmetry Index} = \frac{(\text{Uninjured Limb Impulse} - \text{ACLR Limb Impulse})}{\text{(Maximum of Left and Right Impulse)}} \times 100,
\]

such that a positive number indicated uninjured limb dominance and a negative number indicated dominance in the ACLR limb.

3.2.6 Statistical Analysis

Based on pilot data, a statistical power calculation was performed and a minimum sample size of eight subjects per group was deemed necessary to achieve a statistical power of 80% (\(\beta = 0.80\)) in the primary outcome variables. We expected to find a 10% difference in the kinetic impulse asymmetry index between ACLR ski racers and uninjured ski racers. Where appropriate, a one-way analysis of variance was used to compare the means between the control group and the ACLR group. Due to unequal variances, a one-way test with unequal variances (oneway.test in Stats Package, R) was used to compare the asymmetry index for the concentric phase of the CMJ, the eccentric deceleration phase of the CMJ, SJ Phase 1, and SJ Phase 2. Subsequently, a linear regression analysis was performed to assess the relationship between the asymmetry index in leg muscle mass and the asymmetry index CMJ and SJ phase-specific kinetic impulse asymmetry index. Statistical analysis was carried out using R (Version 0.97.551; R Studio,
Boston, MA, USA). All data are reported as the mean value ± 1 SD, unless otherwise stated. A statistical significance level of \( \alpha = 0.05 \) was chosen.

### 3.3 Results

ACLR ski racers showed an elevated asymmetry index compared with uninjured ski racers in the concentric phase of the CMJ \( (P < 0.05) \), Phase 2 of the SJ \( (P < 0.05) \), and in leg muscle mass \([F(1,16) = 22.3; P < 0.001]\) (Table 3.2). There were no statistically significant differences observed between groups for Phase 1 of the SJ \( (P = 0.32) \) and the eccentric deceleration phase of the CMJ \( (P = 0.32) \). Linear regression analysis examining the relationship between the CMJ and SJ kinetic impulse asymmetry index and asymmetry index in leg muscle mass for all ski racers revealed a moderate relationship for the concentric phase of the CMJ \([r = 0.57; F(1,16) = 8.7, P < 0.01]\) and Phase 2 of the SJ \([r = 0.66; F(1,16) = 13.64, P < 0.01]\) (Figure 3.3). Additionally, large inter-individual variation was observed in the directionality of the CMJ phase-specific kinetic impulse asymmetry index for the ACLR skiers in the eccentric deceleration phase of the CMJ.
Table 3.2: Mean asymmetry indices and 95% confidence intervals for muscle mass, countermovement jump (CMJ) phases and squat jump (SJ) phases for control group and ACLR group (* P<0.05; ** P<0.001).

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>STATUS</th>
<th>MEAN (%)</th>
<th>95% CONFIDENCE INTERVAL (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asymmetry Index CMJ Concentric Phase</td>
<td>ACLR</td>
<td>6.8*</td>
<td>1.5 to 12.0</td>
</tr>
<tr>
<td></td>
<td>CONTROL</td>
<td>0.5</td>
<td>-1.3 to 2.4</td>
</tr>
<tr>
<td>Asymmetry Index CMJ Eccentric Phase</td>
<td>ACLR</td>
<td>5.2</td>
<td>-4.5 to 14.9</td>
</tr>
<tr>
<td></td>
<td>CONTROL</td>
<td>1.0</td>
<td>-1.5 to 3.5</td>
</tr>
<tr>
<td>Asymmetry Index SJ Early Takeoff Phase (Phase 1)</td>
<td>ACLR</td>
<td>-2.6</td>
<td>-11.3 to 6.2</td>
</tr>
<tr>
<td></td>
<td>CONTROL</td>
<td>1.0</td>
<td>-1.9 to 4.0</td>
</tr>
<tr>
<td>Asymmetry Index SJ Late Takeoff Phase (Phase 2)</td>
<td>ACLR</td>
<td>8.8*</td>
<td>0.1 to 17.6</td>
</tr>
<tr>
<td></td>
<td>CONTROL</td>
<td>-1.0</td>
<td>-4.2 to 2.2</td>
</tr>
<tr>
<td>Asymmetry Index Muscle Mass</td>
<td>ACLR</td>
<td>4.3**</td>
<td>1.5 to 7.0</td>
</tr>
<tr>
<td></td>
<td>CONTROL</td>
<td>-2.2</td>
<td>-3.8 to -0.6</td>
</tr>
</tbody>
</table>
**Figure 3.3:** Left Figure: relationship between limb asymmetry in kinetic impulse during the concentric phase of the countermovement jump (CMJ) and asymmetry in leg muscle mass ($r = 0.57$; $F(1, 16) = 8.7$, $P < 0.01$). Right Figure: relationship between limb asymmetry in kinetic impulse produced in Phase 2 of the squat jump (SJ) and asymmetry in leg muscle mass ($r = 0.66$; $F(1,16) = 13.64$, $P < 0.01$). Circles denote ACLR skiers and triangles denote uninjured skiers. Shaded zone indicates 95% confidence interval.

### 3.4 Discussion

To our best knowledge, the present study is the first to evaluate bilateral asymmetry in leg muscle mass and functional asymmetry during multi-joint closed kinetic chain movements in actively competing ACLR elite ski racers and uninjured ski racers including World Cup medalists. Such investigations are important due to the high incidence of ACL injury and re-injury in this athlete population (4, 13, 32, 35). Furthermore, neuromuscular testing and functional asymmetry assessments are useful throughout the return to sport process to ensure that neuromuscular function is adequately restored and to help guide the post-ACLR rehabilitation process (24).
The present investigation offers an applicable assessment of functional asymmetry evaluating kinetic impulse over specific phases of the CMJ and SJ (phase-specific kinetic impulse asymmetry index). The CMJ and SJ phase-specific kinetic asymmetry index addresses the limitations of using single discrete time point analysis with values such as the instant of maximum ground reaction force (26). By evaluating the magnitude of the ground reaction force using kinetic impulse calculations (i.e., area under the force vs time curve), it is possible to obtain information on functional inter-limb asymmetry over a broader selection of the jump force–time curve using a straightforward mathematical approach.

As ski racing involves repeated bidirectional turning with eccentric/concentric movements and large quadriceps muscle loading (5, 18), the ability to identify deficits specific to eccentric and concentric muscular actions from CMJ force–time analysis may provide additional diagnostic information for rehabilitation due to the distinct nature of eccentric vs concentric muscular actions (1). Additionally, ACL injury and ACLR result in chronic knee extensor strength and power deficits (17, 29). Assessing functional asymmetry late takeoff phase of the SJ using jumping kinetics enables the quadriceps muscle group to be evaluated due to the greater contribution of the knee extensors in the proximal to distal sequence of the SJ movement (6, 9). However, it should be mentioned that muscular deficits following ACLR are not limited to the knee extensors (17), and a comprehensive approach for return to sport screening and neuromuscular testing is recommended (24).

The main finding of our study was the presence of a significantly greater CMJ and SJ phase-specific kinetic impulse asymmetry index in top-level ski racers with a history of ACLR compared with uninjured ability-matched ski racers that remained despite a full return to activity. The finding of elevated functional asymmetry conforms to findings in non-athletic populations.
where ACL-deficient and ACLR subjects exhibit elevated bilateral asymmetry during multi-joint lower body movements such as jumping and squatting (8, 11, 19, 30, 34) even up to 2-years post-surgery (8, 30).

However, the CMJ and SJ phase-specific kinetic impulse asymmetry index used in the present investigation revealed individuals with directional shifts in the limb asymmetry throughout the jumping movement and distinct jump phases in which the asymmetry index was the most prominent for the ACLR subjects. Specifically, differences in limb asymmetry between ACLR and uninjured skiers were observed for the concentric phase of the CMJ and late takeoff phase of the SJ but not for the eccentric deceleration phase of the CMJ or the early takeoff phase of the SJ. This result may reflect the chronic knee extensor strength and power deficits associated with ACL injury (17, 29), and the importance of the quadriceps muscle group for maximal mechanical muscle power generation in the proximal to distal sequence of joint actions in the jumping movement (6).

While a statistically significant difference was not found in the eccentric deceleration phase, careful review of each individual subject revealed a single subject who displayed a large eccentric deceleration asymmetry (Asymmetry Index of −16.1%) that reflected dominance in the ACLR limb. This finding was unexpected and emphasizes the importance of maintaining the directionality of the asymmetry index. Furthermore, for practical purposes, it also emphasizes the need to account for the presence of inter-subject variation in the CMJ phase-specific kinetic impulse asymmetry index.

Consistent with the limited scientific data on lower body functional asymmetry in alpine ski racers (31), the present group of uninjured elite alpine ski racers was highly symmetric across all phases of the SJ and CMJ (range = 0.5–2.2%). Our results are consistent with other findings
of marked bilateral limb symmetry in elite ski racers including a quadriceps maximal strength asymmetry of less than 2% in male and female elite alpine ski racers (25). The precise relationship between a low functional asymmetry index, ski performance, and risk for injury is unknown. However, due to the bidirectional nature of ski racing and the large quadriceps muscle loading (5, 18), elevated functional asymmetry would seem disadvantageous. Additionally, a prospective cohort study of over 400 young competitive alpine ski racers found that a significant proportion of first-time lower extremity injuries occurred on the left limb compared with the right limb (40). As there were no physical or functional testing measurements conducted in this study, the mechanisms underlying this finding are unknown. However, these findings provide a rationale for including functional asymmetry profiling using tests such as the CMJ and SJ phase-specific kinetic impulse asymmetry index in competitive alpine ski racers. Future longitudinal study is required to confirm the possibility of a relationship between increased bilateral functional asymmetry and risk for lower extremity injury.

Representing a single case observation, an ACLR athlete experienced an MCL injury to the contralateral limb in the period following the data collection that was sustained during ski training. ACL re-injury is common in elite ski racers (32, 35), and injury is often sustained on the contralateral limb (32). While this subject did not sustain a re-injury to the ACL, this occurrence has relevance to the phase-specific kinetic impulse asymmetry index as this athlete had the greatest asymmetry in the SJ late takeoff phase (asymmetry index of 25.3%), the CMJ concentric phase (asymmetry index of 18.0%), and the CMJ eccentric deceleration phase (asymmetry index of 20.5%).

In other return to sport screening, frameworks ensuring an inter-limb asymmetry of less than 15% has been recommended for functional tests involving jumping movements (24).
Additionally, in athlete and non-athlete populations, functional deficits in multi-joint closed kinetic chain movements are associated with risk for ACL injury and outcome following ACLR (10, 16, 27, 36). Despite the potential relevance for including the CMJ and SJ phase-specific kinetic impulse asymmetry index as a part of a multifaceted approach for assessing outcome in the ACLR ski racer, well-conducted longitudinal studies are lacking. Therefore, at the present time, it is impossible to confirm or disprove the value of this approach for identifying skiers who may be at elevated risk for injury following ACLR.

Consistent with the literature, ACLR ski racers also had significantly greater bilateral asymmetry in leg muscle mass compared with uninjured ski racers, reflecting deficits in the affected limb (22, 23, 38). However, while Konishi et al. (22) found significant deficits in muscle volume in ACLR patients less than 12 months post-surgery, no statistical difference was observed at 18 months post-surgery. In the present investigation, time since surgery was 23.5 ± 10.6 months for the male skiers and 28.4 ± 13.5 months for the female skiers, which is longer than the 18-month post-operative period evaluated by Konishi et al. (22). The reason for the difference in findings between the two studies is unclear but may be attributable to the different populations studied (elite athlete vs untrained) and/or due to the prolonged asymmetrical limb loading due to the extreme physical demands of elite alpine ski racing. There is also evidence highlighting the importance of rehabilitation to restore thigh muscle strength in ACL-deficient subjects (38). In the present investigation, we were unable to obtain specific information regarding each subject's rehabilitation program. However, all subjects received supervised and individualized rehabilitation provided by physiotherapists assigned to the Canadian Alpine Ski Team.
Finally, a moderate relationship was found between the asymmetry index in leg muscle mass and kinetic impulse in the concentric phase of the CMJ \( (r = 0.57) \). This was further supported with a moderately strong relationship observed between the asymmetry index in leg muscle mass and the kinetic impulse asymmetry index for the SJ late takeoff phase \( (r = 0.66) \). In addition to muscle mass, neuromuscular coordination is highly important for performance in movements requiring large impulses and fast rates of force development such as the CMJ and SJ (1). While impaired central activation has not been observed in active ACLR subjects, deficits in neuromuscular coordination and/or activation in ACLR ski racers cannot be excluded (23).

A limitation of our study was the inability to control for sex-related factors. However, previous research suggests that there is no difference in ACL injury rates between male and female elite ski racers due to the preclusion of sex-related risk factors commonly found to be dominant in field sports due to the high-energy injury mechanisms (4, 13). Further limitations include a 7-year age difference between the ACLR male and uninjured male racers, and a relatively small sample size. Despite these limitations and the inherent challenges in studying elite athlete populations, it is important that research efforts be specific to the population of interest to develop effective injury prevention strategies (39). As the CMJ and SJ phase-specific kinetic impulse asymmetry index and DXA scanning were only recently introduced into the annual preseason fitness assessments, we do not have pre-injury measurements. Such information would be valuable to determine if the increased functional asymmetry was present prior to the ACL injury, and if not, the degree to which functional asymmetry was affected following ACLR. Obtaining this type of baseline functional data on uninjured ski racers is an important outcome for future studies.
In conclusion, using dual force plate methodology to assess functional asymmetry, it was observed that actively competing elite alpine ski racers with a history of ACLR displayed an elevated CMJ and SJ kinetic impulse asymmetry index over specific phases of the jumping movement including the concentric phase of the CMJ and in the late takeoff phase of the SJ compared with uninjured ski racers. For both jump phases, the kinetic impulse asymmetry index reflected deficits in the affected limb. In addition, ACLR ski racers also displayed greater asymmetry in leg muscle mass compared with uninjured ski racers who were highly symmetrical across all outcome measures. Due to the moderate relationship between the CMJ and SJ phase-specific kinetic impulse asymmetry index and the asymmetry index in leg muscle mass, future research should include measures of neuromuscular activation (including antagonist muscle co-activation), and muscle synergist coordination as potential mechanisms contributing to the functional asymmetries observed in ACLR ski racers. Further longitudinal research is required to assess the value of the CMJ and SJ phase-specific kinetic impulse asymmetry index as a part of a multifaceted approach for return to sport screening and monitoring to ensure pre-injury performance levels are restored, and to evaluate the relationship between elevated functional asymmetry and risk for re-injury.

3.5 Conclusion

Elite ski racing is an extreme sport with a high incidence of knee injury and re-injury. Due to the large physical demands, objectively obtained functional criteria are important to monitor progress in rehabilitation following ACLR and to establish objective standards for a safe return to sport. The present investigation introduces a new approach to evaluate functional asymmetry using the CMJ and SJ phase-specific kinetic impulse asymmetry index. By measuring the limb kinetic impulse over specific phases of the CMJ and SJ, this approach
provides information relevant to functional movements involved in ski racing (e.g., eccentric/concentric movements), yet is a straightforward analytical technique that offers more information than discrete time point analysis. This investigation reveals the presence of significant functional asymmetry during specific phases of the CMJ and SJ in elite ski racers with a history of ACLR compared with uninjured ski racers despite a full return to sport. Further research using prospective study designs is required to evaluate the use of this functional asymmetry assessment as a part of a multifaceted approach for return to sport screening following ACL injury in elite ski racers.
3.6 References


3.7 Bridge to Chapter 4

The first study (Chapter 3) compared vertical jump functional asymmetries in ACLR elite alpine ski racers and non-injured ski racers. The primary finding was that functional asymmetries persisted despite return to sport. In addition to restoring functional symmetry, hamstring/quadriceps strength is deemed important for successful return to sport following ACL injury. In the second study (Chapter 4), hamstring/quadriceps strength was evaluated in elite alpine ski racers with/without ACL reconstruction. Maximal isometric hamstring/quadriceps strength, rapid force producing ability (RFD), and hamstring/quadriceps strength ratios were measured.
Chapter 4: Rapid Hamstring/Quadriceps Strength in ACL Reconstructed Elite Alpine Racers

4.1 Introduction

Elite alpine ski racing is a physically demanding sport involving high speeds and large external loads imposed on the lower limbs that occur in an unpredictable environment (8, 10, 17). Skiers perform repeated bidirectional turns with forceful eccentric muscle contractions, which typically involve maximal levels of neuromuscular activity in the thigh muscles (10, 17). To meet these demands, elite alpine ski racers display high levels of hamstring and quadriceps strength, an elevated hamstring/quadriceps strength ratio and marked bilateral strength symmetry (24, 34).

Due to the extreme demands of elite alpine ski racing, there is a high risk for lower body injury, especially to the knee joint (11). In a competitive season, knee injuries accounted for over 30% of the injuries suffered by elite alpine ski racers, and more than half of these injuries resulted in a significant time loss from sport (> 28 days) (11). Anterior cruciate ligament (ACL) rupture is the most common form of serious knee joint injury in ski racing (11), accompanied by a high ACL re-injury rate (27). Research into the mechanisms and etiology of non-contact ACL injury in elite alpine ski racing highlights distinct differences compared to ACL injury in field sports, including several mechanisms of high force injury (8). Furthermore, at the elite level, no sex-differences in ACL injury rates are found, which is attributable to the preclusion of sex-related risk factors due to the high force/energy injury mechanisms (9, 11).

To achieve effective injury prevention, it is of importance to identify modifiable risk factors that can be targeted through exercise and training (36). However, to date, only a single scientific study has been conducted that was aimed at assessing the relationship between modifiable (trainable) risk factors and ACL injury in ski racers, suggesting that core strength
deficits were associated with injury in young competitive ski racers (28). However, more senior elite ski racers may be at even greater risk for ACL injury (27). Not only is there a paucity of scientific literature on trainable risk factors for ACL injury prevention in elite alpine ski racers, but also there are no studies on ACL re-injury prevention in actively competing ski racers with a history of previous ACL injury and ACL reconstruction (ACLR).

Following ACL injury, the primary objective is to restore quadriceps and hamstring muscle strength, and this is associated with successful return to sport and activity (6, 26). Restoring thigh muscle strength is especially important for ACLR ski racers because of the importance of quadriceps strength in ski racing (10, 17), and the influence of hamstring/quadriceps strength imbalance on knee injury risk (18, 24, 34). However, long term hamstring and quadriceps strength deficits often persist despite rehabilitation (3, 14, 26), and since coordinated hamstring and quadriceps muscle function is important for ACL protection (5, 23, 30), identifying strength deficits is important.

Several measures of hamstring and quadriceps muscle strength have been proposed for their clinical efficacy (1, 13, 38). However, due to the short time history of non-contact ACL injury in field sports (< 50 ms after foot contact) (22), the assessment of maximal hamstring and quadriceps strength, which often requires more than 300 ms to develop under isometric conditions, has been questioned (38). Instead, the ratio of rapid isometric hamstring vs. quadriceps torque production (rate of torque development: RTD) assessed over shorter time frames (< 200 ms) has been proposed as a relevant measure of dynamic knee joint stabilization (38).

Explosive strength is quantified by the RTD during a maximal voluntary, isometric contraction (MVC) and can be separated into the rate of torque development observed in the very
early phase of the MVC (0-100 ms), also denoted as the initial rate of torque development (initial RTD), and the rate or torque development generated in the later phase of rising muscle force (late RTD), which is defined by the RTD developed from the onset of the MVC to a period between 100 and 200 ms (4). Additionally, the hamstring/quadriceps strength ratio (H/Q Ratio) has been used to assess dynamic knee joint stabilization potential both in alpine ski racers (24, 34) and in other athlete populations (1, 38). Furthermore, as initial RTD, late RTD and maximum muscle strength are relevant to dynamic athletic performance and can be developed by specific training methods, assessment of these strength characteristics may provide important information for optimizing the design of rehabilitation and resistance training programs in ski racers returning from ACL injury (37).

Due to the unique characteristics of non-contact ACL injury in elite ski racers, the risk for ACL injury/re-injury, the importance of quadriceps and hamstring muscle strength for ski performance and injury prevention, and the lack of scientific data on thigh muscle strength in actively competing elite ski racers with/without ACL injury, the aim of the present investigation was to perform a comprehensive hamstring and quadriceps muscle strength assessment and to evaluate lower limb muscle mass in a group of actively competing elite alpine ski racers with/without ACLR. We hypothesized that the ACLR skiers would demonstrate significant deficits in the ACLR limb for muscle mass, hamstring strength and quadriceps strength, both compared to the contralateral limb and to the limb average of uninjured elite skiers (control group). Additionally, in uninjured individuals, we expected female skiers to demonstrate reduced thigh muscle strength compared to male skiers, and no signs of bilateral limb strength.
4.2 Methods

4.2.1 Subjects

Twenty-one uninjured skiers (Males: n=13; Females: n=8) from the Canadian Alpine Ski Team, including World Cup medalists, participated in this study, and were assessed at the start of the off-snow training period. Due to the challenges for subject recruitment in an elite athlete population, only eight actively competing ACLR elite ski racers could be recruited (Males: n=3; Females: n=5), and a comparison between sexes was not made for this group. Of the eight ACLR skiers, three received allografts and five were reconstructed with a semitendinosus autograft. Additionally, five of the eight ACLR ski racers suffered injury on the non-dominant limb, and only a single subject sustained an isolated ACL injury. The pattern of secondary injury associated with the primary ACL injury was consistent with the reports from non-elite ski populations and included meniscus injury, medial collateral ligament injury and sub-chondral bone bruising (12, 25). Subject characteristics (Mean ± 1SD) are provided in Table 4.1. All subjects had medical clearance for ski training and racing. Skiers being treated for lumbar spine injury and/or unrelated lower limb injury such as patellofemoral knee pain and recent leg fractures were excluded from the study. The Conjoint Faculties Research Ethics Board at the University of Calgary approved the experimental protocol and all subjects gave written informed consent to participate in this study.

4.2.2 Test Procedures

Testing was undertaken as part of a routine annual pre-season fitness assessment, and all subjects were familiarized with the testing procedures. However, we were not able to obtain pre-injury testing data. After completing the informed consent, subjects were given a standardized 10-minute warm up on a Monarch cycle ergometer followed by light dynamic stretching for the
lower body muscles. Subjects were then seated in an isokinetic Biodex Dynamometer (System 3, Model 830-210) with the lateral epicondyle of the femur aligned with the axis of rotation of the dynamometer. Subjects were strapped to the dynamometer with two belts crossing the chest and one belt crossing the hips. The knee joint angle was set at 70 degrees of flexion (zero degrees was defined as full extension).

With the arms across the chest, subjects performed three MVCs of isometric knee extension and knee flexion for both the right and the left limbs (38). A short 30-second rest interval separated each repetition and a 60-second rest interval separated each of the contraction types. Subjects were instructed to perform the contractions as quickly and forcefully as possible and to maintain the contraction for two-seconds. Visual feedback was provided on-line using a computer monitor along with strong verbal encouragement. Trials with a noticeable countermovement were discarded and repeated. Torque data were sampled at 1000 Hz and collected using an external A/D converter (DATAQ Instruments, Windaq Data Acquisition Software Version 2.78) and stored on an IBM personal computer. Data were then exported into a custom-built software program for analysis (Matlab Version R2013a).

4.2.3 Data Analysis

Raw torque (voltage) signals were low-pass filtered using a 4th order zero-lag Butterworth filter (2). The raw voltage data were converted to torque (Nm) and gravity-corrected for the weight of the limb and dynamometer arm. The trial with the highest maximal torque was defined as the MVC and was selected for analysis (2). The start of the trial was defined as the time point when torque exceeded four percent of the MVC. Contractile rate of torque development (RTD) was obtained as the mean slope of the torque vs. time curve (i.e. $\Delta$ Torque/$\Delta$ Time, Nm/s) over the four distinct time periods (i.e. 0-50 ms; 0-100 ms; 0-150 ms; and 0-200
ms). RTD calculated between the time intervals of 0-50 ms (RTD<sub>50</sub>) and 0-100 ms (RTD<sub>100</sub>) were used to assess the initial RTD, and RTD calculated between the intervals of 0-150 ms (RTD<sub>150</sub>) and 0-200 ms (RTD<sub>200</sub>) were used to measure late RTD (4, 31). The H/Q Ratio was then calculated for the MVC and RTD as (38):

\[
\text{MVC H/Q Ratio} = \frac{\text{Hamstring MVC}}{\text{Quadriceps MVC}}
\]

\[
\text{RTD H/Q Ratio} = \frac{\text{RTD Hamstring}}{\text{RTD Quadriceps}}.
\]

MVC and RTD values were normalized to body mass for group comparisons (15). Additionally, a limb average was calculated for the uninjured skiers and compared separately to the unaffected limb and ACLR limb of the ACLR skiers (15, 32). Finally, relative RTD was calculated by normalizing RTD to the MVC (i.e. relative RTD = RTD / MVC) (2, 4, 13).

**4.2.4 Body Composition**

Thigh lean mass and body fat percentage were determined by DXA scans according to the manufacturer’s instructions (Discovery A QDR, Software version 12.6.2, Hologic Inc., Waltham, MA, USA). Briefly, subjects were placed supine in the DXA scanner with the lower limbs extended and internally rotated and the upper limbs fully extended and pronated. Using the manufacturer’s predefined procedures in the whole body scan mode, the lower body was partitioned by a horizontal line just proximal to the iliac crests and a centre line separating each lower limb. A diagonal line was drawn through the proximal edge of the femoral head and vertical lines were drawn on the lateral aspect of the lower limb tissue to capture all tissue in each of the lower limbs. A single experienced technician performed the data collection and analysis for all the DXA scans.
4.2.5 Statistical Analysis

Based on pilot data, a statistical power calculation was performed and a minimum sample size of eight subjects per group was deemed necessary to achieve a statistical power of 80% for our primary outcome measures ($\beta=0.80$). As our primary objective was to compare explosive strength and maximal thigh muscle strength in elite ski racers, and not all ACLR subjects had sustained injury on the same leg, paired t-tests were used to assess within group differences, and a one-way analysis of variance was used for between group comparisons. For between group comparisons, the body mass normalized limb average for the control group was compared to each limb of the ACLR skiers, and the body mass normalized limb average was also used to compare uninjured male skiers with the uninjured female skiers. Statistical analysis was carried out using R (Version 0.97.551). All data were carefully assessed for normal distribution and equality of variance and, when required, data were transformed and retested to ensure that normality and homoscedasticity assumptions were satisfied. Non-transformed data are shown and all data are represented as the mean value ± one standard deviation (SD), unless stated otherwise. Statistical significance was set at $\alpha = 0.05$.

4.3 Results

4.3.1 Bilateral Limb Strength Comparisons

Consistent with our hypothesis, there were no significant bilateral differences in lower limb mass for the uninjured male skiers and the uninjured female skiers (Table 4.1). However, contrary to our expectations, ACLR skiers did not display a significant bilateral limb difference in lower limb muscle mass. ACLR skiers demonstrated significant deficits in hamstring and quadriceps maximal strength (i.e. MVC) and late RTD (i.e. RTD$_{200}$ and RTD$_{150}$) in the ACLR limb compared to the unaffected limb ($P<0.05$) (Table 4.2). As expected, uninjured female
skiers did not display significant bilateral limb differences across any of the hamstring and quadriceps strength variables. While uninjured male skiers did not have a significant bilateral limb difference in quadriceps strength measures there was a 5% bilateral limb difference in hamstring maximal strength ($MVC_{Right} = 1.91\pm0.25$ Nm/kg; $MVC_{Left} = 1.80\pm0.24$ Nm/kg, $P<0.05$) and an 8% difference in hamstring late RTD ($RTD_{150\_Right} = 9.07\pm0.99$ Nm/s/kg; $RTD_{150\_Left} = 8.35\pm1.07$ Nm/s/kg, $P<0.05$).

### 4.3.2 Comparison of Limb Strength for Uninjured Males and Uninjured Females

In contrast with our hypothesis, there were no significant differences between uninjured males and uninjured females in maximal quadriceps or hamstring strength (Extension MVC: Females = $3.96\pm0.45$ Nm/kg, Males = $4.17\pm0.59$ Nm/kg; Flexion MVC: Females = $1.66\pm0.24$ Nm/kg, Males = $1.86\pm0.25$ Nm/kg), and no differences in initial RTD or late RTD (Figure 4.1A). When normalized to the MVC, uninjured female skiers demonstrated significantly greater hamstring relative RTD$_{50}$ ($P<0.01$) and relative RTD$_{100}$ ($P<0.05$) compared to the uninjured males (Figure 4.1B).

### 4.3.3 Comparison of Limb Strength for ACLR Group and Uninjured Group

Consistent with our hypothesis, the ACLR limb demonstrated significant deficits in hamstring and quadriceps muscle maximal strength compared to the limb average for the uninjured skiers (Extension MVC: ACLR Limb = $3.44\pm0.63$ Nm/kg vs. Uninjured = $4.09\pm0.52$ Nm/kg, $P<0.01$; Flexion MVC: ACLR Limb = $1.52\pm0.40$ Nm/kg vs. Uninjured = $1.78\pm0.25$ Nm/kg, $P<0.05$). Significant quadriceps explosive strength deficits were also found in the ACLR limb compared to the uninjured group ($P<0.05$) (Figure 4.2A).

No differences in hamstring muscle explosive strength were observed in the ACLR limb compared to the uninjured group. However, relative RTD$_{50}$ (i.e. normalized to the MVC) was
found to be higher in the ACLR limb compared to the uninjured skiers (Figure 4.2B) (P<0.05). Figure 4.2C provides a comparison of the hamstring MVC torque for the ACLR limb versus the contralateral limb, and the ACLR limb versus the limb average of the uninjured skiers, as significant strength deficits were found in both instances.

### 4.3.4 Comparison of H/Q Ratios for Uninjured Males and Uninjured Females

A comparison of the H/Q Ratios between the uninjured female ski racers and uninjured males demonstrated a significant difference for only the H/Q Ratio$_{50}$ (P<0.05) (Figure 4.3A). As the H/Q Ratio can be elevated by diminished quadriceps strength (i.e. smaller denominator), Figure 4.3B illustrates the hamstring and quadriceps RTD$_{50}$ for each subject in the uninjured male and uninjured female group, and is further stratified by subjects who demonstrated an H/Q Ratio$_{50}$ of less than 0.4, between 0.4 and 0.5 and above 0.5. Additionally, the plot is divided vertically by those with a bilateral asymmetry in quadriceps maximal strength of less than 10% and greater than 10%. Only one female ski racer who is highlighted in the bottom right panel of Figure 4.3B presented with a high H/Q Ratio$_{50}$ (>0.5) and a bilateral asymmetry in quadriceps MVC of greater than 10% (individual bilateral asymmetry = 11.1%). Additionally, no significant differences were observed in bilateral quadriceps strength for the uninjured females or in comparison to the quadriceps strength of the uninjured males.

### 4.3.5 Comparison of H/Q Ratios for ACLR Group and Uninjured Group

Contrary to our hypothesis, the ACLR limb displayed an elevated H/Q Ratio$_{50}$ compared to the uninjured group (P<0.05) (Figure 4.3C). Figure 4.3D illustrates the hamstring and quadriceps RTD$_{50}$ measured in the ACLR limb for each of the ACLR subjects. The plot is further divided to show subjects with an H/Q Ratio between 0.4 and 0.5, and those who presented with the highest H/Q Ratio (>0.6). As significant bilateral asymmetries were observed
in quadriceps maximal strength (MVC), the plot is further divided vertically to show those subjects with a bilateral asymmetry in quadriceps maximal strength of less than 15%, between 15% and 25% and those with an asymmetry greater than 25%. The bottom right panel of Figure 4.3D identifies three subjects who presented with a high H/Q Ratio (Range = 0.60-0.89) along with the largest bilateral asymmetry in quadriceps MVC reflecting deficits in the ACLR limb. Furthermore, the ACLR limb also demonstrated significant deficits in quadriceps explosive strength and maximal strength compared to the contralateral limb, and compared to the limb average of the uninjured group.

Table 4.1: Subject characteristics (Mean ± SD).

<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>ACLR SUBJECTS</th>
<th>CONTROL SUBJECTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FEMALE</td>
<td>MALE</td>
</tr>
<tr>
<td>N</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>AGE (Years)</td>
<td>24.2 ±3.2</td>
<td>28.3 ±0.6</td>
</tr>
<tr>
<td>MASS (kg)</td>
<td>69.4 ±4.1</td>
<td>89.0 ±9.3</td>
</tr>
<tr>
<td>LEFT LIMB MASS (g)</td>
<td>9273.8 ±772.4</td>
<td>12606.9 ±1555.4</td>
</tr>
<tr>
<td>RIGHT LIMB MASS (g)</td>
<td>9593.4 ±1168.9</td>
<td>12677.1 ±1122.0</td>
</tr>
<tr>
<td>PERCENT BODY FAT (%)</td>
<td>20.5 ±3.3</td>
<td>13.9 ±3.0</td>
</tr>
<tr>
<td>POST-OP (Months)</td>
<td>28.4 ±13.5</td>
<td>19.3 ±1.2</td>
</tr>
</tbody>
</table>
### Table 4.2: A comparison of body mass normalized hamstrings and quadriceps strength between uninjured male and uninjured female skiers (limb average), and the ACLR limb and unaffected limb of ACLR ski racers (# denotes a significant difference (p<0.05)).

<table>
<thead>
<tr>
<th>STATUS</th>
<th>SEX</th>
<th>LIMB</th>
<th>MOVEMENT</th>
<th>MVC (Nm/kg)</th>
<th>RTD 0°/60°</th>
<th>RTD 1°/5°</th>
<th>RTD 2°/5°</th>
<th>RTD 4°/5°</th>
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<tr>
<td>CONTROL MALE AVERAGE</td>
<td>EXTENSION</td>
<td>3.96±0.45</td>
<td>16.22±0.87</td>
<td>18.91±1.14</td>
<td>21.51±1.27</td>
<td>24.26±2.69</td>
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<tr>
<td>ACLR MALE AVERAGE</td>
<td>EXTENSION</td>
<td>4.17±0.56</td>
<td>15.95±2.45</td>
<td>18.85±2.59</td>
<td>22.52±3.10</td>
<td>26.09±3.89</td>
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<tr>
<td>UNAFFECTED MALE AVERAGE</td>
<td>EXTENSION</td>
<td>4.43±0.67</td>
<td>20.02±2.69</td>
<td>22.89±4.27</td>
<td>22.89±4.66</td>
<td>26.66±8.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR FEMALE AVERAGE</td>
<td>EXTENSION</td>
<td>1.78±0.42</td>
<td>8.30±0.33</td>
<td>10.53±1.17</td>
<td>13.49±2.97</td>
<td>21.33±5.62</td>
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<tr>
<td>UNAFFECTED FEMALE AVERAGE</td>
<td>EXTENSION</td>
<td>1.52±0.40</td>
<td>6.30±0.87</td>
<td>8.30±1.41</td>
<td>10.35±1.77</td>
<td>18.20±5.08</td>
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<td>CONTROL MALE AVERAGE</td>
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<td>1.66±0.22</td>
<td>6.83±0.45</td>
<td>8.30±0.96</td>
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<tr>
<td>ACLR MALE AVERAGE</td>
<td>FLEXION</td>
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<td>9.34±1.14</td>
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<td>18.20±5.08</td>
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<td>4.43±0.67</td>
<td>6.99±1.14</td>
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<td>ACLR FEMALE AVERAGE</td>
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<tr>
<td>UNAFFECTED FEMALE AVERAGE</td>
<td>FLEXION</td>
<td>1.43±0.33</td>
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<td>13.49±2.97</td>
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Figure 4.1: (A) Hamstrings and quadriceps rate of torque development (RTD) for uninjured male and uninjured female ski racers. (B) Hamstrings and quadriceps relative RTD (RTD/MVC) for uninjured male and uninjured female ski racers (* $P<0.05$; ** $P<0.01$).
Figure 4.2: (A) Hamstrings and quadriceps rate of torque development (RTD) for the affected limb of ACLR skiers and limb average of controls (uninjured males and uninjured females). (B) Hamstrings and quadriceps relative RTD for the affected limb of ACLR skiers and limb average of controls. (C) Bilateral comparison of hamstrings MVC in ACLR skiers and controls (* Between Group Difference P<0.05; # Within Group Difference P<0.05).
Figure 4.3: (A) Ratio of hamstrings vs. quadriceps explosive strength (H/Q Ratio) for uninjured male and female ski racers. (B) Individual hamstrings and quadriceps rate of torque development at 50 ms (RTD_{50}) for male and female skiers, range in H/Q Ratio and asymmetry in quadriceps MVC. (C) H/Q RTD Ratio for the affected limb of ACLR skiers and limb average of control group skiers. (D) Individual hamstrings and quadriceps RTD_{50} for the ACLR limb, range in H/Q Ratio and asymmetry in quadriceps MVC (*P<0.05).
4.4 Discussion

4.4.1 Comparison of Limb Strength for ACLR Skiers and Uninjured Skiers

To our best knowledge, the present study was the first to evaluate quadriceps and hamstring strength in actively competing elite alpine ski racers with/without ACLR, and to also use isometric dynamometry to differentiate between maximal strength and explosive strength (i.e. rapid force development ability). Such investigations are important because of the high incidence of ACL injury and re-injury in this athlete population (8, 9, 11, 27). Despite the challenges in studying elite alpine ski racers (e.g. small sample size, availability, training periodization), specific research efforts are required in the population of interest to develop appropriate guidelines for return to sport and strategies aimed at injury prevention (36).

The main findings of this study were the presence of significant deficits in quadriceps maximal strength (MVC) and explosive strength (RTD) in the ACLR limb of actively competing elite alpine ski racers compared to the contralateral limb, and compared to the limb average of uninjured elite alpine ski racers despite long post-operative periods (Mean = 25.0±11.3 months). Because of the substantial risk for injury (11), the importance of quadriceps muscle strength for ski performance (10, 17, 24), and the association between the restoration of quadriceps strength and successful return to activity (6, 26), the identification of quadriceps strength deficits is highly relevant for the ACLR elite alpine ski racer.

Our results are consistent with previous findings where long term deficits in quadriceps muscle strength have been identified in ACLR subjects (14, 15, 21, 26, 35) and ACL deficient knees (3, 33). While there is evidence showing that quadriceps mass and strength is restored at 18 months post-surgery (19), some studies suggest a reduction in quadriceps muscle voluntary activation (35), and peripheral muscle factors (21) as contributors to deficits in quadriceps
strength that are observed long after surgical reconstruction of the ACL. An investigation comparing quadriceps strength in physically active ACLR subjects more than two years post-surgery with physically active controls found a 25% strength deficit in the ACLR limb when torque was normalized to body mass (14). While the present investigation used isometric dynamometry and not isokinetic dynamometry, the mean difference in peak knee extensor torque was 14% in the ACLR limb compared to the limb average of the control group. Furthermore, while Hiemstra et al. (15) did not make bilateral comparisons in the ACLR group due to the possibility of contralateral limb deficits, the results of the present study found no difference in quadriceps strength in the uninjured limb of the ACLR skiers compared to the uninjured skiers.

We found significant bilateral limb deficits in quadriceps maximal strength in the injured limbs compared to the uninjured limbs in the ACLR skiers (Mean Asymmetry = 19%). The implications of significant bilateral asymmetry in quadriceps maximal strength for ski performance and risk for ACL re-injury are unknown. However, uninjured ski racers display marked bilateral symmetry in quadriceps strength (24), and are required to perform repeated bidirectional turns that involve large quadriceps muscle loading (10, 17). Consistent with Neumayr et al. (24), the mean bilateral asymmetry in quadriceps maximal strength found for the uninjured skiers in the present study was less than 2%. This result suggests the importance of bilateral quadriceps strength symmetry for ski racers and the importance of restoring quadriceps strength following ACLR in elite ski racers. Additionally, as these deficits were found in actively competing ski racers, it also provides a rationale for long term monitoring of quadriceps strength post ACLR in this population.

As ski racers regularly perform resistance training exercises to prepare for competition, the large bilateral asymmetry in quadriceps maximal strength may also be related to the
exceptionally high torque values observed in the uninjured limbs (Extensor MVC: Males = 417.8± 17.3 Nm, Females = 291.7±57.7 Nm), which are considerably higher than the torques observed for the uninjured limb in physically active ACLR subjects (19) and in untrained ACLR subjects (35). We did not include information on the type of resistance exercise performed by the subjects in our study. However, the findings of large inter-limb strength discrepancies may warrant further investigation into the use of specific resistance training strategies, such as the long term utilization of unilateral lower body movements, to address strength deficits in the ACLR limb.

Although the restoration of quadriceps strength is associated with successful return to activity in ACLR non-skiers (6, 26), this has not been demonstrated in ACLR elite ski racers. In the present cohort of ACLR skiers, one subject sustained an injury to the contralateral medial collateral ligament during the study period. Notably, this athlete had the second highest asymmetry in quadriceps maximal strength (36.9%). A second ACLR athlete retired due to limitations from the knee injury one World Cup season following the study period. This subject had the largest asymmetry in quadriceps maximal strength (54.2%). While these examples are case related and hence do not provide strict scientific support for a causality between deficits in quadriceps maximal strength and successful return to skiing following ACLR, it suggests the potential relevance for future investigation into the relationship between quadriceps strength deficits and successful return to pre-injury performance levels following ACLR.

In addition to the bilateral deficits observed in quadriceps maximal strength, significant bilateral deficits in quadriceps explosive strength (RTD_{150} and RTD_{200}) were also found in the injured limb of ACLR ski racers compared to their uninjured limb and compared to the limb average of the uninjured group. As non-contact ACL injuries in ski racing occur in time frames
less than 200 ms (8) and the re-loading of the contralateral limb during bidirectional turning in the technical events (slalom and giant slalom) occurs in approximately 150 ms (17), explosive strength may be important for elite ski racers. Furthermore, as explosive strength and maximal strength are distinct abilities, and trained with different forms of resistance training exercise (2, 4, 37), the identification of specific quadriceps strength deficits may be important for the ACLR elite alpine ski racer to attain pre-injury performance levels.

While no bilateral limb differences were observed for the early phase of quadriceps torque development (RTD$_{50}$ and RTD$_{100}$), the ACLR limb still demonstrated lower values than the uninjured group. The early phase of torque development in an isometric contraction is related to intrinsic muscle properties, such as fiber type composition and myosin heavy chain content, as well as to the pattern of initial motor neuron firing frequency (4). Due to the short time frame for non-contact ACL injury in field sports (22), assessing the early phase of isometric torque development has also been proposed as a relevant measure of dynamic knee joint stabilization potential (38). As with the lack of evidence between increased bilateral limb asymmetry in quadriceps maximal strength and return to skiing performance in ACLR skiers, there is currently no evidence relating deficits in early phase explosive strength (initial RTD) and ACL re-injury in elite alpine ski racers.

The injured limb of the ACLR ski racers also displayed significantly lower hamstring maximal strength compared to the uninjured group, and bilateral limb deficits in hamstring maximal strength and late phase explosive strength compared to the uninjured limb. While there is an isolated report of a full restoration in hamstring strength after semitendinosus autograft reconstruction (20), deficits in hamstring strength have been observed in ACLR subjects with semitendinosus autografts compared to uninjured controls (15), and compared to pre-operative
levels two-years following ACLR (14). Additionally, semitendinosus autograft reconstruction has been shown to elongate the knee flexor electromechanical delay, which may impair knee stabilization in injury situations (29). We were unable to recruit sufficient ACLR skiers to control for the graft type, which is a limitation of the present investigation. However, five of the eight ACLR ski racers obtained a semitendinosus autograft, which may partially explain the deficits in hamstring muscle strength observed in this group of ACLR ski racers.

Nevertheless, the hamstring muscles act as an ACL agonist to resist anterior translation of the tibia relative to the femur (7, 23), which is relevant for ACL injury prevention in ski racing due to the existence of a unique injury mechanism involving anterior shear loads imposed upon the tibia (8, 27). Additionally, the hamstring and quadriceps muscles act in a coordinative fashion for knee stabilization and ACL protection (3, 7, 23, 30, 31, 39). A relationship between deficits in hamstring strength and ACL injury has been proposed in high level skiers (18). However, no study has been conducted to evaluate the effects of ACLR or graft-type on hamstring strength deficits, and the corresponding risk for ACL re-injury in elite alpine racers. Given the high risk for ACL injury and an injury mechanism involving large anterior tibial shear loads, further research into this possibility is warranted.

An unexpected finding of this study was the greater relative RTD in the early phase of rising muscle force (0-50 ms) for the ACLR limb compared to the uninjured group. Relative RTD, which involves normalization to the MVC, is often used as a qualitative measure of explosive strength and for differentiation between potential mechanisms underlying adaptations in explosive strength following resistance exercise (2, 13). However, it is important to consider absolute strength values in the interpretation of the relative RTD ratio. In the present study, the ACLR limb had significantly lower maximal isometric knee flexor torque and no difference in
RTD$_{50}$ compared to the uninjured group. As the lower MVC values reduced the magnitude of the denominator in the calculation of the relative RTD$_{50}$ ratio, this result should not be interpreted as a difference in the initial phase hamstring explosive strength ability for the ACLR skiers.

4.4.2 Comparison of Limb Strength for Uninjured Male Skiers and Uninjured Female Skiers

Non-contact ACL injury in elite alpine ski racing is unique in that no clear sex-related difference in ACL injury rates have been identified (9, 11, 27). This finding has been attributed to the preclusion of sex-related risk factors due to the large external forces experienced in ski racing (9, 11). Because of the large quadriceps loading and evidence of pronounced hamstring/quadriceps co-contraction in skiing (10, 17), specific hamstring and quadriceps strength requirements may exist for successful performance at the elite level for male and female ski racers (24). However, there are limited scientific investigations focusing on sex-differences in thigh muscle strength in elite alpine ski racers. While male ski racers were reported to have greater absolute strength values than females assessed with isokinetic dynamometry (24), the use of absolute strength values may not be appropriate when comparing male and female subjects. Instead body mass normalization is recommended (15). In the present investigation, no sex-differences in hamstring and quadriceps strength were found when corrected for body mass, which has been found elsewhere (15).

However, the uninjured female skiers had a greater relative RTD over the initial phase of the isometric MVC (relative RTD$_{50}$ and relative RTD$_{100}$) compared to the male skiers. As discussed above, the relative RTD ratio must be interpreted alongside absolute strength values because of the possibility of a reduced denominator resulting from deficits in the peak isometric hamstring torque obtained during the MVC. However, no bilateral limb deficits were observed.
in hamstring maximal strength (MVC) for the female ski racers, or in comparison to the uninjured males. Therefore, the greater relative RTD$_{50}$ and relative RTD$_{100}$ ratio may provide evidence of a qualitative difference in explosive strength for the male and female skiers included in the present investigation. As we did not include other variables in our analysis that may affect relative RTD, such as physiological factors or type of resistance training exercise employed by the subjects (2, 4), we are unable to explain this finding.

Unexpectedly, while no bilateral limb differences in thigh muscle strength were found for the female skiers, the uninjured male ski racers displayed reduced hamstring maximal strength (MVC) and late phase explosive strength (RTD$_{150}$) in the left compared with values found in the right leg. While the mean deficit in hamstring maximal strength was only 5.3%, this asymmetry was consistently biased in the male ski racers reflecting systematic right-limb dominance. Due to the importance of the hamstring muscle in resisting anterior shear forces that load the ACL (7, 23), and evidence of substantial hamstring/quadriceps co-contraction during ski turns (17), the presence of bilateral limb deficits in hamstring strength may be of concern for elite ski racers. Additionally, while a clear association between bilateral hamstring strength deficits and ACL injury has not been made, hamstring muscle strength has been put forth in the literature as a relevant metric for ACL injury prevention in ski racers (18, 24, 34). Taken alongside the limited scientific research in support of an association between hamstring muscle strength and ACL injury, this finding warrants future study into the relationship between hamstring muscle strength deficits and ACL injury. It also suggests that regular hamstring muscle strength assessments be included in the evaluation of uninjured elite ski racers alongside other established risk factors for ACL injury in ski racing, such as the lower body reactive strength index and core strength (28).
4.4.3 H/Q Ratios in Uninjured Male Skiers, Uninjured Female Skiers and ACLR Skiers

The H/Q Ratio has been purported as an important marker of dynamic knee joint stabilization potential for ACL injury prevention in alpine ski racers (24, 34) and in other populations (1, 16, 38). However, no direct scientific evidence exists linking a diminished H/Q Ratio with ACL injury rates in elite ski racers. Moreover, in a preliminary study, it was concluded that the H/Q Ratio was not predictive of ACL injury prevention in high-level skiers (18). Nevertheless, the H/Q Ratio is often reported in this population (24, 34). A study by Neumayr et al. (24) found H/Q Ratios for elite ski racers ranging from 0.57 to 0.60 for isokinetic dynamometry, which limits a comparison to the present investigation due to the use of isometric dynamometry. In our study, explosive strength and maximal strength H/Q Ratios ranged between 0.42 to 0.55 for the uninjured female skiers and 0.45 to 0.47 for the uninjured male skiers.

Interestingly, the uninjured female ski racers demonstrated a higher H/Q Ratio compared to the male ski racers (0.55 vs. 0.46, respectively). In order to interpret the H/Q Ratio, it is important to consider absolute strength values due to the possibility of an artificially inflated ratio resulting from deficits in quadriceps strength (i.e. reduced denominator) (40). In our post-hoc analysis, we evaluated the individual H/Q Ratios alongside bilateral limb asymmetry in quadriceps maximal strength (MVC). Of all the females presenting with the highest H/Q Ratios, only one had a bilateral asymmetry in quadriceps strength greater than 10% (individual asymmetry = 11%), and the mean bilateral limb asymmetry in quadriceps maximal strength for the remaining uninjured female skiers was 0.6%. Furthermore, the uninjured females did not present with bilateral limb deficits in quadriceps muscle explosive strength. Thus, we feel it is
reasonable to conclude that there was no evidence of a reduction in quadriceps strength that may have contributed to an elevated H/Q Ratio.

Together with these observations, the elevated H/Q Ratio found in the uninjured female skiers may indicate better hamstring/quadriceps muscle strength balance over the initial phase of torque rise in the isometric MVC. While there are very limited reports using the explosive strength H/Q Ratio, our findings differ from those found in other female athlete populations (38). Again, the precise reason for this is unknown. However, as hamstring strength is often identified by experts as an important factor in non-contact ACL injury prevention for ski racers (18, 24, 34), it is possible that an increased emphasis on hamstring strength development in ski racers contributed to the differences between the present investigation and the study performed by Zebis et al. (38) in high level female soccer players. As we did not include information on the resistance training program employed by the subjects, we are unable to explain this finding.

To our knowledge, there are no investigations that were aimed at evaluating the H/Q Ratio in actively competing ACLR elite alpine ski racers, and no associations have been made between the H/Q Ratio and the risk for ACL re-injury. Hiemstra et al. (16) found regional deficits in knee flexor and extensor strength in ACLR subjects that led to an increased H/Q Ratio at small angles of knee flexion. In the present study, the affected limb of the ACLR skiers demonstrated an elevated H/Q Ratio compared to the uninjured skiers. However, due to the persistence of chronic quadriceps weakness in ACLR subjects (3, 14, 15, 26, 33, 35), this result was interpreted alongside individual H/Q Ratios and absolute quadriceps strength values. In this perspective, three of the ACLR ski racers with the highest H/Q Ratios (> 0.6) also had the largest deficits in quadriceps maximal strength (Asymmetry > 25%). This finding is consistent with
reports of others where an elevated H/Q Ratio in ACLR subjects was attributed to deficits in quadriceps strength (40).

An elevated H/Q Ratio resulting from diminished quadriceps strength may indicate better hamstring/quadriceps strength balance. However, as discussed previously, quadriceps strength deficits may be disadvantageous for elite alpine ski racers due to the bidirectional turns and large quadriceps muscle loading. Furthermore, although representing case examples, it should be reiterated that the three ACLR ski racers presenting with the highest H/Q Ratios on the injured limb had the greatest bilateral limb deficits in quadriceps strength, and also included two individuals who were unable to make a full return to skiing. On the basis of the present results, we suggest that the H/Q Ratio be interpreted with caution in ACLR ski racers and alongside absolute hamstring/quadriceps strength values to obtain a comprehensive assessment of hamstring and quadriceps muscle strength.

4.5 Conclusion

In conclusion, we found substantial deficits in quadriceps maximal strength and explosive strength in the affected limb of actively competing ACLR elite alpine ski racers compared to the contralateral limb and compared to uninjured ski racers. Deficits in hamstring maximal strength and late phase explosive strength were also observed in the ACLR limb. Unexpectedly, uninjured male ski racers displayed bilateral limb deficits in hamstring maximal strength and late phase explosive strength. An increased relative RTD over the early phase of rise in isometric torque was found for the uninjured female skiers compared to uninjured male ski racers, whereas no sex-differences were observed in any of the other hamstring or quadriceps explosive strength and maximal strength variables. However, there were limitations to the present investigation that included a relatively small sample size for the uninjured female group and ACLR group.
Additionally, due to limitations in recruiting subjects, we were unable to control for the graft type used in the ACL reconstruction.

Despite these limitations, we conclude that quadriceps and hamstring maximal strength and explosive strength are important determinants for evaluating ACLR ski racers and uninjured ski racers, and that these outcome measures should be included as a part of a comprehensive strength assessment in elite alpine ski racers. These evaluations should be undertaken over long post-surgical periods in ACLR skiers, and should be continued even after full return to ski racing. As explosive strength and maximal strength are developed by specific resistance training methods, identifying such deficits may also assist in the design of rehabilitation and training programs for elite ski racers returning to skiing following ACL loss. Finally, while representing case examples, failure to regain quadriceps strength following ACLR was associated with failure to make a full return to skiing. However, future studies must be undertaken to confirm the possibility of a relationship between quadriceps strength deficits and return to skiing outcome. Additionally, future studies should also control for the graft-types used in ACLR reconstruction, and further examine the relationship between graft-type, hamstring strength loss and outcome following ACLR. The relationship between hamstring and quadriceps strength deficits, and return to skiing outcome, requires careful and systematic evaluation in ACLR elite alpine ski racers to identify ski-specific strength thresholds that should be met following injury. It is hoped that in future longitudinal studies, these issues will be addressed, and assessments between hamstring and quadriceps strength and ACL injury/re-injury in elite alpine ski racers will be made as a part of a multi-faceted approach to injury prevention, including other risk factors for non-contact ACL injury in ski racing.
4.6 References


4.7 Bridge to Chapter 5

In the first two studies (Chapter 3 and Chapter 4), we demonstrated that ACLR elite alpine ski racers have persistent neuromuscular deficits compared to non-injured alpine racers, and that these deficits are present despite return to sport. In the third study (Chapter 5), an 80 second repeated squat jump test was administered in ACLR elite alpine ski racers who were on average three years post ACL surgery. The acute effects of fatigue on functional asymmetries, jump performance, and quadriceps vs. hamstring muscle activity were compared in elite alpine ski racers with/without ACLR.
Chapter 5: Asymmetry and Thigh Muscle Co-Activity in Fatigued ACL Reconstructed Elite Skiers

5.1 Introduction

Anterior cruciate ligament (ACL) injury and re-injury occur frequently in elite alpine ski racers (9, 33) presumably when injury risk stemming from acute fatigue is increased (8). There are several high-energy injury mechanisms associated with rapid rotational and shear loading of the knee (7). Despite having returned to sport, ACL reconstructed (ACLR) ski racers may continue to display elevated bilateral functional asymmetry, and hamstring/quadriceps strength deficits in the affected (ACLR) limb (27, 28). To address these concerns, a return to sport neuromuscular assessment was proposed to evaluate a ski-specific envelope of function and ensure that ACLR skiers are safely fitted to return to racing (26).

Dynamic stabilization of the knee using active muscular restraints is thought to be important for ACL injury prevention (22, 23, 39). Of interest is the preparatory quadriceps vs. hamstring muscle activity that helps to stiffen the knee joint prior to dynamic loading events, such as landing from a jump (6, 14, 35, 39, 41), which is a common mechanism of ACL injury in ski racing (7). Preparatory muscle activity is crucial for injury prevention due to the short time course (<100 ms) of ACL injury (29), which limits the potential for feedback loops to protect the knee (16, 24, 38). Athletes exhibiting increased quadriceps muscle dominance in the pre-touchdown phase of landing, or change in direction, may be at increased risk of ACL injury (39). Conversely, hamstring muscle co-contraction is important for reducing anterior shear forces in the knee (4, 10, 37).

Consistent with the findings in elite alpine skiing, fatigued athletes are at increased risk for injury (20). Fatigued athletes may display lower limb landing kinematics that is associated with increased ACL loading (30) and diminished hamstring activity (5). For example, female
handball players had reduced preparatory hamstring activity prior to landing after a sport-specific fatigue protocol (41). Similarly, fatigued male elite handball players demonstrated reductions in vertical jump height, hamstring/quadriceps rapid force production, hamstring/quadriceps maximum voluntary contraction force, and quadriceps vs. hamstring maximum EMG amplitudes (35).

The effects of acute fatigue on functional asymmetry in ACLR athletes, including ski racers, has received little scientific attention. Yet, there appears to be a differential response in functional asymmetry indices between fatigued ACLR and uninjured subjects (36). In previous studies, ski racers without ACLR were characterized by high levels of functional inter-limb symmetry that is believed to be important for performance given the bidirectional high force turns in alpine ski racing (7, 8, 27). Thus, the relationship between fatigue and functional asymmetry in elite alpine ski racers with/without ACLR may prove important for sport performance and injury prevention alike.

After ACLR, neuromuscular testing is recommended to ensure injury related deficits are satisfactorily restored prior to return to sport (23, 25, 26, 27, 31). Neuromuscular testing may include an assessment of quadriceps vs. hamstring muscle activity and functional asymmetry in propulsive and decelerating actions like those found in the vertical jump (24, 31). As fatigued elite ski racers are at higher risk for injury, it seems important that neuromuscular assessments are not only ski-specific but also are performed with rested and acutely fatigued athletes (25, 31). This type of neuromuscular testing may assist in developing individualized exercise programs for ACL injury prevention and rehabilitation.

The purpose of this study was to assess the effects of acute neuromuscular fatigue on vertical jump performance, bilateral functional asymmetry, and quadriceps vs. hamstring muscle
activity in elite alpine ski racers with/without ACLR. Fatigue was induced using an 80s repeated squat jump protocol (jump-test). We hypothesized that vertical jump performance decreases with fatigue for both groups, and that functional asymmetry over the jump-test for the ACLR group increases compared to that observed in the uninjured Control group athletes. We also hypothesized diminished hamstring activity in the pre-landing and landing-phases with fatigue, and a reduced quadriceps activity in the ACLR limb compared to that measured in the contralateral limb.

5.2 Methods

5.2.1 Subjects

Based on previous research and a power analysis (27), it was estimated that 18 skiers were required to achieve a statistical power of 80% for the primary outcome variables. Thus, 22 elite skiers competing at the International level were recruited from Canada’s national alpine skiing and skier cross programs including 11 actively competing ACLR skiers [Females (n=5): Age = 23.6±1.8 years, Mass = 61.0±5.3 kg; Males (n=6): Age = 26.5±5.8 years, Mass = 84.4±9.0 kg] and 11 matched controls with no history of ACL injury [Females (n=5): Age = 21.8±3.2 years, Mass = 63.7±4.6 kg; Males (n=6): Age = 23.3±3.3 years, Mass = 84.7±5.1 kg]. Due to the small sample size, no sex-specific comparisons were made. The mean post-operative period for the ACLR group was 3.0±2.8 years. Controls were included if they were 18 years of age or older and active competitors at the International level defined as participation in the Federation International de Ski (FIS) World Cup circuit. Subjects were excluded if they had a lower body injury or lumbar spine injury that might impair vertical jump performance.

For the ACLR group, only actively competing athletes at the FIS World Cup level with full medical clearance to compete, aged 18 years or older, more than 12-months post-surgery and
with a history of primary ACL injury were included in the study. Subjects were excluded if they had a lower body injury or lumbar spine injury that impaired vertical jump performance. Seven subjects had a torn left ACL and four had a torn right ACL. Seven subjects received a semitendinosus autograft, one subject received a bone-patellar tendon-bone autograft, and three subjects received a cadaver allograft. The associated injury pathology was consistent with the literature and included medial/lateral meniscal tears, subchondral bone bruising, and first/second degree sprains of the collateral ligaments (18, 32). The Conjoint Research Ethics Board at the University of Calgary approved the experimental protocol and all subjects gave written informed consent to participate in this study.

5.2.2 Subject Preparation

The study was undertaken during routine annual fitness testing in the pre-competition period and all subjects were familiarized with the testing protocol. Subjects performed a standardized 10-minute warm up on a cycle ergometer followed by a dynamic stretching routine for the lower limb musculature. The same researcher identified the vastus medialis, vastus lateralis, biceps femoris and semitendinosus muscles. The skin over these muscles was carefully shaved and cleaned using an isopropyl alcohol solution. Bipolar surface electrodes with a two cm inter-electrode distance (Norotrode, Ag/AgCl electrodes) were applied to the skin in the middle part of the muscle bellies on both limbs according to the recommendations from SENIAM 8 (21). Skin impedance was assessed and a value of 7 kilo-Ohms or greater resulted in re-preparation of the skin and application of new electrodes. Following electrode placement, the EMG pre-amplifiers were taped to the skin, and a wide piece of compliant medical bandage was carefully secured over the electrodes and amplifiers to reduce movement artefacts.
5.2.3 Test Procedures

Subjects were placed in a custom built isometric dynamometer (MARK IV, University of Alberta, Alberta, Canada) with the knee angle set to 70° of knee flexion. Subjects performed three maximal voluntary contractions (MVC) of isometric knee extension and flexion with 60 seconds rest between tests. Following the isometric MVCs, subjects were given a six-minute rest interval before starting the jump-test protocol. Prior to commencing the jump-test, subjects stood on two adjacent and levelled force plates with each leg placed on a separate force plate (25, 27) and descended to the squat jump start position set at 90° of knee flexion. The squat jump start position was marked using an adjustable rope that contacted the hips directly behind the subjects. The squat jump depth was carefully monitored and controlled throughout the jump-test by a certified strength and conditioning expert who stood directly beside the testing station. Additionally, a piece of tape was symmetrically placed on each of the two force plates measuring the natural hip-width stance of the subjects, and foot placement on the force plates was monitored and controlled throughout the entire jump-test. Subjects were instructed to perform each jump maximally and were provided with loud verbal feedback throughout the test to ensure a maximal effort was given on each single jump.

Subjects descended to the squat jump start position with the hands placed firmly on the hips and held this position for four seconds. A metronome timer indicated the start of the test and was set to repeat every four seconds. Following each maximal jump, subjects landed back in the squat jump start position and maintained this position until they were cued for the next jump by a strong verbal command from the tester. Subjects performed 20 maximal jumps over the 80s jump-test protocol. The operational definition of fatigue used for this study was an exercise-induced decrease in lower limb muscle power, which was evaluated using vertical squat jump
testing (17). The test protocol was arrived at through pilot testing with elite skiers in which different combinations of jump repetitions and time intervals were tested so that the technical parameters of the protocol could be controlled and the intensity was deemed comparable to that of a typical training run in ski racing.

5.2.4 Data Acquisition and Signal Processing

The eight surface EMG signals were recorded using a telemetric EMG receiver (Telemyo DDTS Desktop Receiver, Noraxon, Scottsdale, Arizona, USA). EMG signals were pre-amplified with an overall gain of 500, filtered with a first order high pass filter set at 10 Hz and low pass filtered with a cut-off at 500 Hz. Each EMG channel had a common mode rejection ratio greater than 100 dB. The vertical ground reaction force (Fz) from the right and left limbs was measured using a dual force plate system (Accupower Force Platform, AMTI, Wattertown, Massachusetts, USA), and were recorded synchronously with the EMG signals (MyoReserch Version 3.8, Noraxon, Scottsdale, Arizona, USA) at a sampling frequency of 1500 Hz. The EMG force data from all testing were collected and stored on a personal desktop computer for subsequent off-line analysis.

5.2.5 Data Analysis

Following data collection, the data were exported for further analysis using custom-built computer scripts (Matlab Version R2015a, Mathworks, Nattick, Massachusetts, USA). Prior to data analysis, the alignment of the force and EMG signals was verified. The raw Fz voltage signals for the right and left limbs were then converted to Newtons using a calibration curve and analyzed according to procedures described elsewhere (27, 35). The takeoff velocity of the body centre of mass (BCM) was obtained using the impulse-momentum relationship of the vertical ground reaction force from the start of the (stationary) jump (BCM velocity equals zero) to the
instant of takeoff. Jump performance was quantified using takeoff velocity (TOV) with vertical jumping height of Body Center of Mass (H_{BCM}) calculated as \( H_{BCM} = \frac{TOV^2}{2g} \) with \( g = 9.81 \text{ m·s}^{-2} \).

Functional inter-limb asymmetry was calculated using the vertical ground reaction force impulse for both legs independently over three defined time intervals (25, 27): early-phase, late-phase, and landing-phase interval. The early-phase asymmetry was calculated from the initiation of the jump (time = 0 s) to the midpoint of the jump (time = \( \frac{1}{2} \) of the total jump time). The late-phase asymmetry was calculated from the midpoint of the jump to the instant of takeoff (27). The landing-phase asymmetry was calculated between the time points of touchdown and re-stabilization (return of Fz to stable body mass level). To identify the time point of re-stabilization the standard deviation of Fz obtained from the start of the trial during quiet standing (quiet period) representing the subject’s system weight was calculated. Re-stabilization was defined when the vertical ground reaction force variation reached a level that was twice the standard deviation observed in the quiet period prior to jumping. This time point captured the entire landing phase without extending into the quiet period for the subsequent jump. The kinetic impulse asymmetry index (AI) was calculated using the following formulae (27):

\[
\text{Asymmetry Index Control} \\
AI = \frac{(\text{Left Limb Impulse} - \text{Right Limb Impulse})}{(\text{Maximum of Left and Right Impulse})} \times 100
\]

\[
\text{Asymmetry Index ACLR} \\
AI = \frac{(\text{Contralateral Limb Impulse} - \text{Affected Limb Impulse})}{(\text{Maximum of Contralateral and Affected Limb Impulse})} \times 100
\]

The EMG signals were high pass filtered (cut-off frequency = 10 Hz) using a Butterworth 4th order zero-lag filter and smoothed using a point-by-point moving 50 ms symmetric root-mean-square (EMG rms) filter (1). The EMG rms for each muscle during the jump-test was
normalized to the maximal EMG rms amplitude obtained from the respective muscle during the isometric MVCs. The maximal EMG rms amplitude was obtained for the ascent phase and landing phase of each jump. Additionally, the EMG rms amplitude was obtained for a 50 ms window around the instant of takeoff (toe-off) and the 25 ms interval preceding touch down (pre-landing) (6, 39, 41). The time windows for the EMG amplitude analysis were chosen based on the short time course of the ascent and landing phases in the squat jump, and the inclusion of a discrete time point at takeoff. The timeframe for the pre-landing phase was chosen due to the reliability and relevance of short duration pre-landing activation for detecting ACL injury risk in other athlete populations (6, 39).

5.2.6 Outcome Measures

To evaluate the acute effects of fatigue on functional asymmetry, the asymmetry indices were averaged over sets of five jumps (Set 1 = Jumps 1-5; Set 2 = Jumps 6-10; Set 3 = Jumps 11-15; Set 4 = Jumps 16-20). The fatigued state (Set 4) could be compared to the rested state (Set 1). The effects of fatigue on jump performance were also compared by evaluating the $H_{BCM}$ averaged over the final five jumps (Set 4) with the averaged $H_{BCM}$ obtained for the first five jumps.

Overall quadriceps muscle activity was quantified by taking an average of the vastus lateralis and vastus medialis EMG rms amplitudes, and gross overall hamstring muscle activity was obtained by taking an average of the biceps femoris and semitendinosus EMG rms amplitudes. To evaluate quadriceps vs. hamstring muscle activation dominance, the magnitude of differential quadriceps-hamstring muscle activity was measured by calculating the normalized quadriceps muscle activity minus the normalized hamstring muscle activity (Quad-Ham), as described in detail elsewhere (39, 40). Additionally, the magnitude of valgus related differential
thigh muscle activity was calculated as the difference in vastus lateralis-semitendinosus (VL-ST) EMG activity by taking the normalized vastus lateralis muscle activity minus the normalized semitendinosus activity (39). Muscle activity outcomes measures in the fatigued state (Set 4) were compared to the baseline rested state measurements obtained from Set 1.

5.2.7 Statistical Analysis

Due to the correlated nature of the outcome measures, linear mixed effect models (R, Version 0.98.1102, lme4 package) were fit separately for the jump performance outcome and the asymmetry indices with fixed effects for the factors group, jump set (Factor Levels: Set 1, Set 4) and jump phase (Factor Levels: Early-Phase, Late-Phase, Landing-Phase), and random intercepts for the athlete. Linear mixed effect models were also fit for the quadriceps muscle activity, hamstring muscle activity, VL-ST difference and the Quad-Ham difference for the jump phases of interest with fixed effects for the factors jump set and limb status (Factor Levels: Affected Limb, Contralateral Limb, Control Limb). For the muscle activity models, random intercepts were set for the athlete and the limb within an athlete. Normality of the model errors was assessed and a sensitivity analysis was performed to evaluate the influence of outliers. Post-hoc analysis for assessing the effects of jump set on muscle activity was performed using a contrast to compare the outcomes for Set 4 against the baseline value (Set 1). The Control Limb (left and right limbs of the controls) was compared to the Contralateral Limb and Affected Limb of the ACLR subjects. The Contralateral Limb and Affected Limb of the ACLR subjects were also compared. All post-hoc comparisons were adjusted using the single-step method in the multcomp package (R, Version 0.98.1102). Statistical significance was set at $\alpha=0.05$ using a two-tailed test design.
5.3 Results

5.3.1 Jumping Performance and Functional Asymmetry

Vertical jump performance declined across the jump-test for both groups [$\chi^2(130.6)$, df = 3, P<0.0001], and there was no difference between groups [P=0.08]. When controlling for the group effects, the mean (± SE) decrease in vertical jump height from Set 1 to Set 4 was 5.9 (0.3) cm [P<0.0001]. Further, there was no change in functional asymmetry indices with acute fatigue [P=0.76]. However, an interaction was found between the jump phase and subject grouping [$\chi^2(41.0)$, df = 2, P<0.0001]. No difference in the asymmetry indices over the three jump phases was found for the control group (Figure 5.1, right panel). However, ACLR athletes displayed a systematic change in asymmetry in the late-phase of the jump takeoff which was reflected by reduced impulse in the Affected (ACLR) vs. the Contralateral Limb. [P<0.0001] (Figure 5.1, left panel).

5.3.2 Muscle Activity in the Squat Jump Ascent Phase

No limb differences were found for hamstring muscle activity in the ascent phase [P=0.08] or in the final takeoff phase [P=0.65]. However, there were main effects of fatigue on maximal hamstring muscle activity for the ascent and final takeoff phases [main effect of fatigue for ascent phase: $\chi^2(23.1)$, df = 3, P<0.0001; main effect of fatigue for final takeoff phase: $\chi^2(19.3)$, df = 3, P<0.001]. Hamstring muscle activity decreased across all three limb conditions with fatigue (Table 5.1). No differences were found between limbs for the maximal quadriceps muscle activity levels in the ascent phase [P=0.24] but there was a main effect of fatigue [\[\chi^2(11.3)$, df = 3, P<0.05] (Table 5.2). During the final takeoff phase, there was a main effect of limb status on quadriceps activity with lower quadriceps activity in the Affected Limb compared to the Contralateral Limb [$\chi^2(7.6)$, df = 2, P<0.05] (Table 5.2). Additionally, quadriceps muscle
activity at takeoff declined with fatigue for all three limb conditions $[\chi^2(18.3), \text{df} = 3, P<0.001]$ (Table 5.2).

5.3.3 Muscle Activity in the Squat Jump Landing Phase

No differences were found between limbs for maximal hamstring muscle activity in the landing-phase [$P=0.12$]. However, there was a main effect of fatigue on hamstring activity $[\chi^2(29.6), \text{df} = 3, P<0.0001]$. Maximal hamstring muscle activity decreased with fatigue across all limb statuses in the final jump set (Table 5.3). The preparatory hamstring activity was greater in the Affected Limb of the ACLR subjects compared to the Control Limb in the pre-landing phase [$P<0.01$] (Table 5.3). Also, there was a main effect of fatigue on preparatory hamstring activity with a decrease observed for all limb conditions in the final jump set $[\chi^2(84.0), \text{df} = 3, P<0.0001]$ (Table 5.3). For the landing-phase, there were no limb differences in the maximal quadriceps activity [$P=0.54$], but there was a main effect of fatigue on quadriceps activity $[\chi^2(36.7), \text{df} = 3, P<0.0001]$. Landing-phase quadriceps activity increased significantly in the final set of the jump-test for all limb conditions (Table 5.4). Additionally, the preparatory quadriceps activity was lower in the Affected Limb compared to the Contralateral Limb of the ACLR group [$P<0.01$]. In an opposite direction to the hamstring activity, there was a main effect of fatigue on preparatory quadriceps activity with an increase observed for all limb conditions in the final set of the jump-test $[\chi^2(28.6), \text{df} = 3, P<0.0001]$ (Table 5.4).

5.3.4 Preparatory Quadriceps-Hamstring Co-Activity

There was a main effect for limb status on the differential preparatory Quad-Ham muscle activity (quadriceps EMG minus hamstring EMG) in the pre-landing phase $[\chi^2(12.1, \text{df} = 2, P<0.01]$. Quad-Ham was lower in the Affected Limb compared to the other two limb conditions, reflecting more hamstring dominance and/or less quadriceps dominance in the ACLR limb.
However, no limb differences were found in VL-ST co-activity difference (Figure 5.2B). Finally, differential Quad-Ham muscle activity $[\chi^2(73.8, \text{df} = 3, P<0.0001)]$ and differential VL-ST activity $[\chi^2(76.1, \text{df} = 3, P<0.0001)]$ were elevated in the final set of the jump-test irrespectively of limb status, reflecting increased preparatory quadriceps activity and decreased preparatory hamstring activity in response to fatigue (Figure 5.2A, Figure 5.2C).

**Figure 5.1:** Mean functional asymmetry indices obtained in ACL reconstructed (ACLR) and non-injured (Control) athletes. An interaction between jump phase and injury status (group allocation) was observed $[\chi^2(41.0, \text{df} = 2, P<0.0001)]$. ACLR demonstrated systematically skewed asymmetry in the late takeoff phase of the squat jump (less vertical jumping impulse generated by the affected limb) compared to the early phase $[P<0.0001]$ and the landing phase $[P<0.0001]$. Data is shown as the mean asymmetry index ± 95% confidence interval. **** denotes significant difference from early-phase and late-phase asymmetry $[P<0.0001]$. 

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Table 5.1: Hamstring muscle activation (%MVC) across limbs (Affected: ACLR limbs, Contralateral: uninjured limb, Control: non-injured controls) and jump sets for the ascent phase and at takeoff. Muscle activity is expressed as the EMG rms amplitude normalized to an isometric maximum voluntary contraction. ### significantly different from Set 1 (P<0.001).

<table>
<thead>
<tr>
<th>Limb Status</th>
<th>Jump Set</th>
<th>Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
<th>Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
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<tr>
<td></td>
<td></td>
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<td>Upper</td>
<td>Lower</td>
<td>Upper</td>
<td>Lower</td>
<td>Upper</td>
</tr>
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<td>0.274</td>
<td>0.232</td>
<td>0.273</td>
</tr>
<tr>
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<td>0.283</td>
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<tr>
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<td>0.271</td>
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<td>0.268</td>
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<tr>
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<td>0.515</td>
<td>0.516</td>
<td>0.330</td>
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Table 5.2: Quadriceps muscle activation (%MVC) across limbs (Affected: ACLR limbs, Contralateral: uninjured limb, Control: non-injured controls) and jump sets for the ascent phase and at takeoff. Muscle activity is expressed as the EMG rms amplitude normalized to an isometric maximum voluntary contraction. ## significantly different from Set 1 (P<0.01). * Denotes significantly different from the Contralateral Limb (P<0.05).

<table>
<thead>
<tr>
<th>Limb Status</th>
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<th>QUADRICEPS ACTIVITY AT TAKEOFF</th>
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<tr>
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<td>Set 4</td>
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</tr>
<tr>
<td>Contralateral</td>
<td>Set 1</td>
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<td>0.114</td>
</tr>
<tr>
<td></td>
<td>Set 2</td>
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<td>0.114</td>
</tr>
<tr>
<td></td>
<td>Set 3</td>
<td>1.285</td>
<td>0.114</td>
</tr>
<tr>
<td></td>
<td>Set 4</td>
<td>1.248</td>
<td>0.114</td>
</tr>
<tr>
<td>Affected</td>
<td>Set 1</td>
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<td>0.114</td>
</tr>
<tr>
<td></td>
<td>Set 2</td>
<td>1.156</td>
<td>0.114</td>
</tr>
<tr>
<td></td>
<td>Set 3</td>
<td>1.135</td>
<td>0.114</td>
</tr>
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<td></td>
<td>Set 4</td>
<td>1.098</td>
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<td>Limb Status</td>
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<td>HAMSTRING ACTIVITY PRE-LANDING ACTIVITY</td>
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<td>----------</td>
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<tr>
<td></td>
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<td>Mean</td>
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<tr>
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<td>Set 1</td>
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<td>Set 4</td>
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<td></td>
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<tr>
<td></td>
<td>Set 4</td>
<td>0.295</td>
<td>0.030</td>
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**Table 5.3:** Hamstring muscle activation (%MVC) in the landing-phase and pre-landing activity levels across limb levels (Affected: ACLR limbs, Contralateral: uninjured limb, Control: non-injured controls). Muscle activity is expressed as the EMG rms amplitude normalized to an isometric maximum voluntary contraction. **###** Denotes significantly different from Set 1 (p<0.001). **††** Significantly different from Control Limb (p<0.01). From Set 1 (p>0.001).
Table 5.4: Quadriceps muscle activation (%MVC) in the landing-phase and quadriceps pre-landing activity levels across limb levels (Affected: ACLR limbs, Contralateral: uninjured limb, Control: non-injured controls) and jump sets. Muscle activity is expressed as the EMG rms amplitude normalized to an isometric maximum voluntary contraction. \* Denotes significantly different from Set 1 (P<0.001). ** Denotes significantly different from Contralateral Limb (P<0.01).

<table>
<thead>
<tr>
<th>Limb Status</th>
<th>Jump Set</th>
<th>QUADRICEPS ACTIVITY LANDING PHASE</th>
<th>QUADRICEPS PRE-LANDING ACTIVITY</th>
</tr>
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<td>Set 4</td>
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<td>Set 4</td>
<td>1.068</td>
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Figure 5.2: A comparison of the vastus-lateralis-semitendinosus difference (top panels) and the quadriceps-hamstring muscle activity difference (bottom panels) for the pre-landing phase across jump sets and limb status. A main effect was found for fatigue $\chi^2(73.8), \text{df} = 3, P<0.001$ and limb status $\chi^2(12.1), \text{df} = 2, P<0.001$ on the vastus-lateralis-semitendinosus difference. A main effect was also found for fatigue on the quadriceps-hamstring difference $\chi^2(76.1), \text{df} = 3, P<0.0001$. Data is shown as the mean asymmetry index ± 95% confidence interval. ### Denotes significantly different from Set 1 [P<0.001]. ** Denotes significantly different from Contralateral Limb [P<0.01]. † Denotes significantly different from Control Limb (P<0.05).

5.4 Discussion

We evaluated the acute effects of fatigue on functional inter-limb asymmetry and quadriceps vs. hamstring muscle activity including preparatory (pre-landing) co-activation during squat jump takeoff and landing in elite alpine ski racers with/without ACL reconstruction.
It is important to undertake specific studies with elite ski racers due to the high prevalence of ACL injury (9), the unique injury mechanisms (7, 8), and the high number of elite ski racers returning to competition post-ACL reconstruction (19).

5.4.1 Vertical Jump Performance and Functional Asymmetry

Fatigue was defined as an exercise induced impairment in muscle power evaluated by vertical jump height (17). Vertical jump height declined over the jump-test for both groups. Contrary to our expectation, ACLR skiers did not display increased functional asymmetry with acute fatigue. This contrasts with recent reports where ACLR males who returned to sport had reduced bilateral functional asymmetry with fatigue (36). The discrepancy between studies may be related to the testing methods. We characterized functional asymmetry over the entire takeoff and landing phases of the squat jump instead of a single time point (i.e. the instant of the peak vertical ground reaction force). The asymmetry index was calculated using the left and right limb impulses over discrete jump-phases. This method has a high sensitivity for detecting deficits in ACLR skiers (27). The divergent results may also be caused by the longer post-operative period and the lower functional asymmetry values for the ACLR skiers in this study compared to the subjects in the Webster et al. (2015) study. Consistent with previous research, increased inter-limb asymmetry reflecting deficits in the Affected Limb of the ACLR skiers were observed only in the late takeoff phase of the vertical squat jump (27). It was speculated that this may represent a neuromuscular adaptation resulting from the proximal to distal sequence of lower limb joint torque generation in the squat jump (11, 27) and reduced knee extensor moments in ACLR limbs (3, 13, 14, 36, 38). The latter was potentially a result of reduced neuromuscular knee extensor activity at takeoff (present study) and/or from elevated levels of hamstring muscle co-activation reflecting an ACL protective motor strategy (3).
5.4.2 Maximal and Preparatory Muscle Activity Levels

The Affected Limb of the ACLR skiers displayed reduced quadriceps muscle activation at takeoff compared to the Contralateral Limb, which was consistent with an elevated functional asymmetry index for the late takeoff phase. Previous studies reported that tensile loading of the ACL was increased at small angles of knee flexion and with high levels of quadriceps muscle activation (10, 13, 38). Despite the observation of maximal quadriceps activation in jumping (4), it is possible that the reduced quadriceps activity at takeoff in the Affected Limb was a result of chronic knee joint instability following ACL repair (13, 38).

All three limb conditions demonstrated quadriceps dominance for the pre-landing phase with fatigue. Preparatory quadriceps muscle activity increased and hamstring muscle activity decreased resulting in a higher quadriceps-hamstring and VL-ST co-activity difference. The magnitude of differential VL-ST or valgus-related preparatory muscle activity recorded prior to touchdown in a side cut maneuver has been thought to be a predictor of ACL injury in female athletes (39). It was speculated that increased dominance of the lateral quadriceps relative to the medial hamstring muscles may reflect an impaired ability of preventing valgus knee collapse (39). Preparatory muscle activity was deemed important for ACL injury prevention because afferent mechanosensory feedback loops from the knee are too slow (>100 ms) to help stabilize the joint in case of high ACL loading (16, 24, 29, 38). This observation was supported by studies highlighting the importance of quadriceps vs. hamstring co-activation for dynamic knee joint stabilization (2, 4, 10, 37).

Despite the increased quadriceps dominance with fatigue, the ACLR Limb showed reduced preparatory quadriceps activity and elevated preparatory hamstring activity compared to the other two limb conditions. Thus, preparatory quadriceps-hamstring co-activity prior to
landing was systematically shifted towards increased hamstring dominance in the ACLR Limb (cf. Fig 5.2). There was no straightforward explanation for this finding. Our elite ACLR ski racers were high functioning and had made a full return to sport. In other settings, subjects who coped well with ACL deficiency demonstrated increased hamstring activity compared to non-copers (12,13), and ACL deficient individuals had greater hamstring co-activation during maximal isolated knee extension compared to uninjured controls (3). Additionally, athlete subjects presented with reduced hamstring activity compared to non-athletes, which was thought to be caused by an emphasis on forceful, dynamic knee extension training (4). In this case, regular hamstring strengthening exercise counteracted quadriceps dominance by increasing hamstring co-activity (4). Whether the increased preparatory hamstring activity in the Affected Limb was a result of pre-injury training or post-injury rehabilitation cannot be determined with the current study design. Nevertheless, increased preparatory activity of the lower limb muscles, including the hamstrings (well known as ACL synergists), is an important determinant for the evaluation of successful return to sport after ACLR (23, 31).

The present results were consistent with findings in the scientific literature that demonstrate acute reductions in hamstring muscle activity, hamstring strength and hamstring reflex response following fatiguing exercise protocols (5, 35, 41). Zebis and coworkers (2011) observed systematic post-match decrements in hamstring muscle activity for female elite handball players in the pre-landing and post-landing phases with no change in quadriceps muscle activity. This result paralleled acute reductions in hamstring and quadriceps MVC torque. They concluded that lower hamstring activity with fatigue might be a compensatory mechanism to maximize mechanical efficiency in the presence of quadriceps muscle fatigue (41).
Perhaps more critically, match-induced fatigue was reported to evoke marked acute impairments in quadriceps and hamstring rapid force production (RFD) (35), which may be a critical element for return to sport after ACLR in elite ski racers (28). Biomechanical studies confirmed that impaired neuromuscular function of the hamstring muscles with acute fatigue resulted in increased tibial translation and elevated ACL strain in response to external anterior shear forces (5). The mechanisms of ACL injury in elite alpine ski racing involves high external shear forces in the knee (7), and injuries typically occur towards the end of a race, presumably when fatigue is present (8). In the present study, the shift towards quadriceps dominant preparatory and post-landing muscle activity in response to fatigue suggests that future research should be directed towards a better understanding of how quadriceps-hamstring co-activation may be involved in ACL injury for elite skiers.

Finally, ACLR skiers displayed less inter-limb loading variation (i.e. demonstrated a more stereotypic loading pattern) compared to uninjured skiers who were highly symmetric across all jump-phases. Notably, while the ACLR group loaded the ACLR Limb to a lesser extent in the late takeoff phase, a greater impulse was generated by the ACLR limb in the early jump takeoff phase and landing-phase. The effects of returning to high level ski racing with persistently elevated functional asymmetry remain unclear at this time. Given the high prevalence of knee OA following ACLR (34), assessing inter-limb loading variation with ACL injury and subsequent rehabilitation may be relevant for future research (15).

5.5 Limitations

This study had limitations including the inability to control for the graft type and the inclusion of only high functioning ACLR elite alpine ski racers. Thus, this sample of ACLR skiers might not be representative of all ACLR elite skiers. Additionally, due to limitations with
recruiting subjects, we were unable to make a comparison between sexes and we were not able to present pre-injury data. To add clinical value to our results, prospective research aimed at further evaluating the relationship between functional asymmetry, quadriceps-hamstring muscle co-activity and ACL injury/re-injury (23, 24, 39) is needed. Not only do ACLR elite alpine ski racers often make a successful return to competition (19), they may continue to display persistent functional deficits (27). In this context, increased emphasis on the development of sensitive neuromuscular tests for return to sport assessments is important to safeguard against injury/re-injury (22, 23, 26, 27, 31).

Fatigue is a complex process and no simple solutions for improving fatigue-resistance by means of injury prevention training have been found. However, it is important to identify neuromuscular deficits in ACLR and uninjured skiers that may be addressed through individualized training programs. The 80s jump-test used in the present study assessed functional outcome measures in both a rested and acutely fatigued state. Thus, the present research may provide the clinician and practitioner working with ACLR and uninjured ski racers with a useful and practical assessment tool to evaluate skiers across an envelope of function relevant to the demands of alpine ski racing.

5.6 Conclusion

In conclusion, signs of elevated and systematic inter-limb asymmetry were observed in the late takeoff phase of the vertical squat jump in elite alpine ski racers with ACLR. However, no systematic changes in functional asymmetry indices were observed with acute fatigue. Additionally, we observed decreased quadriceps muscle activity at jump takeoff in the ACLR Limb compared to the Contra-lateral Limb, which was consistent with the finding of increased functional asymmetry in the late phase of the jump takeoff. All three limb conditions (i.e. ACLR
Limb, Contralateral Limb and limbs of uninjured Controls) became quadriceps dominant with fatigue (increased quadriceps activity concomitant with decreased hamstring activity) for the pre-landing and landing phases of the squat jump. As this shift has been identified as a risk factor for ACL injury in other athlete populations, prospective research should evaluate its role in ACL injury/re-injury for elite ski racers. Finally, likely reflecting an ACL protective strategy, the ACLR Limb demonstrated increased hamstring dominance compared to the Contralateral Limb and the limbs of non-injured elite alpine ski racers.
5.7 References


5.8 Bridge to Chapter 6

Based on the first three studies (Chapters 3, 4, 5), elite alpine ski racers with ACLR displayed persistent neuromuscular deficits compared to their non-injured counterparts. ACL injury mechanisms in ski racing are high energy, and in addition to the ACL tear itself, sport-specific injury patterns are expected. The associated pathology is thought to be important for recovery following ACL injury. In the final study (Chapter 6), the associated pathology with primary ACL injury was evaluated along with the injury progression in elite alpine ski racers. As a subset to this study, the recovery in functional symmetry was modeled as a function of time following surgery in ACLR elite alpine ski racers.
Chapter 6: Associated Pathology and Lower-Limb Asymmetries in Elite Ski Racers with ACL Tears

6.1 Introduction

Knee injuries account for more than one-third of the injuries suffered by elite alpine ski racers, and ACL tears are the most frequent diagnosis (6, 11). Nearly half of all knee injuries amongst alpine ski racers were severe resulting in more than 28 days lost from sport (11). A twenty-five-year retrospective study on French alpine ski racers determined that 39% of ACL injured skiers required a second ACL reconstruction either for the same knee or the contralateral knee including 30% who suffered bilateral ACL injuries (36). The prevalence of ACL injury was highest amongst top-ranked alpine ski racers with 50% sustaining one ACL injury, and half of these skiers going on to have multiple ACL injuries over their careers (36). Thirty-nine percent of top ranked alpine ski racers had a bilateral ACL injuries (36). This is a higher incidence than in the general population with estimates ranging from 6% (27) to 21% in a young athlete population (34). The percentage of alpine skiers that require ACL revision surgery (19%) is higher than reports from other athlete and non-athlete populations, which range from approximately 2% in the general population to about 4-9% in young athletes (2, 24, 27, 33, 34). Despite efforts to mitigate injury risk, ACL injury rates remain high (13, 36), and knee injury prevention is deemed a high priority amongst scientific experts (11, 36). Unlike in field sports (35), there is no difference in ACL injury rates between male and female elite skiers (6, 11). Thus, ACL injury prevention efforts should be focused equally on male and female elite alpine ski racers (6). The overall high risk for ACL tears in elite alpine ski racing and the finding of no sex-differences may be due to the unique high energy injury mechanisms that generate external abduction (valgus) and internal rotation forces on the knee (5). Contrary to ACL injury in field or court sports, the equipment (skis, ski boot, ski bindings) and the environment (snow
conditions, course setting) also contribute to knee loading in ski racing (5). Despite the frequent occurrence of ACL tears (11), ACL reconstructed elite ski racers have longer careers compared to ski racers who did not suffer an ACL injury (14, 36), and they may have an exceptional capacity to return to sport and exceed their pre-injury performance level (14) compared to other athlete populations (3). In addition to attaining longer racing careers, a study evaluating French alpine ski racers found that the ACL injured group of skiers reached better international performance rankings compared to ski racers without ACL injury (14). Further, a significantly greater number of podium performance finishes occurred in the post-injury period compared to the pre-injury period in alpine ski racers with ACL injury (14).

Despite a successful return to sport, recent studies show that ACL reconstructed elite alpine ski racers who returned to competition had significant and persistent neuromuscular deficits such as increased inter-limb functional asymmetries in the vertical jump, decreased hamstring/quadriceps strength and altered quadriceps vs. hamstring muscle activity patterns (19, 20, 21). The impact of these persistent deficits on future injury risk and long-term knee joint health remains unclear. However, returning to sport too soon following ACL reconstruction, and/or with significant neuromuscular deficits, is thought to increase risk for re-injury (4, 29). To this end, assessing lower limb functional asymmetry, and extending the return to sport transition until pre-injury function is restored, is recommended to mitigate the risk for re-injury and/or further progression of the primary injury (4, 18, 28, 29).

Recently, vertical jump functional asymmetry testing was proposed as an assessment tool for elite alpine ski racers following ACL injury and throughout the return to sport transition (19, 21). Instead of discrete time point analysis (e.g. instant of the peak vertical ground reaction force), the vertical ground reaction force impulse was calculated over discrete jump phases.
including the eccentric deceleration, concentric and landing phases (19, 21). The proposed advantages of this method are the objective quantification of functional asymmetry over the entire force-time curve compared to discrete time point analysis, the common occurrence of these movements in alpine ski racing, and the practicality of this assessment tool in a high performance sport environment (19).

Following ACL injury, functional asymmetries are expected to diminish over time as a result of rehabilitation exercise, and serial monitoring of patients throughout the recovery period is important in the development of evidenced based return to sport timelines and protocols (28, 29). Return to sport monitoring is also important as elevated functional asymmetry is found in ACL patients more than two years post-surgery (9), and ACL reconstructed athletes are at elevated risk for re-injury in the first two years following surgery (33, 34). The two-year period post-surgery may be important for both functional recovery and tissue healing (29). Currently, no guidelines for return to sport seem to exist for elite alpine skiers after ACL injury, and little is known about the time course of functional recovery following ACL reconstruction in this population (18). As ACL injury is the most common injury type in elite alpine ski racing, and given it is considered an extreme sport with a well-documented risk for traumatic lower limb injury (6, 11), ski-specific scientific research on the functional recovery process following ACL injury seems important not only to establish evidence based return to sport protocols but also to evaluate clinical practices aimed at ensuring skier health and safety after injury. For instance, the development and implementation of objective neuromuscular assessment protocols may help to support clinical decision making regarding clearance of alpine skiers for return to sport after ACL injury.
Long-term knee joint health in young adults appears adversely affected by ACL injury due to an increased risk for early onset of OA (37). An increased OA risk is a well-documented consequence of ACL injury and ACL tearing is often associated with multi-ligament tears in the knee, meniscal tears and articular cartilage (chondral) lesions (24, 31, 37). Associated meniscal and chondral injury occurring with ACL tears is thought to lead to worse outcomes following ACL reconstruction and accelerated progression of knee joint osteoarthritis (8, 23, 31, 37, 38). The pattern of associated injury with primary ACL tears has been investigated in the general population (7, 24, 31), athletes (12), recreational skiers (10, 32) as well as in professional alpine skiers (15). However, only limited data exist on the pathology associated with ACL tears in elite alpine ski racers. An improved understanding of the pathology associated with ACL injury in elite alpine ski racers may help clinicians to anticipate rehabilitation requirements, improve predictions for return to sport timelines, and identify specific injury patterns that can be addressed through medical/rehabilitation interventions.

Thus, the purposes of this retrospective study were three-fold: (1) to characterize the pattern of associated pathology including meniscal tears, chondral lesions, and multi-ligament injuries at the time of primary ACL reconstruction in elite alpine ski racers; (2) to use operative reports obtained in surgeries that occurred subsequently to the primary ACL reconstruction to evaluate the state of the chondral lesions, meniscal tears, and the occurrence of ACL re-injury; and (3) to undertake exploratory analysis of the time course of functional recovery in vertical jump inter-limb asymmetry following primary ACL reconstruction in a subset of skiers who were tested at various time points following surgery from early-phase rehabilitation (4.5 months) up to 12 years post-surgery.
We hypothesized that at the time point of primary ACL reconstruction, ACL tears would be accompanied by a greater proportion of lateral meniscal tears, lateral compartment chondral lesions, and multi-ligament injury involving the medial collateral ligament (MCL) compared to the other injury sub-types. At the time point of subsequent surgery following primary ACL reconstruction, we expected to find a significant number of subjects with a deterioration in their meniscal injuries and chondral lesions. Finally, we expected that functional inter-limb asymmetry would improve (diminish) from early-phase rehabilitation (4.5 months/138 days) through to the testing endpoint (12 years/4444 days), and that more than two years would be required for asymmetry values to reach levels comparable to those found in non-injured elite ski racers.

6.2 Methods: Evaluation of the Associated Pathology with ACL Tears

6.2.1 Study Design

A retrospective study design approved by the University of Calgary Research Ethics Board was employed, and a search of the physical fitness testing database housed at the Canadian Sport Institute Calgary (CSI) was undertaken to identify skiers who competed for the Canadian Alpine Ski Team between 2000 and 2015. As the Canadian Alpine Ski Team conducted their annual physical fitness testing at the CSI, the database contained a comprehensive record of Canadian national team alpine ski racers. The database search generated a list of 137 skiers. With the help of current/former coaches, team physicians, and physiotherapists, alpine ski racers who suffered an ACL injury during this period were identified (n=39) (Figure 6.1). These individuals were contacted regarding their participation in the study, and to verify their history of ACL injury.
Thirty-two subjects responded, provided informed consent, and completed a questionnaire to provide background information on their ACL injuries [Males (n=15): Time Competing on National Team = 8.5±5.7 years, Right Limb Dominant n=13, Left Limb Dominant n=2; Females (n=17): Time Competing on National Team = 8.2±4.0 years, Right Limb Dominant n=12, Left Limb Dominant n=1, No Limb Dominance n=4]. Limb dominance was defined as the preferred limb for kicking a ball. Of the 32 subjects included in this study, seven sustained bilateral ACL injuries bringing the total number of knees with primary ACL injury to 39. At the time point of a future ipsilateral ACL re-injury, one subject also sustained a contralateral ACL tear (i.e. ipsilateral ACL re-injury/contralateral ACL injury). There were no bilateral primary ACL ruptures in this subject group. Using the questionnaire data, we determined: (1) the date of primary ACL reconstruction; (2) limb (left or right) that was injured; (3) graft type; (4) name of the surgeon; (5) whether the reconstructed limb was revised or a contralateral ACL tear was sustained following the primary ACL injury; (6) date of eventual revision or contralateral ACL reconstruction following the primary ACL injury; (7) name of the surgeon who performed the revision or contralateral ACL reconstruction; (8) subject’s level of agreement on whether or not a full return to the pre-injury performance level was attained following primary ACL reconstruction. While annual physical fitness testing was performed at the same testing laboratory over the 15-year study period, the Canadian Alpine Ski Team program was not consistently centralized in the same city. Thus, specific documentation was unavailable regarding the post-operative care procedures, and the subjects did not follow a standardized rehabilitation program. Further, given the limitations of the retrospective study design, we could not determine the specific return to sport date.
Figure 6.1: Overview of subject recruitment process.

Six Canadian orthopedic surgeons contributed operative reports for the primary ACL surgery for 28 knees. This information included four operative reports for contralateral ACL surgeries. Operative reports that occurred after the primary ACL surgery (future surgeries) including surgery for ACL revisions, meniscal tears or chondral lesions were obtained for 20 knees. One knee had a magnetic resonance imaging (MRI) report that was used to identify progression of diagnosed articular cartilage injury. For all knees without primary ACL surgery operative reports, questionnaire data were only used to obtain the date of the primary ACL reconstruction, the limb injured, and the graft type. In the event of missing operative reports subsequent to the primary ACL surgery, questionnaire data were used to determine whether or
not an ACL revision or contralateral ACL injury was suffered and the date of the surgery.
Subject questionnaire data were not used for assessing multi-ligament injuries, meniscal tears, or chondral lesions.

The data from the operative reports were coded and transferred into a spreadsheet (Microsoft Excel, Version 15.24) by a researcher with medical knowledge. Additionally, a second researcher reviewed the operative reports independently to verify the accuracy of the data. In the event of discrepancies, the corresponding surgeon was contacted directly for verification. The primary ACL reconstruction and future surgery operative reports were used to determine the following binary (yes/no) outcome measures: complete or partial tear of the ACL; presence of multi-ligament injury; presence of meniscal tears; and presence of chondral lesions. The location of chondral lesions was classified as lateral compartment, medial compartment and patellofemoral compartment. A modified Outerbridge rating system (30) was used to classify the severity of chondral lesions: Grade 1 (softening and fibrillation); Grade 2 (partial thickness defect with fissures on the surface that did not reach subchondral bone or exceed 1.5 cm in diameter); Grade 3 (fissuring to the level of subchondral bone in an area greater than 1.5 cm); Grade 4 (exposed subchondral bone). Meniscal tears were classified according to the location (medial or lateral meniscus) and the tear type. Operative reports that followed the primary ACL reconstruction were used to evaluate the presence of contralateral ACL tear or ACL revision, the progression of meniscal tears, and the progression of chondral lesions.

6.2.2 Statistical Analysis

Descriptive statistics, including the group mean and standard deviation, were calculated for all continuous variables (RStudio, Version 0.99.902). The proportion of subjects sustaining chondral lesions, meniscal tears, multi-ligament injuries, ACL revisions and contralateral ACL
tears was compared within the subject group using a Chi-Square test of proportions. A Chi-Square test of proportions was also used for within-group comparison of the number of subjects showing a progression in their chondral lesions and meniscal tears over time. A Yates continuity correction was used and statistical significance was set at $\alpha=0.05$ using a two-tailed design.

6.3 Methods: Evaluation of Functional Asymmetry

6.3.1 Study Design

A retrospective study design was used to retrieve functional inter-limb vertical jump asymmetry testing from the fitness testing database. Functional asymmetry testing sessions had been conducted for seventeen of the 32 subjects included in part one of this study [Males: n=9; Females: n=8]. Testing sessions were performed between 138 days and 4444 days following the date of primary ACL surgery. Subjects performed between 1 and 14 functional asymmetry testing sessions (mean of 3.7 sessions). As the inter-limb, vertical jump functional asymmetry tests had only recently been introduced into the National fitness testing battery, pre-injury data were only available for one subject. To evaluate the effects of time since the primary ACL surgery on recovery of functional inter-limb asymmetry following ACL injury, only testing sessions that followed the initial surgery, but preceded a future surgery for meniscal tears or chondral lesions, were included in the analysis.

6.3.2 Functional Asymmetry Test Procedures

The vertical jump functional asymmetry test procedures have been described in detail elsewhere (16, 19, 21). In brief, the testing session included five maximal bilateral countermovement jumps (CMJ) and five maximal squat jumps (SJ). All subjects were familiar with the test procedures as both jump techniques were routinely used in training and testing. Subjects were first given a standardized warm up of ten minutes of light cycling on a bicycle
ergometer and dynamic stretching for the lower body. Subjects then were positioned on two leveled force plates aligned side by side, with each foot placed on a separate force plate in a marked position that permitted a natural hip wide stance (16, 19, 21).

CMJ testing was performed first. Subjects were instructed to descend rapidly to a knee joint angle of about 90° of knee flexion and jump maximally while keeping the hands placed firmly on the hips. Subsequently, subjects were given a five-minute rest interval before performing the SJs. For SJ testing, subjects stood on the force plates and descended to attain a static posture at about 90° of knee flexion. This was marked with an adjustable rope that contacted the hips directly behind the subjects. The squat jump depth was carefully controlled throughout the SJ test by a certified strength and conditioning expert who stood directly beside the testing station. Subjects descended to the start position and maintained a static squat for four seconds before being instructed to jump maximally while keeping the hands placed firmly on the hips. Individual jumps were separated by ten seconds of quiet standing on the force plates. Subjects were provided with loud verbal feedback throughout the test session to ensure a maximal effort was given on each jump.

6.3.3 Data Acquisition and Analysis

The vertical ground reaction force from the right and left limbs, respectively, were measured using a dual force plate system sampling at a frequency of 1500 Hz (Accupower Force Platform, AMTI, Wattertown, Massachusetts, USA). Following data collection, the data were exported for further analysis using custom-built computer scripts (Matlab Version R2015a, Mathworks, Nattick, Massachusetts, USA).

Functional inter-limb asymmetry was calculated by time integration of the vertical ground reaction force (i.e. impulse) for the right and left limb separately over three defined time
intervals (18, 20). For the CMJ analysis, these phases included the body centre of mass eccentric deceleration phase, the body centre of mass acceleration phase (concentric phase) and the landing phase. The SJ analysis involved evaluation of the early takeoff phase (time = 0 to time = 50% of total jump time), late takeoff phase (time = final 50% to the point of toe-off), and landing phase. The impulse asymmetry index was calculated as a five-jump average. The following equation was used such that 0% represented zero asymmetry, a positive value represented non-injured limb dominance and a negative value represented injured limb dominance (18, 20):

$$\text{Asymmetry Index} = \frac{(\text{Uninvolved Limb Impulse} - \text{Involved Limb Impulse})}{(\text{Maximum Impulse Value of the Left or Right Limb})} \times 100$$

6.3.4 Statistical Analysis

Due to the correlated nature of the repeated asymmetry measurements from the same subject and the complex change in functional asymmetry as a function of time since surgery, separate general additive mixed models were fit for the asymmetry indices. Additionally, each mixed model included a random intercept for the subject. Statistical significance of the effects of time since the primary ACL surgery was checked by approximate F-testing. Normality and homoscedasticity of the model errors, and the normality of the random subject effects were evaluated as well. A sensitivity analysis was performed to evaluate the influence of outliers on the model fit. The adjusted R-squared values are reported as a measure of model fit. All models were fit with the gamm function in the mgcv package in RStudio (Version 0.99.902). Statistical significance was set at $\alpha=0.05$ using a two-tailed test design.
6.4 Results

6.4.1 Associated Pathology at the Primary ACL Surgery

Thirty-eight complete ACL tears and one partial tear were identified through the questionnaire (Table 6.1). Twenty-three of the 39 ACL tears (59%) occurred on the left knee. Using the primary ACL surgery operative reports, 5/28 knees (18%) had only isolated tears and 23/28 (82%) knees had associated injury. A comparison of these two proportions was significantly different \( \chi^2(20.6), df = 1, P<0.0001 \). Nine of 28 knees (32%) had multi-ligament injuries including seven medial collateral ligament (MCL) tears (Table 6.1). Fifteen of the 28 knees (54%) had chondral lesion(s). More chondral lesions occurred in the lateral compartment (11/15 knees) versus the medial compartment (4/15 knees) \( \chi^2(16.8), df = 2, P<0.001 \) (Table 6.1). Seventeen of the 28 knees (61%) had meniscal tears at the time of the primary ACL surgery. Compared to single dimension meniscal tears, there was a greater number of complex meniscal tears (i.e. included a combination of at least two tears either in the vertical, horizontal or radial direction) \( \chi^2(5.9), df = 1, P<0.05 \) (Table 6.1). Eight meniscal tears were repaired, eight tears were resected, and one meniscal tear was not treated.

6.4.2 ACL Revisions, Contralateral ACL Injuries, and Progression of Chondral/Meniscal Injury

Seven of the 32 subjects (22%) sustained bilateral ACL tears, bringing the total number of knees with primary ACL tears to 39 (Table 6.2). Using questionnaire data alongside future operative reports that followed the primary ACL surgery, it was determined that 11/39 (28%) knees underwent an ACL revision and four subjects had two or more revisions (Median Time to ACL Revision = 2.3 years). Fifteen of the 39 knees (38%) underwent subsequent surgery after
primary ACL surgery for meniscal tears or chondral lesions (Median Time to ACL Revision = 2.3 years). Following primary ACL surgery, there were 20 operative reports for 20 different knees for either meniscal tears, chondral lesions or ACL revisions. The mean time to the subsequent surgery was 4.7±5.4 years (Table 6.2). At the time of the subsequent surgical procedure, 40% of the meniscal tears had worsened. Seven subjects with meniscal repairs or resections at the time of primary ACL reconstruction went on to have subsequent surgery. The meniscal tears of three patients with resection were worse, and the tears of two patients with meniscal resections and two patients with meniscal repairs were unchanged. The proportion of knees with worsening chondral lesions (16/20) was greater than the number of chondral lesions that had remained the same since the primary ACL surgery (4/20) \( \chi^2(12.1), df = 1, P<0.001 \) (Table 6.2). Ten knees were identified with grade 3/4 chondral lesions compared to three at the time of primary ACL reconstruction. One subject who presented with a partial ACL tear, complete posterior cruciate ligament (PCL) tear and complete MCL tear underwent a primary PCL/MCL reconstruction followed by an ACL reconstruction and MCL revision 13 months following the accident.

6.4.3 Effect of Time Since Primary ACL Surgery on Functional Asymmetry Indices

Time since the primary ACL surgery was a predictor for the improvement of the CMJ concentric phase asymmetry index \( [df = 4.1, F=14.7, P<0.01; \text{Adjusted } R^2 = 0.54] \) and the CMJ eccentric deceleration phase asymmetry index \( [df = 4.8, F = 9.2, P<0.0001; \text{Adjusted } R^2 = 0.31] \) (Figures 6.2A, 6.2B). Time since surgery explained 26% of the variance in the SJ early takeoff phase asymmetry index \( [df = 4.9, F = 5.2, P<0.001] \) and 44% of the variance for the late takeoff phase asymmetry index \( [df = 4.5, F = 13.0, P<0.0001] \) (Figure 6.2C, 6.2D). Time since the primary ACL surgery was not a significant predictor of the CMJ landing phase asymmetry index
[P=0.71] or the SJ landing phase asymmetry index [P =0.16]. Finally, there was an overall agreement amongst study participants that at the time of study a full return to pre-injury sports performance level had been attained after the primary ACL surgery [$\chi^2(17.4), df = 4, P<0.01$] (Table 6.3).

**Figure 6.2:** Effects of time since the primary ACL reconstruction (days) on countermovement and squat jump functional asymmetry indices. The solid black line represents the mean recovery in functional symmetry. Grey band represents the 95% confidence interval. The asymmetry index is calculated such that a positive value indicates the uninvolved limb dominance. The horizontal line represents 0% asymmetry. Time since the primary ACL reconstruction was a significant predictor of the CMJ concentric phase asymmetry index [df = 4.1, F=14.7, P<0.01, Adjusted $R^2 = 0.54$], the CMJ eccentric phase asymmetry index [df = 4.8, F = 9.2, P<0.001; Adjusted $R^2 = 0.31$], the SJ early takeoff phase asymmetry index [df = 4.9, F = 5.2, P<0.001; Adjusted $R^2 = 0.26$] and the SJ late takeoff phase asymmetry index [df = 4.5, F = 13.0, P<0.0001; Adjusted $R^2 = 0.44$].

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Table 6.2: ACL revisions, contralateral ACL tears, and future state of chondral lesions and meniscal tear repairs (** P<0.001). ACL/MCL: anterior cruciate ligament/medial collateral ligament.

<table>
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<tr>
<th>Revision</th>
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<th>Days to Future Surgery</th>
<th>State of Cartilage at Future Surgery</th>
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</thead>
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Number of ACL Revisions

| 1313.1 (1025.9) |

Number of Future Meniscus or Chondral Surgeries

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Days to First Revision

| 1187.5 |

Mobilization

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</tr>
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Exploratory Scope

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<td>1</td>
</tr>
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Exploratory Scope

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Exploratory Scope

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</tr>
<tr>
<td>2</td>
<td>Chondral/Meniscus</td>
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Exploratory Scope

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</table>

ACL/MCL: anterior cruciate ligament/medial collateral ligament.

*** P<0.001.
Table 6.3: Subject agreement regarding the ability to make a full return to the pre-injury performance level (** P<0.01).

<table>
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<th>Agree</th>
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<tbody>
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6.5 Discussion

6.5.1 Associated Pathology at the Primary ACL Surgery

Despite the high risk for musculoskeletal injury in alpine ski racing (11), a significant number of elite alpine ski racers have a positive prognosis following ACL injury (14, 36). However, we observed that the present group of elite alpine ski racers suffered significant amount of associated traumatic knee injuries. Thus, only 18% of the skiers sustained isolated ACL tear with no associated pathology, compared to 28% to 44% isolated ACL tears in other sporting populations (12). A majority of subjects demonstrated meniscal tears at the time of primary ACL surgery (61%). A high fraction (82%) of these meniscal tears were complex compared to the prevalence of complex tears (8%) in non-elite alpine skiers (10, 12).

This finding is of concern as meniscal injuries alongside ACL tears are known to accelerate the progression of knee joint osteoarthritis (8, 23, 25, 31, 37, 38). In a general, non-athletic population, the prevalence of meniscal damage with ACL tears is 34% to 51%, which appear substantially lower than the present finding of 61% in the alpine ski racers (7, 8, 22, 24). Meniscal tears in recreational skiers occur in 41% to 50% of all ACL injuries, with the majority occurring in the lateral meniscus (10, 32). In contrast to the present study, ACL injuries in professional alpine skiers have previously been associated with meniscal injuries in 80% of all cases, which primarily affected the medial meniscus (15). In the current group of elite ski racers,
lateral meniscal tears occurred more frequently (53%) than in the professional skiers studied three decades ago by Higgins and Steadman (15), followed by combined lateral/medial meniscal tears (41%). We only observed a single knee with an isolated medial meniscal tear. The reason underlying the discrepant findings between the Higgins and Steadman study performed in 1987 (15) and our present results is unclear, but could be related to the changes in equipment and increased demands of elite alpine ski racing (including the elevated racing speeds) that have taken place over the past 30 years (13).

Articular cartilage lesions were found in 54% of the knees at the time of the primary ACL reconstruction surgery, which also seem elevated compared to the 15-47% reported for the general population (7, 17, 22, 23, 24, 26). The majority of our elite ski racers sustained lateral compartment injuries (73%) with their ACL tears. This is consistent with the literature showing acute ACL tears to coincide predominantly with lateral compartment tibiofemoral injury (7, 23). The greater prevalence of lateral compared to medial compartment chondral lesions is also consistent with the injury patterns observed in non-elite alpine skiers (9, 32). A greater prevalence of lateral compartment injury in skiers may be related to the high-energy injury mechanisms that result in combined tibial internal rotation/valgus loading of the knee joint and likely the subluxation of the femur off the back of the tibia (5, 32).

Thirty-two percent of the skiers in the current study sustained a multi-ligament injury along with their ACL tears, and all but one involved rupture of the ipsilateral MCL. ACL/MCL tears are less prevalent in the general population (8% - 13%) than in our elite ski racers (22, 24). Additionally, skiers may be 1.9 times more likely to suffer ACL/MCL injuries compared to soccer players (12). The present findings are also consistent with data from non-elite alpine skiers showing ACL/MCL injuries occurred in 31% to 38% of all ACL injuries (10, 32). Again,
the unique injury mechanisms in skiing that involve the lever arm of the ski and a stiff boot restricting ankle range of motion may contribute to the greater occurrence of multi-ligament injuries in skiers (5).

6.5.2 ACL Revisions, Contralateral ACL Tears, and Progression of Chondral/Meniscal Injury

ACL revision surgery consequent to re-injury is required in less than 4% of the general population (2, 24). Young soccer players are at an increased risk for ACL revision (2, 27, 34) and contralateral ACL injury (33, 34) compared to the general population. The percentage of patients with ACL revision returning to sport (46%) is less than following primary ACL reconstruction (65%) (1, 3) and ACL revision is less successful than primary ACL reconstruction (39). The prevalence of ACL re-injury is high in elite alpine ski racers (36). In the present group of elite skiers, 28% of the knees underwent ACL revision surgery, and four knees (13%) required multiple revisions. Seven out of the overall 32 subjects (22%) suffered a second ACL tear to the contralateral limb compared to 30% in a comparative group of elite alpine ski racers (36). While the mean time period to the contralateral injury was 3.6 years and 3.3 years for revision surgery, the data was skewed towards shorter time frames (Median Time to Contralateral ACL Tear = 2.3 years; Median Time to ACL Revision = 2.3 years). Consistent with other findings, this suggests that the two-year time span following primary ACL reconstruction represents a period of increased vulnerability for ACL re-injury (29, 34).

The progression of chondral lesions and meniscal tears following ACL revision surgery is crucial for future knee health, including early onset of OA (1, 8, 25, 31, 37, 40). In a group of 109 subjects (non-athletes), 29% presented with a grade 3 or grade 4 cartilage loss, and 59% with medial meniscus tears at the time of ACL revision surgery (1). A study including 1205 patients found that 59% had signs of abnormal articular cartilage and menisci at the time of ACL revision
surgery, which negatively impacted patient self-reported outcome at the time of ACL revision surgery (40). Based on the present data, elite ski racers demonstrated elevated prevalence of chondral lesions and meniscal tears compared to the general population. Thus, 38% of the present ACL injured knees underwent a meniscal or chondral surgery. At the time of ACL revision surgery, or meniscal/chondral surgery, 60% of the skiers had more meniscal damage and 80% had worsened chondral lesions than at the time point of initial knee surgery. Ten of the chondral lesions (63%) were characterized as Grade 3/4.

Based on the small sample size and the retrospective nature of this study design, it is difficult to determine the degree to which our results are representative of the elite alpine ski racing population in general. Further, the precise injury sequela and the confounding factors that may have contributed to the injury progression could not be determined. Nevertheless, the present findings may be of clinical importance, as advanced articular cartilage lesions and meniscus injury are thought to accelerate the progression of knee joint osteoarthritis in young adults (37). The present findings may help clinicians to predict concurrent injuries with ACL tears in elite ski racers, and to devise suitable timelines for safe return to sport to protect skiers against re-injury and/or injury progression.

6.5.3 Effects of Time Since Surgery on Functional Asymmetry

Neuromuscular testing is recommended to ensure ACL reconstructed athletes are safely fitted to return to sport (4, 16, 18, 19, 28). However, there appears to be an overreliance on post-operative time and subjective characteristics to return athletes to sport (4). Functional lower-limb asymmetry assessments in bilateral (or unilateral) movements such as the vertical jump should be a standard component of return to sport neuromuscular testing (16, 18, 19, 21, 28). Importantly, ACL reconstructed athletes may not attain pre-injury neuromuscular testing values
for up to two years following surgery, at which time point most athletes have been cleared for return to sport (29).

Recent studies in ACL reconstructed elite alpine ski racers confirm the existence of persistent neuromuscular deficits in the lower limbs including elevated inter-limb functional asymmetries in the vertical jump (19), hamstring/quadriceps strength deficits (20) and altered quadriceps vs. hamstrings muscle activity patterns compared to the contralateral limb and non-ACL reconstructed elite skiers (21). Additionally, elite ski racers with no history of ACL injury displayed low inter-limb asymmetry in vertical jumping (19). This has been considered as a potentially important performance factor given the high-energy bidirectional turns in elite alpine ski racing.

In the present study, we employed a previously published functional asymmetry assessment protocol that is sensitive in detecting neuromuscular deficits in ACL reconstructed elite skiers (19, 21), and undertook exploratory data analysis into the functional recovery of elite alpine ski racers following ACL injury. This functional asymmetry assessment evaluates movements relevant to elite alpine ski racing such as the eccentric deceleration phase and acceleration phase of the vertical jump, and can be readily administered in a high performance sport environment. We evaluated functional asymmetry in elite ski racers at different time points following primary ACL surgery, and found the time from surgery was a significant predictor of the recovery in functional symmetry (Range in Explained Variance for Four Separate Jump Phases = 26% to 51%). On average, it took 328 days from the time of primary ACL reconstruction surgery for the averaged inter-limb asymmetry index to decrease below 10%, and 695 days (1.9 years) for it to return to comparable inter-limb asymmetry index values for elite ski racers without ACL injury (19, 21). These findings are consistent with previous research that
suggests that two years of rehabilitation recovery might be needed following primary ACL reconstruction surgery to ensure that baseline neuromuscular function is fully restored (9, 29). The present results may help clinicians to better define return to sport timeframes for ski racers following ACL reconstruction, and this study provides a practical assessment technique for evaluating the functional recovery of alpine ski racers after ACL reconstruction in a rehabilitative setting.

6.6 Limitations

This study has several limitations that should be kept in mind when interpreting the present findings. First, the primary ACL surgery and future surgery operative reports were not available for all subjects. Thus, questionnaire data was used for determining the surgery occurrences and surgery dates for these subjects. Additionally, in some instances the operative reports only reported the presence of pathology and not the absence of pathology. The precise location of meniscal tears and chondral lesions were not recorded in a consistent manner across the surgeons involved. This study is also limited by the small sample size. Given the small sample and the limitations encountered with the operative reports, we were unable to undertake more detailed analysis of the precise location of meniscal tears and chondral lesions. Therefore, chondral lesions and meniscal tears were merely classified by the knee joint compartment in which they occurred. The small sample size may also limit the generalizability of the present findings to the elite alpine ski racing population at large. Further, the small sample size may have impacted the power of the statistical modelling and the ability to evaluate the effects of time on functional asymmetry. No study participant provided functional asymmetry data over the entire study period, and there was a range in the number of vertical jumping testing sessions across the group of skiers examined. Given the retrospective study design, we could not make an accurate
determination of a specific return to sport date, and we could not control for the subjects’ rehabilitation after ACL reconstruction. Despite these limitations this study and the retrospective approach provides important insights on ACL reconstructed elite alpine ski racers including a characterization of the associated pathology at the time of primary ACL reconstruction, and the injury progression (notably chondral/meniscal injuries). While exploratory in nature, the present study also provides information on the time course of functional recovery in vertical jump inter-limb asymmetries following ACL reconstruction. Given that ACL injury/re-injury is the most common injury type in elite alpine ski racing and expert scientific opinion recommends specific research be undertaken into ACL injury prevention in elite alpine ski racing (6, 11, 36), the present study may provide important insights into future research possibilities on how to safeguard skier health and safety after ACL injury.

6.7 Conclusion

In conclusion, this group of elite alpine ski racers demonstrated more combined ACL injuries versus isolated ACL tears compared to reports in the scientific literature from other athletic and non-athletic populations. Complex meniscal tears were the most prevalent comorbidity, and there was a significantly greater proportion of lateral compartment chondral lesions compared to medial compartment lesions. Most multi-ligament injuries involved the MCL. The progression of meniscal tears and chondral lesions appeared to be more severe in the present group of alpine ski racers compared to other athlete groups. In agreement with previous research, there was a high percentage of ACL re-injury. Based on the exploratory-type data analysis performed here, we found that elite alpine ski racers may require about two years to fully remove functional asymmetry in the vertical jump following ACL reconstruction surgery. This type of evaluation may help clinicians improve decision making around return to sport.
outcomes for ACL reconstructed alpine ski racers. Future research using a prospective study design and a larger sample size than used here is required to confirm the findings of the present investigation, and to work towards evidence based return to sport assessments and guidelines. Additionally, it seems important to evaluate the effects of surgical treatment for meniscal tears, chondral lesions and multi-ligament injury on return to sport performance outcomes and long-term knee joint health. Finally, the relationship between ACL injury mechanisms, the associated pathology, functional recovery, performance outcomes, and long-term knee joint health (e.g. early development of knee joint OA) should be undertaken to help optimize return to sport after ACL reconstruction for alpine ski racers.
6.8 References


Chapter 7: Conclusions and Future Directions

The primary aim of this thesis was to evaluate the effects of ACL injury on neuromuscular function and performance in elite alpine ski racers. This was accomplished in part by developing a framework for neuromuscular testing across an envelope of knee function that can be used to evaluate alpine ski racers for ACL injury prevention, ACL re-injury prevention, and monitoring skiers following ACLR throughout the return to sport transition. Neuromuscular assessments for athletes who participate in high risk sports for ACL injury are recommended for primary injury prevention, secondary injury prevention, and monitoring athletes to ensure they are physically prepared to return to sport after ACLR (6, 24, 34, 35, 47, 48, 56, 57, 58). In this PhD thesis, two gaps in the scientific literature were addressed, namely: (i) a lack of scientific data on the effects of ACL injury on neuromuscular performance/function in elite alpine ski racers; and (ii) the need for improved functional neuromuscular testing for ACL injury/re-injury prevention in alpine ski racing.

In Chapter 2, we conducted a narrative literature review on ACL injuries in alpine ski racing. A narrative review was chosen due to the paucity of prospective studies on ACL injuries/re-injuries in alpine ski racing limiting us from undertaking a quantitative review. With respect to van Mechelen’s (70) four stage injury prevention model, the epidemiology and etiology of ACL injuries in elite alpine ski racing is well described in the scientific literature (9, 10, 11, 12, 13, 27, 28, 29). Notably, the knee was the most commonly injured body part and ACL injuries were the most frequent diagnosis (28). No sex-differences in ACL injury rates were found (28). Additionally, there appeared to be a high prevalence of ACL re-injury (61). Three key ACL injury mechanisms were identified that involved tibial anterior shear/internal rotation loads and high energy force transmission from the equipment/environment to the knee.
(10, 11, 13). The scientific evidence on risk factors for ACL injury is limited, and only one neuromuscular risk factor has been identified, namely a trunk flexion/extension strength imbalance in younger alpine ski racers (62). Longitudinal studies are required to evaluate the efficacy of neuromuscular assessments for ACL injury/re-injury prevention and monitoring athletes throughout return to sport after ACLR. Additionally, ski-specific ACL injury prevention training programs that focus on modifiable risk factors are necessary alongside high quality randomized control trial studies to evaluate their effectiveness for reducing ACL injuries/re-injuries.

In Chapter 3, a new test of functional asymmetry was presented to detect neuromuscular deficits in ACLR elite alpine ski racers. As elite alpine ski racing involves high force bidirectional turns (14, 38), and alpine ski racers demonstrate a high degree of inter-limb strength symmetry (51), a dual force plate system that simultaneously measured the ground reaction force from the right and left limbs was used to measure inter-limb asymmetry during vertical jumping. The inter-limb functional asymmetry in vertical jumping and inter-limb asymmetry in lower limb muscle mass were evaluated in non-injured elite alpine ski racers and ACLR elite alpine racers who had made a full return to competition. Subjects performed two different vertical jump techniques, the countermovement jump and the squat jump. The impulse was calculated by time integration of the ground reaction force over discrete jump phases including the concentric phase and eccentric deceleration phase, two movements that occur frequently in alpine ski racing. An advantage of the proposed testing method is its practicality for use in a high performance sport environment. Despite a full return to sport and competition, ACLR skiers displayed persistently elevated inter-limb functional asymmetries compared to non-injured control skiers. There was a significant correlation between functional asymmetries and asymmetry in lower limb muscle
mass. In the post-study period, one skier suffered a contralateral medial collateral ligament injury. Notably, this athlete displayed the highest functional asymmetry in the late takeoff phase of the squat jump, the concentric phase of the countermovement jump, and the eccentric deceleration phase of the countermovement jump. Future research is required to evaluate the utility of these tests for detecting neuromuscular deficits related to ACL injury/re-injury in elite alpine ski racers.

In Chapter 4, we evaluated hamstring/quadriceps strength in elite alpine ski racers with/without ACLR. The hamstring muscle group is an important ACL agonist (synergist) that resists tibial anterior shear forces (8, 66). Hamstring strength imbalance was identified as a differentiator between elite alpine ski racers who went on to suffer ACL injury and those who did not (40), and there are ACL injury mechanisms in ski racing that involve tibial anterior shear loads (11). Restoring quadriceps strength is also an important functional determinant after ACLR (54). In addition to evaluating maximal hamstring/quadriceps strength, we evaluated explosive strength or the rapid force producing capability (RFD) (73). This is important as the time course of ACL injury in alpine ski racing is short (< 60 ms) (13), and maximal strength can require more than 300 ms to develop (73). Consistent with the results presented in Chapter 3, ACLR elite alpine ski racers displayed significant hamstring/quadriceps strength deficits in the affected limb compared to the contralateral limb and the limb average of non-injured controls. No sex-differences in body mass normalized hamstring/quadriceps strength were found between non-injured male and female elite alpine ski racers. Hamstring/quadriceps strength ratios (H/Q Ratios) were calculated, and the ACLR limb displayed elevated H/Q Ratios compared to the contralateral limb. However, further analysis revealed that the ACLR skiers with the highest H/Q Ratios also displayed the greatest bilateral difference in quadriceps strength. Hence, the
elevated H/Q Ratio in the ACLR limb reflected quadriceps strength deficits and not superior hamstring strength. As hamstring/quadriceps strength is a predictor of ACL injury in other athlete populations (47) and is also important for functional outcomes after ACLR, future work should include prospectively designed research studies to evaluate the relationship between hamstring/quadriceps maximal strength and explosive strength (RFD), and the risk for ACL injury/re-injury.

In Chapter 5, the functional asymmetry test introduced in Chapter 3 was employed using a fatiguing 80-second repeated squat jump protocol in elite alpine ski racers with/without ACLR. The aim was to evaluate the acute effects of fatigue on neuromuscular function in ACLR elite alpine ski racers who had made a full return to competition compared to non-injured ski racers. The jump protocol was arrived at to simulate a typical race in alpine ski racing. A progression from Chapter 3 was that the ACL group was on average 3 years post-surgery vs. 2 years post-surgery. Surface EMG was recorded from the vastus lateralis, vastus medialis, semitendinosus and biceps femoris muscles. The acute effects of fatigue on functional asymmetry and thigh muscle activity levels were evaluated. Of importance was the quadriceps vs. hamstring co-activity difference in the pre-landing phase, which was predictive of ACL injuries in other athlete populations (74). There were no measurable effects of fatigue on functional asymmetry indices for either the ACLR skiers or the control group. However, the ACLR group displayed systematic inter-limb asymmetries across the jump phases whereas the control group skiers were highly symmetric. The ACLR group loaded the affected limb in the early takeoff phase of the vertical jump, the contralateral limb in the late takeoff phase, and then landed with greater impulse on the affected limb. The effects of this systematic shift in functional asymmetry over the jump phases is unclear but given the prevalence of early onset OA following ACLR, the
implications of a more rigid inter-limb loading strategy on long term knee joint health should be evaluated. The affected limb of the ACLR skiers displayed reduced quadriceps muscle activity in the late takeoff phase of the SJ. The affected limb also displayed less quadriceps dominant muscle activity in the pre-landing and landing phases compared to the contralateral limb and the control subjects. This was reflective of elevated hamstring muscle activity and reduced quadriceps activity. The effects of this muscle co-activity pattern are unclear but it may be possible that this is an important protective strategy to safeguard the surgical limb. Additionally, all three limb conditions (affected limb, contralateral limb, and limbs of non-injured controls) displayed quadriceps vs. hamstring dominance with fatigue. Quadriceps dominant landings are a known risk factor for ACL injury in other athlete populations, and alpine ski racing injuries tend to occur in the final sections of the race presumably when fatigue increases injury susceptibility. More research is required to evaluate the relationship between quadriceps vs. hamstring dominant landings and ACL injury risk.

To our knowledge, the studies presented in Chapters 3, 4 and 5 are the first to compare neuromuscular function between ACLR elite alpine ski racers and non-injured elite alpine ski racers. These studies provide important data on the effects of ACL injury on neuromuscular function in elite alpine ski racers. The inclusion of elite athletes in these studies is novel. Additionally, as risk factors for injury are sport-specific (45) and sport-specific neuromuscular testing following ACLR is recommended (24, 47), the methods employed in these three studies provide a new framework to assess elite alpine ski racers with ACLR. There are persistent neuromuscular deficits in ACLR elite alpine ski racers compared to non-injured ski racers despite return to sport and competition. Given the limitations of the present study designs, the relationship between these neuromuscular deficits and risk for ACL injury/re-injury could not be
determined. Additional limitations included the small sample sizes and the inability to control for sex-differences. While there are no sex-differences in ACL injury rates amongst elite alpine ski racers, there are important anatomical and biological differences between males and females that are implicated in ACL injury risk (16, 60). The reasons underlying the absence of sex-differences in ACL injury rates in elite alpine ski racing are unclear. It has been speculated that the high energy ACL injury mechanisms in alpine ski racing and the involvement of unique equipment/environment factors may preclude risk factors typically associated with female ACL injuries such as biomechanical and neuromuscular deficits (12). Additionally, given the high strength requirements of elite alpine ski racing and based on the present data that showed no sex-differences in hamstring/quadriceps strength to exist in elite alpine ski racers, it is possible that female elite alpine ski racers may have developed sufficient protective muscular strength and neuromuscular control to override the typical injury patterns seen in the female athlete. However, there are no studies to date that have investigated this possibility.

In the final study (Chapter 6) the associated pathology with ACL tears was characterized alongside the injury progression following primary ACLR. The associated pathology including meniscal tears, chondral lesions, and multi-ligament injuries affect outcome after ACL injury including the time course of recovery for return to sport and long term knee joint health (50, 53, 63). Thirty-two elite alpine ski racers with ACLR completed an online questionnaire to obtain background information such as the number of ACL injuries, date of injury, and surgeon who performed the ACLR. Twenty-eight operative reports for primary ACLR were analyzed along with twenty operative reports following primary ACLR. Injury pathology including location and type of meniscal tears, location and type of chondral lesions, and the presence of multi-ligament injury were recorded. Distinct injury patterns were found in the surgical group of ACLR ski
racers. There was a higher proportion of complex meniscal tears compared to one-dimensional tears, and a higher proportion of lateral compartment chondral lesions compared to medial compartment lesions. At the time of future surgeries after primary ACLR, a significant proportion of skiers had worsening chondral lesions compared to those whose lesions remained unchanged. As a subset to this study, 17 skiers had performed functional asymmetry testing using the methods described in Chapter 3. Testing was performed at various time points following ACLR. A non-linear statistical model was used to evaluate the effects of time on the recovery in functional symmetry after primary ACLR. Time since surgery explained a significant amount of the variance in functional asymmetry indices, and it took nearly two years for asymmetry values to reach levels comparable to non-injured elite alpine skiers. Future research should evaluate the relationship between the associated pathology with ACL tears, neuromuscular function, and return to sport outcomes in ACLR skiers. Further research is also required to evaluate the effects of ACL injury on long term health outcomes such as the development of early onset knee joint OA. The statistical modeling in this study was limited by the small sample size, and the fact that no single skier was tested over the entire time range. Systematic short term and long term monitoring with a larger sample size of ACLR elite ski racers is necessary to determine thresholds for return to sport and the recovery in functional indices after injury.

Injury causation is considered a multi-factorial process and it is important that a broad approach be employed for effective injury prevention including the assessment of extrinsic and intrinsic risk factors (45). The studies presented in this thesis address potential intrinsic (i.e. internal to the athlete) modifiable injury risk factors for injury that may be addressed through future injury prevention research (45). Further, van Mechelen’s four stage model of injury
prevention including first establishing the injury incidence, second the injury etiology, third the introduction of injury prevention strategies, followed by a return to step one to evaluate the ensuing effects on the injury incidence provides a framework for reducing ACL injury/re-injury in alpine ski racing (70). This thesis provides a basis for future research surrounding Step 3 of van Mechelen’s four stage model, namely directions for future research into intrinsic and modifiable risk factors for ACL injury/re-injury.

Future research into ACL injury/re-injury prevention specifically focused on modifiable risk factors that can be addressed with neuromuscular training programs is essential. While several studies demonstrate a high degree of effectiveness of injury prevention training programs in other sports with a high risk of ACL injury (1, 2, 17, 18, 49, 55, 67, 69), there are no studies to date that have employed such an approach with alpine ski racers. Further, given the prevalence of ACL re-injury amongst ACLR elite alpine ski racers, better neuromuscular assessments are required to ensure skiers transition back to support successfully after surgery, and equal emphasis should be placed on re-injury prevention training programs. Of importance is the potential relationship between the concurrent pathology with primary ACL injury (e.g. meniscal tears, chondral lesions, multi-ligament tears) and the restoration of neuromuscular function. Given the extreme nature of alpine ski racing including high eccentric loading, more specific investigations into on-snow neuromuscular assessments and the development of off-snow technologies that can replicate the demands of alpine ski racing in a more specific manner may prove valuable for detecting neuromuscular deficits in ACLR alpine ski racers. Thus, these three initiatives including (i) prospective research to evaluate trainable neuromuscular risk factors for ACL injury, (ii) prospective research the relationship between concurrent injuries with primary ACL tears and recovery in neuromuscular function, and (iii) on-snow neuromuscular
assessments and the development of off-snow technologies for sport-specific evaluations are important next-steps for this research area.

7.1 Final Summary

In summary, the main finding was that significant deficits in neuromuscular function and performance persist in actively competing ACLR elite alpine ski racers compared to their non-injured counterparts. These deficits include elevated inter-limb functional asymmetries, asymmetry in lower limb muscle mass, and hamstring/quadriceps strength deficits. The surgical limb also displayed distinct quadriceps vs. hamstring muscle co-activity patterns compared to the contralateral limb and to the limbs of non-injured skiers. Fatigue appeared to increase quadriceps dominance in the pre-landing and landing phases for ACLR skiers and non-injured skiers alike. Finally, ACLR alpine ski racers suffered traumatic knee injuries that worsened over time. Nearly two years were required for functional asymmetry indices to reach values comparable to those of non-injured elite ski racers. The studies in this PhD dissertation highlight the importance of evaluating the effects of ACL injury on neuromuscular performance and function in elite alpine ski racers. Prospectively designed research studies are required to evaluate the efficacy of these testing methods for ACL injury/re-injury prevention in alpine ski racers. Future research should also include young developmental alpine ski racers and control for important sex-related ACL injury risk factors. Through these research efforts, it is hoped that ACL injury risk can be reduced in elite alpine ski racing, and that health and functional outcomes can be improved for ski racers after ACL injury.
References for Chapter 1 (Background) and Chapter 7 (Conclusions and Future Directions)


Appendix 1: Case Studies on Recovery in Functional Asymmetries in Two ACL Reconstructed Elite Alpine Ski Racers

Case Study #1

The subject was a 26-year old male elite alpine ski racer. The subject suffered a complete tear of the ACL and MCL, and a radial tear in the lateral meniscus. Both ligaments were surgically repaired along with the meniscal tear.

Figure 1: Pre-surgery and post-surgery functional asymmetry indices for the countermovement jump (CMJ) and squat jump (SJ).
Case Study #2

The subject was a 21-year old female elite alpine ski racer. The subject suffered a complete tear of the ACL and MCL, a grade 1 lateral tibial plateau chondral lesion, and a complex tear to the medial and lateral mensici. Both ligaments were surgically repaired. The meniscal tear was resected.

Figure 2: Post-surgery functional asymmetry indices for the countermovement jump (CMJ) and squat jump (SJ).
Appendix 2: Informed Consent

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.
7.2 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.

7.3

7.4 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.

7.5 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.
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.
INFORMED CONSENT FORM

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

Investigators: Walter Herzog, Matthew Jordan

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.

Background

Anterior cruciate ligament (ACL) injury is very common amongst elite alpine skiers, and despite significant scientific attention and equipment modification injury rates have remained unchanged. Furthermore, after the first ACL injury, elite alpine skiers 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. While there have been no studies to date evaluating the bilateral limb asymmetries in elite alpine skiers with a history of ACL injury, healthy skiers display marked symmetry. This may be an important performance indicator given the extreme physical demands of alpine ski racing.

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

Purpose

The purpose of this research project is to investigate the long-term effects of ACL injury on bilateral limb asymmetry during the squat jump, isokinetic knee extension, isokinetic knee flexion, and muscle activation in the hamstrings and quadriceps muscles in elite alpine ski racers. 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 you are required to undergo five maximal contractions of knee extension and knee flexion in an isokinetic dynamometer, and perform a series of vertical jumps and landings on a force plate system. Throughout the testing protocol surface measurements will be taken from your quadriceps and hamstrings muscles to assess the degree of muscle activation.
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.

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

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 elite alpine ski racers. 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 alpine ski racers returning from ACL injury.

Obligation to Participate and Withdrawal of Consent

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. Furthermore the investigators reserve the right to withdraw you from the study should any factor arise that may affect the research question.

Personal Information

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 right nor release the investigator or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation. 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  Date

__________________________________________  ________________________
Investigator  Date

__________________________________________  ________________________
Witness  Date

A copy of this consent form has been given to you to keep for your records and reference.
Appendix 3: Questionnaire Employed for Chapter 6

**Background Information**

1. What is your name?

2. Please select your performance level.
   - a. National Team
   - b. National Development Team
   - c. Other

3. How many years did you compete for the Canadian National Team?

4. Enter your birthdate.

5. Enter your age in years.

6. Select your sex.
   - a. Male
   - b. Female

**ACL Injury Details**

1. How did your ACL injury happen?
   - a. Slip and catch while turning
   - b. Landing back weighted
   - c. Dynamic snow plow
   - d. During a fall
   - e. I don’t remember
   - f. Other

2. What factors contributed to your ACL injury?
   - a. Lack of strength and fitness
b. Poor snow conditions

c. Fatigue

d. Equipment failure

e. Skier error

f. Other

3. When did you have your last ACL reconstruction?

4. Did you have a second or third ACL reconstruction?

5. Who did your surgery?

6. Where was the surgery done?

7. On which side did you have an ACL reconstruction?

   a. Left
   
   b. Right
   
   c. Both

8. If you had a second ACL reconstruction, on which side did it occur?

   a. Left
   
   b. Right
   
   c. Both

9. What graft was used for your ACL reconstruction?

   a. Left hamstrings
   
   b. Right hamstrings
   
   c. Left patellar tendon
   
   d. Right patellar tendon
   
   e. Left quadriceps tendon
f. Right quadriceps tendon  
g. Allograft (cadaver)  
h. I don’t know  

10. Select any additional injuries you sustained with your ACL injury.  
   a. Medial meniscus  
   b. Lateral meniscus  
   c. Bone bruising  
   d. Patellar tendon  
   e. Medial collateral ligament  
   f. Lateral collateral ligament  
   g. Posterior cruciate ligament  
   h. Other  

11. Please tell me your preferred hand for writing.  
   a. Left  
   b. Right  
   c. I can write equally well with BOTH hands.  

12. Please tell me your preferred foot for kicking a soccer ball.  
   a. Left  
   b. Right  
   c. I can kick a soccer ball equally well with BOTH legs.  

13. I believe I made a full recovery after my ACL reconstruction to my pre-injury performance level.  
   a. Strongly Agree
b. Agree

c. Neutral

d. Disagree

e. Strongly Disagree

14. Is there anything else you want to share?
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Please let me know if you have any questions or concerns, and thank you again for touching base with us.

All best,
Theresa

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Kind regards

Ann

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