Development of sports-specific classification for Paralympic skiers with visual impairment

by

Amritha Stalin

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Examining Committee Membership

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

External Examiner	Alex Bowers Associate Professor of Ophthalmology, Harvard Medical School
Supervisor	Kristine Dalton Associate Professor, School of Optometry and Vision Science, University of Waterloo
Internal Examiners	Benjamin Thompson Professor, School of Optometry and Vision Science, University of Waterloo
	Susan Leat Professor, School of Optometry and Vision Science, University of Waterloo
Internal-External Examiner	James Danckert Professor, Department of Psychology, University of Waterloo

Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Amritha Stalin was the sole author of all the first drafts of the Chapters and Appendices in this thesis, which were written under the supervision of Dr. Kristine Dalton.

This thesis consists of five Chapters, which describe all of the studies conducted towards developing evidence-based classification systems for Para nordic and Para alpine skiers under the supervision of Dr. Kristine Dalton. Chapter 2 was a manuscript written for publication. Exceptions to sole authorship of material are described below.

Research presented in Chapter 2:

Author	Concept/ Design	Data Collection	Data Analysis	Article Writing	Article Editing
Kristine Dalton	✓	✓	Advised	Advised	Edited
Ben Thompson			Advised		
Susan Leat			Advised		
Amritha Stalin	✓	✓	✓	✓	✓

Dr. Kristine Dalton contributed to a major part of the study design and participant recruitment was conducted with the help of the International Paralympics Committee (Bonn, Germany) and the National Sports Centre for the Disabled (Colorado, United States). Dr. Kristine Dalton and Amritha Stalin conducted the experiments, in which the nordic and alpine skiers participated. The data analysis was conducted by Amritha Stalin under the supervision of Dr. Kristine Dalton and with valuable inputs from Dr. Benjamin Thompson and Dr. Susan Leat, who were part of Amritha Stalin's Ph.D. committee.

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David Mann	Advised		Advised		
Rianne Ravensbergen			Advised		
Ben Thompson			Advised		
Susan Leat			Advised		
Michael Dorr			Advised		
Marieke Creese	✓	✓			
Amritha Stalin	✓	✓	✓	✓	✓

The studies were designed by Dr. Kristine Dalton in consultation with the International Paralympic Committee and Dr. David Mann at Vrije Universiteit Amsterdam. The data were collected by Dr. Kristine Dalton, Marieke Creese, and Amritha Stalin. The data analysis presented in this Chapter was conducted by Amritha Stalin under the supervision of Dr. Kristine Dalton and with valuable inputs from Dr. Benjamin Thompson and Dr. Susan Leat, who are part of Amritha Stalin's Ph.D. committee. Amritha Stalin drafted the manuscript and Dr. Kristine Dalton provided input on manuscript drafts. Dr. David Mann and Dr. Rianne Ravensbergen at Vrije Universiteit, Amsterdam also contributed by giving suggestions on some of the data analysis. Dr. Michael Dorr (CTO, Adaptive Sensory Technology) provided the test equipment for assessing the contrast sensitivity and assisted with some aspects of data analysis. Part of the data from this research was also used to write a manuscript, which was submitted and has been accepted for publication.

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Dr. Kristine Dalton designed the study and Amritha Stalin contributed to the study design. The data collection was completed by Amritha Stalin and Dr. Kristine Dalton, and the data analysis was conducted by Amritha Stalin with assistance from Dr. Kristine Dalton.

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Information presented in Appendix A to C:

Amritha Stalin designed the 'Ocular Health and Skiing Experience Questionnaire' in the Appendix A, under the guidance of Dr. Kristine Dalton. Appendix B and C contains detailed descriptions on the simulated vision impairments and some of the results for the studies described in Chapter 2, written by Amritha Stalin under the supervision of Dr. Kristine Dalton.

Information presented in Appendix D:

The 'Developmental History Questionnaire' presented in Appendix D was provided by Dr. David Mann and Dr. Rianne Ravensbergen at Vrije Universiteit, Amsterdam for the classification research studies described in Chapter 3 and Chapter 4.

Information presented in Appendix E:

Appendix E includes information on the rescored VF data and the results of the repeated analysis using the rescored data of the Para nordic and Para alpine studies described in Chapter 3 and Chapter 4. The protocol for rescoring the VFs was provided by Dr. David Mann and Dr. Rianne Ravensbergen. Amritha Stalin rescored the data and repeated the analysis under the supervision of Dr. Kristine Dalton.

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Abstract

Introduction

The Paralympic Games are not only a platform for athletes with disabilities to achieve their dreams, but the Games also play a major role in changing societal attitudes towards people with disabilities and accelerating the progress towards achieving a goal of equality for all. Classification plays a significant role in making Paralympic competitions fair for all athletes. The overall purpose of the studies described in this thesis was to design evidence-based classification systems for the visually impaired category of Para nordic and Para alpine skiing. The specific objectives of the thesis were four-fold. The first and second objectives were to determine a minimum disability criterion that determines eligibility for competition and to develop additional criteria that group athletes with similar impairments into competition classes, respectively, in both Para nordic and Para alpine skiing. The third objective was to investigate the effect of the use of blindfolds on the skiing performance of Para skiers in the most severe visual impairment class, as the Paralympics rules currently mandate the use of blindfold by those skiers in Para nordic and Para alpine skiing. The final objective was to assess the validity of visual field measurements conducted with the Arc perimeter, which was the perimeter used in all the previously mentioned studies.

Experiment I

Eight visual acuity and contrast sensitivity impairments and six peripheral visual field impairments were simulated in able-sighted skiers who participated in the study. The visual acuity, contrast sensitivity, and visual fields of each participant were assessed with and without the simulated impairments. The participants raced through specially designed short nordic or alpine racecourses with and without the simulated impairments and the changes in the race times with and without the simulated impairments were analyzed to identify the minimum levels of vision impairment that significantly affected skiing performance. These studies suggested that moderate reductions in visual acuity, contrast sensitivity, and visual field appear to have significant detrimental effects on nordic and alpine skiing performance.

Experiment II and III

A wide range of visual functions such as static and dynamic visual acuities, light sensitivity, glare sensitivity, glare recovery, contrast sensitivity, translational and radial motion perception, and visual

field was assessed binocularly in elite Para nordic and Para alpine skiers who participated in the studies. The relationships between skiing performances, which were calculated using modified Para nordic and Para alpine skiing points systems based on participants' raw times, and the levels of visual functions assessed were analysed 1) to identify the visual functions associated with skiing performance (Experiment II) and 2) to develop sports class allocation criteria (Experiment III). It was concluded that VA and VF are the only visual functions that need to be included in classification. It was also concluded that Para nordic and Para alpine skiers with light perception or no light perception vision performed significantly worse compared to the skiers with measurable vision, and thus should be allocated to a different class than participants with measurable visual acuity.

Experiment IV

Participants, who were elite Para nordic and Para alpine skiers, were asked to ski specially designed short nordic or alpine courses with and without their blindfolds in randomized orders. Time taken to complete the courses were compared between the two blindfold conditions to assess the effect of the blindfold on skiing performances. Results from these studies suggested that the blindfolds do not significantly affect performances in Para nordic and Para alpine skiers who are eligible to compete in the B1 class and that blindfolds need not be mandatory in both the sports.

Experiment V

Visual acuity and visual fields were assessed binocularly in adult participants with monocular or binocular visual field defects. The functional visual field scores obtained using an Arc perimeter were compared with the functional visual field scores obtained using a Humphrey Field Analyzer, and the agreement between both methods was assessed using Bland-Altman plots to assess the validity of the visual field measurements obtained using Arc perimeter. This final study concluded that the functional scores obtained using an Arc perimeter could be used as an efficient and feasible way to assess visual fields for classification research purposes.

Conclusion

The results from these studies provide evidence to support the development of sport-specific classification systems for the vision impairment category in both Para nordic and Para alpine skiing. The decision to change, or not change, the Para nordic and Para alpine skiing classification regulations for athletes with vision impairments remains at the sole discretion of the International Paralympic Committee.

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Dedication

This work is dedicated to all the people in my life who encouraged me throughout my studies and life, especially my parents, who are eternal sources of unconditional love, my brother who always holds my hand even for some of the craziest things that I do, my husband, who put his career ambitions on hold so that I can achieve my dreams. I am truly thankful for having you all in my life.

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List of Abbreviations

AMA – American Medical Association
ANOVA – analysis of variance
AULCSF – area under the log contrast sensitivity function curve
BRVT – Berkeley Rudimentary Vision Test
CI – confidence interval
CS – contrast sensitivity
CSF – contrast sensitivity function
DH – downhill
ETDRS – Early Treatment Diabetic Retinopathy Studies
FIS – International Ski Federation
GLR – glare recovery
GLS – glare sensitivity
GS – giant slalom
HFA – Humphrey Visual Field Analyzer
II – intellectual impairment
IPC – International Paralympic Committee
LP – light perception
LS – light sensitivity
MDC – minimum disability criteria (also known as minimum impairment criteria)
NLP – no light perception
PI – physical impairment
PWG – Paralympic Games
RMP – radial motion perception
ROC – receiver operating characteristic curve
SC – super-combined
SD – standard deviation
SG – super-G
SL – slalom
SPSS – Statistical Package for the Social Sciences
TMP – translational motion perception (TMP),
VA – visual acuity
VF – visual field
VI – visual impairment
WC – World Cup
WCH – World Championships
WPAS – World Para Alpine Skiing
WPNS – World Para Nordic Skiing

Chapter 1
Literature Review and Objectives

This chapter includes brief descriptions of the Paralympic movement, the classification systems, and the Para sports for the athletes with visual impairment, laying out the background for the thesis. It also provides an introduction to the sports of nordic and alpine skiing and the techniques and visual demands involved in them.

1.1 Literature Review

1.1.1 Paralympics

The modern Paralympic movement started in the 1940s when Dr. Ludwig Guttman began promoting sports participation as an innovative means of rehabilitation at the Stoke Mandeville Spinal Injuries Unit, England. Sixteen participants from two rehabilitation facilities participated in the first Stoke Mandeville Games on the opening day of the 1948 Olympic Games in London. The popularity of the Stoke Mandeville Games continued to grow, attracted international participation, and the first Paralympic Games took place in 1960 in Rome, using the Olympic venues.[1,2,3] Since then, the Paralympic Games inspire and encourage individuals with disabilities to participate in sport and become athletes. In turn, these newly inspired athletes develop good training habits, including self-discipline, become more physically fit, and experience the feeling of belonging that comes with being part of a team, as well as the satisfaction of overcoming obstacles and achieving their goals in the sport.[4,5]

There are three eligible impairment categories in the Paralympic Games: physical impairment (PI), visual impairment (VI), and intellectual impairment (II). VI was included as one of the eligible impairment categories in 1976.[6] Each of these categories includes athletes with a wide range of impairments, and if all those athletes compete against each other within their category, athletes with less severe impairments could be at an advantage compared to the athletes with more severe impairments. To ensure competition is fair and to encourage increased participation of athletes in the Paralympic Games, the International Paralympic Committee (IPC), which is the global governing body of Paralympics, classifies athletes based on their level of impairment.[6,7]

1.1.2 Classification systems in the Paralympics

The initial classification systems used in Paralympics were based on medical diagnoses. According to these systems, athletes were classified based on the clinical grading of their medical condition (e.g., level of spinal code injury, level of amputation, or visual field extent), but these systems do not necessarily consider if the athletes' respective sports performance is affected by the impairment.[6] Besides, the initial classification systems did not take into account the unique physical and intellectual demands of each sport. The impact of an amputated hand on an athlete's performance on a sport that requires upper body strength (e.g., archery or rowing) will be greater compared to another sport, which demands lower body strength (e.g., athletics or cycling). Likewise, in the VI category, athletes with peripheral visual field loss might have more difficulty in a sport that has peripheral vision demands (e.g., skiing or table tennis) compared to a sport that has only central vision demands (e.g., shooting or track athletics). Thus, it was recognized within the Paralympic community that valid classification systems based on the level of impact of the impairment on sports performance must be designed to make the sports competitions fair. As a result, medically based classification systems slowly transitioned into sports-specific functional classification systems in the 1970s, especially in the PI and II categories.

Functional classification systems were designed to allocate athletes to classes based on the extents to which an impairment affects an athlete's sports performance. Based on their functional classifications, athletes with varying diagnoses might be able to compete in one class if their impairments affect performance in that particular sport similarly. For example, individuals having loss of leg function from above knee level due to spinal cord injuries and amputations might have the same activity limitation during a wheelchair sport. Even though the functional classifications developed for the PI and II categories were sports-specific, they were based on expert opinion and lacked the support of scientific evidence. The need for evidence-based functional classification systems instead of the medical and functional classification systems based on expert opinion, was first described in the Athlete Classification Code published by the IPC in 2007.[8] Following this, Tweedy and Vanlandewijck[7] published a Position Stand to describe the scientific methods to adopt while designing classification systems. The IPC classification code mandates that each Paralympic sports must develop its own evidence-based classification system.[9] The Position Stand clearly defines the purpose of classification and details the guidelines for designing evidence-based classification systems.[7]

The purpose of a classification system is to "promote participation in sport by people with disabilities by minimizing the impact of impairment on the outcome of competition".[7] The International Classification of Functioning, Disability, and Health (ICF) defines impairment as any "problem related to body function or structure of individuals such as significant deviation or loss".[10] Thus, to achieve the purpose of classification, researchers should identify measures of impairment that are valid, reliable, and resistant to training. In addition, sport-specific and standardized measures of sports performance should also be identified to assess the relationship between impairment and performance. Analyzing the strength of the associations between measures of impairments and measures of performance will help in defining the eligibility criteria as well as in identifying the sports classes.

Eligibility criteria, known as the minimum impairment criteria or the minimum disability criteria (MDC) define the level of impairment at which athletes have a disadvantage in sports performance compared to able-bodied athletes despite having other favourable physiological and psychological characteristics. Sports classes are groups to which each athlete will be allocated such that within each class, the athletes have comparable levels of impacts of impairments on sports performance.[11]

1.1.3 Sports for individuals with visual impairment in the Paralympics

There are a total of 28 sports in the Paralympics, out of which 14 sports, including nine Summer Games sports and two Winter Games sports, allow participation of athletes with VI.[12] All the VI sports, except shooting Para sport, use the same criteria, set by the International Blind Sports Federation to determine the eligibility and sport classes of athletes. While the different sports all use the same criteria, some sports such as football 5-a-side, goalball, Para judo, Para cycling, Para equestrian, Para rowing, and Para triathlon have additional sport-specific rules about either eligibility or sport classes (Table 1-1).

1.1.3.1 Current classification criteria for VI sports

For all the VI sports excluding shooting Para sport, Para equestrian and football 5-a-side, athletes are eligible to participate in a Paralympic event if their best-corrected visual acuity (VA) is worse than or equal to 1.0 logMAR and/or their visual field (VF) radius is less than or equal to 20 degrees in the better eye. Once determined eligible, athletes are further divided into three classes for competition. The class with most severe impairments (B1) consists of athletes with quantifiable static VAs worse than 2.6 logMAR as well as athletes with and without light perception vision. Athletes with static VAs ranging from 1.5 logMAR to 2.6 logMAR or a VF radius of less than or equal to 5 degrees are classified into the moderate severity (B2) class. The class with the least severe impairments (B3) includes athletes with static VAs ranging from 1.0 logMAR to 1.4 logMAR or a VF radius of less than or equal to 20 degrees.[8]

Goalball and football 5-a-side are exclusive VI sports first introduced in 1976 and 2004, respectively. Goalball is played by two teams of three players who try to throw a three-pound goalball that is embedded with bells into the opposite goal and score points.[13] Athletes in B1, B2, and B3 classes are eligible to participate in goalball, however in this sport all athletes must wear blindfolds to participate, thus there is only one sport class for competition. Football 5-a-side is a Para sport exclusive for athletes with the most severe VI (B1) class only. It is played with four B1 outfield players who wear blackout masks and one fully sighted or partially sighted goalkeeper along with a coach and another guide in each team.[14] Like goalball, there is only one sport class for competition in football 5-a-side.[15,16]

In Para judo, athletes in B1, B2, and B3 classes compete in weight categories rather than vision impairment categories for competition, so again there is technically only one VI sport class in judo.[17] In Para cycling, all athletes ride tandem bikes with a sighted guide and compete in a single class.[18] In Para equestrian, B1 and B2 athletes are eligible to compete, but compete for separate medals in different functional categories where they are combined with athletes with physical impairments for competition.[19] Athletes classified as B3 can only compete in Para equestrian if they have an additional physical impairment that also impacts their riding performance. Para rowing lets all athletes with VI compete together for one medal as one class, which also includes athletes who have residual function in their legs that allows them to slide the seat. Finally, in Para triathlon, B1, B2, and B3 athletes compete as one class with the mandatory aid of a guide, and similar to Para cycling, all athletes ride a tandem bike for the bike segment. All Para triathlon B1 athletes are required to wear blackout glasses during all segments of the triathlon, and the final times of B2 and B3 athletes are equally factored by about 3 to 4 seconds.[20]

Shooting Para sport implemented a new evidence-based classification system with modified criteria for eligibility and class allocation in February 2019.[21] The modified MDC, accepted and implemented by the IPC in February 2019 states that an athlete is eligible to compete in shooting Para sport if their static VA is poorer than or equal to 1.1 logMAR or their static VA is between 0.6 and 1.0 logMAR and their contrast sensitivity (CS) is poorer than or equal to 1.4 logCS. Athletes all compete as one class in the shooting Para sport according to the new rules.[21]

1.1.3.2 Modifications used in Paralympic VI sports

Most Paralympic sports use modifications compared to their able-bodied counterparts to ensure safe participation by athletes with impairments. These modifications could either be in the form of assistance (or assistive devices) or rule changes. For example, in VI sports, sighted guides are allowed in many sports to assist with the orientation and mobility issues that the VI Para athletes might face while performing sports that require moving around in environments with speed and accuracy (e.g., Para skiing, Para swimming). These guides are responsible for safely leading the athletes through competitions. Thus, the presence of guides enables the performance of athletes in such sports in a safe manner.

One other significant modification in some of the Para sports is the mandatory use of blindfolds or eyeshades in some VI sports (e.g., blackened goggles in Para swimming, opaque goggles in Para alpine and Para nordic skiing). Rules regarding blindfolds were developed as an effort to equalize the impact of athlete's impairments within the B1 class and ensure that athletes who were totally blind were not at a disadvantage to other athletes in the B1 class who had some residual vision, thereby eliminating the need for further classification.[22,23] The inside of the blindfolds or eyeshades must be completely black, and the athlete should not be able to see any light while wearing the goggles.[22] The use of blindfolds varies between sports and different sport classes. In most sports, use of blindfolds is mandatory only for athletes in the B1 class (e.g., Para nordic and Para alpine skiing, Para swimming).[24–26] However in goalball and football 5-a-side, all athletes (except the football goalkeeper) are required to wear blindfolds.[16, 15] A summary of all the VI sports and the specifics of the classification systems used in each of them are provided in Table 1-1.

Table 1-1: Summary of Paralympic VI sports, the classification systems used, individual competition events, and the rules regarding guides and blindfold.

Sport	Eligible VI Classes	Use of factor system	Individual events	Use of guides	Use of blindfold
Alpine skiing[24]	B1, B2, & B3	FIS nordic formula	Downhill Giant Slalom Super G Slalom	B1, B2, & B3 -- Obligatory	Class B1
Athletics[27]	B1(T/F11), B2 (T/F12), & B3 (T/F13)	Raza Point Score System	Throwing events Jumping events Running events	T/F11, T/F12 – one T/F11 – two, T/F12 - one T/F11 – one or two T/F12 - one	Class B1
Cycling[18]	B1, B2, and B3	No factor system. All VI athletes compete together	Tandem	B1, B2, & B3 -- Obligatory	None
Equestrian[19] Mixed Gender	B1 (Grade III) & B2 (Grade II)	No factor system. Separate medals in each class	Dressage	B1 & B2 – Obligatory	Class B1
Football5-a-side [15]	B1	No factor system	No separate events	3 sighted guides, Obligatory	All athletes
Goalball[16]	B1, B2, and B3	No factor system. All VI athletes compete together	No separate events	No guides	All athletes
Judo[17]	Classified based on weight	No factor system	No separate events	No guides	None
Nordic skiing[22]	B1, B2, & B3	FIS nordic formula	Cross-country skiing Biathlon	B1 (Obligatory) B2 & B3 (Optional)	Class B1
Rowing[28]	B1, B2, & B3	All VI athletes compete together	Single sculls	No guides	All athletes[29]
Shooting[21]	One (new MDC and class allocation criteria)	No factor system	10m Air Rifle Standing Prone	All athletes - loading assistant, Obligatory	None
Swimming[30]	B1 (S11), B2 (S12), & B3 (S13)	Factor system	Freestyle Backstroke Butterfly Breaststroke Medley	All athletes - assistant (tapper), Obligatory	Class B1
Triathlon[20]	B1 (PTVI 1), B2 (PTVI 2), & B3 (PTVI 3)	B2 and B3 factored equally. All VI athletes compete together	PTVI	All athletes – guides, Obligatory	Class B1

1.1.4 Evaluation of current VI classification system

Even though the current classification system has been used since the inclusion of VI sports in the Paralympic Games, there is no previous research (except in shooting Para sport) that the chosen levels of letter-chart acuity or VF extent affect performance in any of the VI sports. In addition, the current classification criteria do not take the unique visual demands of each sport into consideration. Ravernsbergen et al.[31] conducted a four-round Delphi study to identify the classification research priorities in the VI category. Twenty-five participants who were experts in VI sports, such as coaches, athletes, classifiers and/or Paralympic sports administrators participated in the study, which concluded that there is strong support within the Paralympic movement to change the current VI classification system. The study participants believed that the new VI classification systems should be sport-specific and supported by research evidence to ensure fairness of competition. The majority of the participants also felt that the current classification procedures for athletes with VI do not entirely fulfil the purpose of classification.[31]

Based on this study, the highest priorities within the VI sport classification research were: (1) to establish the most appropriate measures of visual function to be used during classification and (2) to establish MDC specific to each sport. Suggestions for additional measures of visual functions to be included in the classification were: contrast sensitivity (CS), dynamic VA, light sensitivity, colour vision, depth perception, and reaction time.[31]

Regarding the modifications used in VI sports, there was no consensus on the mandatory usage of blindfolds in some VI sports. The majority of the panellists (96%) agreed that it is not appropriate for all athletes to wear blindfolds; however, 77% of the panellists felt that wearing blindfolds might be required in some sports or some situations. Some experts argued that an athlete with some amount of vision or light perception might have an advantage over athletes with no light perception. Others argued that the athlete’s limited remaining vision could impair the athlete’s performance by distracting the athlete from the auditory information provided by the guide.[31] The role played by blindfolds on the performance of an athlete could be sports-specific, and should be confirmed by controlled observations.

1.1.4.1 Guidelines on designing sport-specific classification for athletes with VI

The IPC Athlete Classification Code (published in 2007, revised in 2015), along with the Position Stand, detailed the necessary guidelines to design classification systems.[8,9,7] However, these guidelines were focused on the needs of the PI and II categories. Mann and Ravensbergen[32] published a Joint

Position Stand on the sport-specific classification of athletes with VI to provide guidelines on research approaches to design evidence-based classification systems by taking unique adaptations and characteristics of VI sports into consideration.[32]

The Joint Position Stand recommended that all the visual functions that could affect performance in a particular sport should be considered while designing the test battery for the classification research. Currently, static VA and VF of the best eye are the only visual function measures considered for VI classification. The athletes may have impairments in other visual functions such as CS or colour vision, which could also negatively affect sports performance. While the IPC Classification Code, as well as the Position Stand, recommended the use of functional vision tests while choosing the test battery for classification, the Joint Position Stand pointed out that the performance of athletes on functional vision tests could be improved by training, and thus, cannot accurately represent the impact of impairment. Thus, generic tests of visual function such as static VA and CS testing using letter charts, or VF testing using a perimeter are still suitable for classification purposes. The MDC should be designed based on the athletes' performance on non-adapted forms of the sport. However, since the use of guides enhances the performance of athletes, all the adaptations and modifications used in the sport (e.g., use of guides and blindfolds) must be considered while deciding the sports classes.[32]

The Joint Position Stand also recommended that procedural changes might be required to make the testing more representative of the sports performance environment. For example, if the athlete performs the sport with both their eyes open and using the visual input for both the eyes, the testing should also be conducted binocularly (e.g., skiing or swimming). In addition, the lighting conditions during the sports performance should also be considered while designing the test battery as athletes with some eye conditions (e.g., albinism) might have increased difficulty adapting to changing lighting conditions compared to other athletes. Thus, testing the athletes' visual functions at varying light levels might be necessary to understand the impact of that impairment on sports performance.

To summarize, the Joint Position Stand recommended steps while designing evidence-based classification systems for VI sports are: 1) identifying vision aspects predictive of sports performance; 2) defining the sports classes (including the MDC), and 3) identifying the sport class boundaries. The vision aspects predictive of sports performance could be identified based on the existing literature and expert opinion. A vision test battery for further research should include accurate and feasible visual function tests (e.g., letter-acuity chart, D-15 colour vision test) that are proven to measure these visual aspects. They also recommended models that could be adopted in classification research. A correlation model could be used to identify the visual functions that are predictive of sports performance, comparing the visual function measures and the performance measures using correlation and regression analyses. Further analysis methods such as clustering or regression trees on this data could help to define and identify sports classes. Finally, a simulation model could help to identify the level of minimum impairment that starts to impact sports performance while simulating a range of visual functions in able-sighted skilled athletes.

1.1.5 Progress in VI classification research

Since the publication of the Classification Code and the Position Stand, there has been extensive research conducted towards developing evidence-based, sports-specific classifications, especially in VI sports. An evidence-based classification system was developed for shooting Para sport in 2019, and there have been research initiatives in Para alpine and Para nordic skiing (presented in this thesis), Para swimming, Para judo, and Para athletics towards designing such classification systems.[21,33–36]

1.1.5.1 Shooting Para sport

Shooting Para sport is performed with the help of aiming devices, guiding shooters by emitting sound according to the proximity of the aim to the target. Myint J et al.[37] reported that as the athletes rely on the auditory information for targeting, the severity of the VI did not affect rifle-shooting performance. They concluded that one competition class was sufficient for fair competition in the shooting Para sport VI category.[37] Further studies were conducted by simulating static VA and CS impairments on elite able-sighted shooters to determine the MDC for shooters, which revealed that moderate reductions in static VA and CS (poorer than 0.50 logMAR and 0.80 logCS) were associated with reduced shooting performance in the non-adapted or able-sighted form of the sport.[38,39] Based on the results from these studies, a new MDC was developed that included both static VA and CS.

As mentioned previously, the modified MDC, accepted and implemented by the IPC in February 2019 states that an athlete is eligible to compete in shooting para sport if the SVA is poorer than or equal to 1.10 logMAR or SVA between 0.60 and 1.00 logMAR (inclusive) and a CS poorer than or equal to 1.40 logCS. Athletes all compete as one class in the shooting Para sport according to the new rules.[21]

1.1.5.2 Para swimming

Swimming has been part of the Paralympics since the 1960 summer Paralympic Games in Rome, Italy. Swimmers with VI are allowed to have guides who tap them to let them know when they are close to the end of the pool so that they can safely make a turn. Currently, within the most severely impaired category (S11), athletes swim with blackened swim goggles. It was reported that the degree of visual impairment might not be the most predictive factor of swimming performance as Para swimming performance depends on various forms of feedback such as proprioception, vestibular contributions, and instructions from guides or coaches as direct sources of information, in addition to visual information.[40] Malone et al.[41] analysed the swim performance data at the 1996 Paralympic Games, and reported that the swimming performances of athletes in B2 and B3 classes are similar, and are different from that of athletes in B1 class. Similar findings were reported by the documentary research of Souto[42] and by the video race analysis by Daly et al.[43] on the London 2012 and the Sydney 2000 Paralympic games respectively.

Most recently, a three-round Delphi study was conducted with 16 Para swimming experts who are either athletes, coaches, administrators, or scientists to understand the expert opinions about, and requirements for Para swimming classification. The panel agreed that the current system is not efficient and that additional vision assessments such as depth perception and CS should be explored in addition to the static VA and VF assessments. The panel also identified swimming performance measures that could be used for classification research.[34] Currently, there is extensive research being conducted on designing evidence-based classification systems for Para swimming, however, no published research is currently available specific to the MDC or sports classes.

1.1.5.3 Paralympic judo

Judo is a combat sport and is the only martial art within the Paralympic Games, first introduced in 1988. In VI Paralympic judo, judokas start the fight holding onto each other with both hands, unlike starting a few meters apart as in the able-bodied version of the sport. Based on the assumption that starting the fight having a grip on each other eliminates the need for having visual information to succeed in the fight, judokas are divided into classes based only on their weight, and within each weight category, the athletes compete as one class without using blindfolds. Krabben et al.[44] reported that this assumption might not be right since the number of medals won by the B1 athletes was significantly lower compared to that of the B2 and B3 athletes. They also reported that wearing a blindfold significantly affected able-sighted athletes' performances, when fighting against another able-sighted athlete who was not wearing a blindfold even if the fight started with a grip on each other.[44]

A three-round Delphi study was conducted with 18 Paralympic judo experts who were either athletes, coaches, administrators, referees, or classifiers to identify the research needs in Para judo. This study concluded that the current classification criteria in Paralympic judo do not adequately fulfill the aim of classification and that the measures of vision function affecting judo performance must be identified. There was also consensus that the testing should be binocular using the best correction that the athlete has and that the MDC for judo needed to be revisited. There was no consensus on the issues related to the use of blindfolds.[45,35,46] Current research in Para judo is focused on identifying the MDC and determining the allocation of classes.

1.1.5.4 Para athletics

Para athletics is one of the most popular summer Paralympic sports and includes multiple running events which differ in terms of distance, as well as jumping and throwing events. Grogg and Johnson[47] reported statistically significant differences in the 100 m sprint average finish times among the three VI sports classes at the 1996 Atlanta Paralympic Games. The average finish times were quicker in athletes with lesser impairments compared to the athletes with severe impairments.[47] There have been attempts to identify factors predicting sprinting performance of athletes with VI and one study reported that 66% of sprint performance variance was explained by the performance on vertical jump tests.[48]

A recent three-round Delphi study involving a panel of 17 VI track athletics experts identified the central VF as one of the visual functions essential for track athletics and also identified performance measures that could be included in the classification research. There was consensus that the current classification system in track athletics does not fulfill the aim of classification, as well as that the age of impairment acquisition should be considered as a variable in classification research. The experts also suggested that the MDC should be at least as severe as it is presently and that there should be more than one sports class. There was also consensus that the vision assessments are to be conducted when using both eyes together and with the best optical correction worn. There was no consensus on the issues related to the use of guides or the efficacy of the current classification system.[36]

1.1.6 Para skiing

The two winter Paralympic sports are nordic skiing and alpine skiing. Both Para nordic and Para alpine skiing are highly dynamic sports. Nordic skiing includes the cross-country skiing and biathlon disciplines; biathlon combines rifle shooting and skiing. Para nordic skiing has four individual competition events: sprint, short distance, middle distance, and long-distance. The main individual disciplines within Para alpine are downhill (DH), super-G (SG), super-combined (SC: DH/SG & 1SL Run), giant slalom (GS), and slalom (SL).

1.1.6.1 Visual demands in Para nordic and Para alpine skiing

Both Para nordic and Para alpine skiing have vision demands at far distances, often at more than 3m. Skiers have to process visual information, either to identify boundaries and follow the course or to avoid obstacles, often while moving at high speeds. Skiers need to identify the exact direction or position of obstacles such as gates, trees, or fellow skiers to navigate safely through the terrain. They also have to make quick decisions and vary their speed, direction, or body position based on visual feedback. The visual complexity of skiing was confirmed by a recent study of alpine skiers.[49] Elite alpine skiers self-reported a total of 23 visual cues related to gates, slope/ terrain, or background that they look for in their environment while skiing. The major reported cues related to the gates were 1) oncoming gate, 2) gate after next, 3) current gate, 4) outer gate, and 5) the last gate of a curve. The slope or terrain related cues were 1) initiation of the turn, 2) pole, 3) blue line, 4) slope, 5) take-off point, 6) curve, 7) distinctive holes and bumps, and 8) remarkable transitions. It is also interesting to note that the alpine skiers reported that they tried to look one to two gates ahead, and their gaze often jumped between the current gate, the next two gates and the slope, especially in the technical events. Skiers reported that the blue-coloured markings (blue lines) on the left and right side of the slope in speed disciplines help them to orient, especially in fog or shadow. The background cues that a few skiers reported to use for orienting themselves were forest, mountains, or houses.[50]

Identifying the above-mentioned visual cues would require the skiers to have good VA and depth perception while they are static, as well as while moving. Senner et al.[51] reported that a 20% decrease in static VA could significantly affect the reaction times of leisure skiers to smaller and low contrast objects such as ice patches, even though their reaction times to larger obstacles such as standing or moving skiers were not affected. Senner et al.[52] also reported that static VA and depth perception are vital for skiers to recognize potential danger spots on the ski slopes.

Identifying the hill contours and slope characteristics while skiing involves processing of subtle differences in contrast along with other visual information. In addition, the skier's motion and reduced visibility due to extrinsic factors related to weather, lighting, or snow conditions reduces the relative contrast of the visual information, causing an increased demand on contrast processing.[53] Thus, CS might be another visual function that could have an impact on skiing performance. Since the skiers also have to adjust their speed and direction based on the slope and distance judgments, the judgment of depth might also be crucial in skiing.[53]

Finally, dynamic and reactive sports like skiing need the athlete to have balanced central and peripheral visual attention.[53] Unlike team sports, skiing may depend more on central visual information to determine the timing of responses or the most advantageous path. However, the visual space, which the skier needs to process, is typically larger than most of the other sports like tennis or swimming, which suggests that there are also peripheral vision demands while skiing. One of the earliest studies conducted on SL skiers in 1955 reported that while occlusion of central vision caused minor difficulties of motor control, occlusion of peripheral vision caused marked deterioration in skiing performance; skiers with occluded peripheral vision had difficulty in following the course and judge distances.[54]

Although nordic and alpine skiing are similar in terms of the challenging environments in which they take place, and the high demands the sports place on vision, the sports are different in terms of terrain and skiing techniques. Nordic skiing is practiced on flatter terrain with gently rolling undulating hills and tracks are often narrow and grooved, while alpine terrains are steeper with sharp changes in direction. Nordic courses tend to be longer than alpine courses, thus nordic skiing requires sustained visual and physical performance for a longer time compared to alpine skiing, which is completed in much shorter durations. The visual demands during the competition could be higher in alpine skiing (albeit for a short durations) due to the relatively higher speed of alpine compared to nordic.[53] Due to these differences in variations in the visual tasks involved in these sports, the visual functions associated with performance, and the impairment levels affecting the sports performance could vary between nordic and alpine skiing.

1.1.6.2 Modifications used in Para nordic and Para alpine skiing

Para nordic and Para alpine skiing use various kinds of modifications and assistance to make the sports competitions safer for athletes with VI.[8] In Para nordic skiing, the use of guides is optional for athletes in B2 and B3 categories, whereas it is obligatory for athletes in the B1 class. All Para alpine skiers are required to use guides during competitions. A guide's responsibility during the competition is to ski ahead of the skier and to continuously give verbal instructions while keeping a proper space between the skier and the guide (the guide and skier should not have physical contact). The guides give detailed directional voice commands to the skiers regarding the terrain and ski courses such as the position of a slope, the size of a turn, or bumps in the course. Most guides use voice-activated speakers or personal two-way radios to improve the voice clarity and to reduce the need to shout while skiing.[55] The run time of the guide is neither recorded nor considered during a competition. The finish time of the athlete is determined to 1/100 precision (e.g., 3:22.38). It is mandatory for skiers in the B1 class to wear a blindfold when they ski in competition in both Para nordic and Para alpine skiing.[56]

A percentage is assigned to each class, and skiers raw race time is "factored" or multiplied by the assigned percentage to come up with an adjusted race time that will be used to determine the overall results of the race.[22] The Para nordic skiing percentages assigned since 2016/2017 season for B1, B2, and B3 are 88, 99, and 100, respectively, and are the same for all events (sprint, short distance, middle distance, and long-distance).[57] The Para alpine skiing percentages assigned for B1, B2, and B3 in various disciplines are calculated separately for each discipline, and the percentages assigned during the 2016/2017 season are given in Table 1-2. In both sports, the percentages are determined by the Sports Technical Committees and are re-evaluated after every season if needed.

Table 1-2: Para alpine skiing percentages for the 2016/2017 season.

Sport class	DH	SG	GS	SL
B1	0.61	0.61	0.60	0.59
B2	0.88	0.88	0.88	0.83
B3	0.92	0.92	0.91	0.87

1.1.6.3 International competitions for Para nordic and Para alpine skiing

World Para Nordic Skiing (WPNS) and World Para Alpine Skiing (WPAS) are the international federations for Para nordic skiing and Para alpine skiing, respectively. The major international competitions conducted under the guidelines of WPNS and WPAS are the Paralympic Winter Games, World Championships, World Cups, European Cups, WPAS North American Cups, and WPAS Continental Cups.

1.1.6.4 Course characteristics in Para nordic skiing

The WPNS competitions take place on valid homologated courses. The typical skiing distances for Para Nordic individual events vary from 800 m to 20km (Table 1-3). In any Para nordic course, the first 50m is the start zone, the final 50 to 100m is the finish zone, and in between is the course.

Table 1-3: Para nordic skiing events and the racecourse distances.

Competition	Gender	Total distance
Sprint - Qualification	Men & Women	0.8km (+/-200m)
Sprint - Finals	Men & Women	1.2km (+/-400m)
Short	Men	5km
	Women	2.5km
Middle	Men	10km
	Women	7.5km
Long	Men	20km
	Women	15km

The skiers use either classic technique or freestyle techniques to ski. The techniques that skiers are required to compete with alternate annually and will alternate from PWG to PWG and from WCH to WCH. A typical nordic course for classic style skiing will be 3m wide, with two tracks that are at least 1.2m apart. A typical course for freestyle skiing will be 6m wide, with one track on the side. A course designed for both classic and free techniques will be 9m wide with two tracks on the side. Since multiple skiers participate simultaneously in a sprint event, the minimum width of a typical sprint course could be 6m to 12m, and the course will have no sharp corners. In all these types of Para nordic courses, the finish area will be 12m in width. For all Para nordic disciplines except the sprint finals, real race times are recorded for each skier, multiplied by their percentages according to their classification, and the calculated time is displayed on the scoreboard. The results are calculated by order of finish for the sprint finals.[25]

1.1.6.5 Course characteristics in Para alpine skiing

WPAS competitions also take place on valid homologated courses. Slalom is a technical event over a shorter course than other events but with a higher number of gates that the competitor must negotiate. Slalom is completed in two runs on two different courses. Giant slalom is another technical event with two runs on a longer course and fewer gates than SL. In both SL and GS, the number of gates is determined by the vertical drop of the course, and if a competitor misses a gate, they are disqualified. Downhill is a speed event with the longest course, which is completed either in one run or two depending on the vertical drop of the course. Super G is another speed event where competitors complete one run down the course with their finish time determining the final order based on ascending time. Super G courses are generally shorter than DH but longer than SL and GS. The terrain should preferably be undulating and hilly in both GS and SG courses compared to SL courses, which are shorter and DH courses, where steepness is a priority. If a discipline event consists of two runs on the same day, times from both the runs are added together to determine the final order based on ascending total time. The recommended course characteristics of all the different Para alpine disciplines are listed in Table 1-4, and the gate characteristics in each discipline are depicted in figure 1-1.

Table 1-4: Para alpine skiing discipline, course characteristics, and number of runs. * denotes that this information was not available in the IPC website or published reports.

Discipline	Vertical drop	Gate characteristics	Width of gates	Distance between gates	No. of runs	Course Width
DH	450-800m	4 SL poles, 2 gate panels	8m	*n/a	1 or 2	*n/a
SG	400-600m	4 SL poles, 2 gate panels	6m to 8m	8m to 12m	1	30m
GS	300-400m	4 SL poles, 2 gate panels	4m to 8m	Greater than 10m	2	40m
SL	140-220m	2 poles	5.5m to 6.5m	9m to 13m	2	*n/a

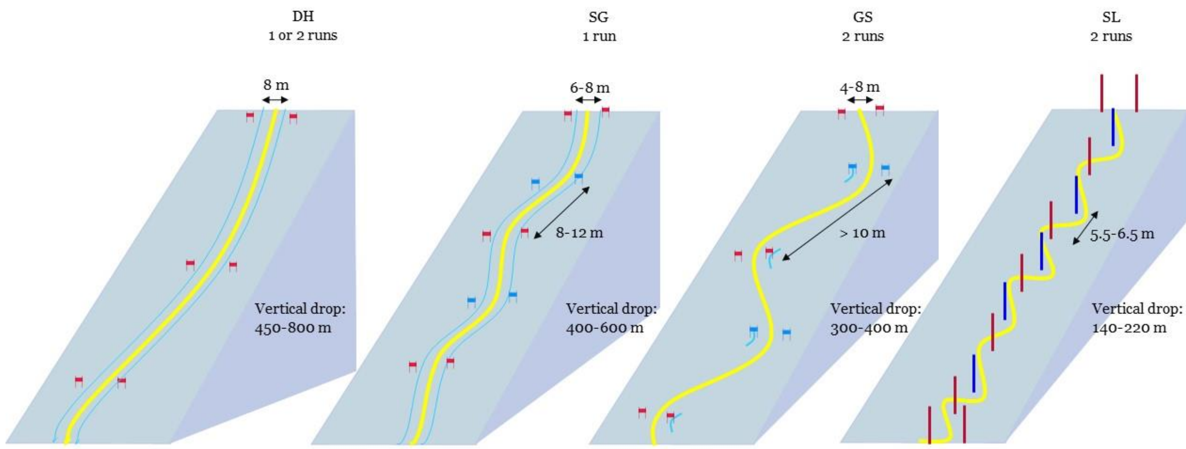

Figure 1-1: Gate and slope characteristics of the different Para alpine skiing disciplines. Figure drawn and modified by the author based on an image and information found in the World Para Alpine Skiing Rules and Regulations.[58]

1.1.6.6 Classification research in para nordic and para alpine skiing

After the 2015 VI classification experts meeting hosted by the International Blind Sports Federation (Amsterdam, Netherlands), the research team from the Vision & Motor Performance lab at University of Waterloo made observations at the 2015 Para alpine World Championships (Panorama, Canada), and asked Para alpine athletes, coaches, team members, classifiers, and administrators about the concerns and issues with the classification; based on these discussions research priorities were identified. Issues with Para Nordic skiing classification were discussed with classifiers and sport administrators initially, and later with members of the sport during the preliminary studies conducted in the 2015-2016 season. According to expert opinion, the current classification system did not account for the dynamic nature of the sports or for the wide variety of vision impairments that the athletes had. It was felt that an ideal classification system would include tests to mimic the dynamic nature of the sports and would account for the wide array of vision impairments in the sport.[59]

Following these surveys, preliminary studies were conducted to identify what visual aspects that could be measured in Para nordic and Para alpine skiers. Creese et al.[60] reported that a variety of visual functions, including static VA, CS, dynamic VA, low contrast static VA, colour vision, glare sensitivity, and glare recovery, could be measured in athletes with VI. The study also reported that the Pelli-Robson chart for CS assessment was not feasible for testing in both the Para nordic and Para alpine populations.[60] Further analyses on the data suggested that glare sensitivity (in the best eye) and static VA had the potential to be predictive of Para nordic skiing performance, and that static VA was a significant predictor of Para alpine slalom skiing performance. It was also determined that colour vision was not an important factor in Para nordic or Para alpine skiing performance. Finally, it was determined that low contrast VA did not add any additional information about skiing performance that was not already measured using static VA and CS.[33,61]

1.2 Objectives and Hypotheses

The purpose of this thesis was to develop evidence-based, sport-specific classification systems for both Para nordic and Para alpine skiing and address specific concerns related to the current classification systems in each sport. The following experiments were conducted to achieve these overall aims.

1.2.1 Experiment 1

The purpose of this experiment was to determine the minimum level of visual impairment, which prevents a skier from competing fairly in the non-adapted forms of nordic and alpine skiing in two different studies. Visual impairments were simulated in multiple levels in able-sighted skiers, and changes in their skiing performance were analyzed to identify the MDC. It was hypothesized that the current MDC levels might be too conservative and might not be representative of the minimum level of impairment impacting skiing performance.

1.2.2 Experiment 2

The purpose of the second experiment was to identify the measures of visual function that were associated with Para nordic and Para alpine skiing performance. A broad range of visual functions were assessed in elite Para nordic and Para alpine skiers and the associations of these visual functions with skiing performance were explored. It was hypothesized that dynamic measures of visual function such as dynamic VA and translational motion perception, CS, and glare sensitivity were associated with skiing performance in addition to Static VA and VF.

1.2.3 Experiment 3

The third experiment aimed to determine whether the current VI competition classes were appropriate in both Para nordic and Para alpine skiing. Once the visual functions associated with skiing performance were identified in Para nordic and Para alpine skiers, hierarchical cluster analyses were used to determine the unique groups with similar skiing performance within the populations of Para Nordic and Para alpine skiers. All the vision and experience variables were included in the cluster analyses to account for other factors that may affect skiing performance in addition to visual functions. It was hypothesized that the current criteria to allocate skiers into classes does not correctly represent the groups of skiers who have similar levels of sports performance limitations due to their vision impairments.

1.2.4 Experiment 4

The fourth experiment investigated the impact of the mandatory usage of blindfolds by Para nordic and Para alpine skiers classified as B1 on skiing performance. B1 skiers' performances with and without blindfolds were assessed to understand the effect of blindfolds on skiing performance. It was hypothesized that blindfolds would not have an impact on skiing performance.

1.2.5 Experiment 5

The fifth and final experiment of this thesis was to validate binocular VF measurements using the Arc perimeter. The binocular VF scores (using a modified American Medical Association scoring method) obtained using an Arc perimeter on participants with VF impairments were compared with functional VF scores obtained using a Humphrey Visual Field Analyzer (HFA III, FF246 method). It was hypothesized that functional VF scoring using both instruments would not differ significantly.

1.2.6 Additional studies

In addition to the above-mentioned experiments, additional studies were conducted to compare different methods of scoring visual fields and determine what aspects of the visual field were important for performance in Para nordic and Para alpine skiing.

Chapter 2
Exploration of the Minimum Visual Disability Criteria for Para Nordic and Para Alpine Skiing using Simulated Vision Impairments

2.1 Chapter summary

Introduction: Para sport classification consists of: 1) minimum disability (or impairment) criterion that determines eligibility for competition, and 2) additional criteria that group athletes with similar impairments into competition classes. This project determined the minimum level of vision impairment that negatively affected nordic and alpine skiing performance using simulated impairments in sighted skiers.

Methods: Twenty-two nordic (28.09 ± 9.68 years; 16 male) and eleven alpine (37.91 ± 18.9 years, 11 male) normally sighted ski racers participated. Eight visual acuity (VA) and contrast sensitivity (CS) impairments (Cambridge Simulation Glasses, University of Cambridge) and six peripheral visual field (VF) impairments (bespoke goggles; University of Waterloo) were simulated. Each sport-specific study consisted of: 1) a visual function assessment to assess VA, CS, and VF with and without the simulated impairments, and 2) an on-snow session where skiers raced with each of the simulated impairments. Clear goggle (no impairment) trials were used as controls. The order of the simulated impairments and control goggles were randomized and each run was timed. Race time was the chosen performance metric. ROC analysis was used to determine cut-offs for 'expected' and 'below expected' performance.

Results: Skiing performance was significantly different between simulated impairments (VA/CS $p<0.001$; VF $p<0.001$). Nordic: The optimum cut off criteria obtained for VA, CS, and VF extent were at 0.81 logMAR (59% of performances correctly identified), 1.14 logCS (60%), and 62% VF extent (50% of performances correctly identified) respectively. Alpine: The optimum cut off criteria obtained for VA, CS, and VF extent were at 0.59 logMAR (81%), 0.89 logCS (78%), and 46% VF extent (59% of performances correctly identified) respectively.

Conclusions: Moderate reductions in visual acuity, contrast sensitivity and visual field appear to have significant detrimental effects on nordic and alpine skiing performance.

2.2 Introduction

Classification systems are essential to ensure fair competition in the Paralympics considering the wide range of impairments among athletes competing in the Para sports.[6,7] Paralympic classification consists of two major components; 1) deciding which athletes are eligible to compete in a Para sport (eligibility criteria or minimum disability criteria (MDC)), and 2) allocating athletes into classes in a way that within each class athletes' impairments have similar levels of impact on their sports performance. In other words, the MDC defines the level of impairment at which athletes have a disadvantage in sports performance compared to able-sighted athletes despite having other favorable physiological and psychological characteristics like excellent physical fitness and training.[11]

Of the 28 Paralympic sports, athletes with vision impairment (VI) are eligible to compete in 14 different sports, including nine sports at the Summer Games and two sports at the Winter Games.[12] Currently, for all the Paralympic sports, except for shooting and goalball which have unique eligibility criteria, athletes are eligible to participate in a Paralympic event if their best-corrected visual acuity is worse than or equal to 1.0 logMAR and/or visual field radius is less than or equal to 20 degrees.[8] These eligibility criteria have been used since VI sports were first included in the Paralympic Games, however, there is little evidence that these specific impairment levels affect Para sports performance. Furthermore, there is little evidence that these criteria account for the unique visual demands of each sport.

2.2.1 Paralympic classification research

The Athlete Classification Code published by the International Paralympic Committee[7] (IPC, 2007) and the Position Stand published by Tweedy and Vanlandewijck[8] detail the need for, and methods to adopt when establishing evidence-based and sports-specific classification criteria for determining eligibility and sport class allocation. A Delphi study including 25 participants who were experts in VI sports by Ravernsbergen et al.[31] identified establishing the MDC specific to each Para sport as one of the highest VI classification research priorities. Mann and Ravensbergen[32] published a VI specific Joint Position Stand, which concluded that valid MDC should be designed based on the athletes' performances in non-adapted forms of the sport. They also recommended that while generic tests such as visual acuity (VA) or contrast sensitivity (CS) testing could be used for classification research, the testing conditions should be representative of the sports performance environment.[32] For example, if the athlete performs the sport with both their eyes open using the visual input from both the eyes when competing, then testing should also be conducted binocularly.

There has been an increase in research to develop evidence-based and sports-specific classification criteria in the past five years, including one study investigating the MDC for the shooting Para sport by simulating VA and CS impairments on elite, able-sighted, shooters, and determining the minimum impairment level, which significantly affected their shooting performance. The study concluded that moderate reductions in VA and CS (worse than 0.5 logMAR and 0.8 logCS) were associated with diminished or reduced shooting performance in the non-adapted or able-sighted form of the sport.[38,39] The modified MDC for shooting Para sports implemented by the IPC in February 2019 states that the athletes are eligible to compete in shooting Para sport if they have either 1) VA worse than or equal to 1.1 logMAR or 2) VA between 0.6 and 1.0 logMAR (inclusive) and CS worse than or equal to 1.4 logCS. These criteria were decided on after taking the sensitivities and specificities of various cut-off levels into consideration.[21] Research investigating the MDC in other Para sports such as swimming, judo, and athletics is ongoing, although this research has not been published yet.

2.2.2 Para nordic and Para alpine skiing

Para nordic skiing and Para alpine skiing are the only two VI sports in the Winter Paralympics. Para nordic skiing consists of cross-country skiing and biathlon disciplines.[25] The four major disciplines in Para alpine skiing are downhill (DH), super-g (SG), giant slalom (GS), and slalom (SL). SL and GS are technical events, while SG and DH are speed events.[24]

Both Para nordic and Para alpine skiing are highly dynamic sports, which have vision demands at long distances (greater than 3m). Skiers have to process visual information to identify course boundaries, judge the contours of the hill, and follow the course or to avoid obstacles while making quick decisions regarding their speed, direction, or body position while moving at high speeds through the course.[62] Identifying visual cues while skiing becomes even more difficult when visibility is reduced due to conditions such as fog, cloud cover, and overcast skies.

While nordic and alpine skiing are similar in terms of the challenging environments in which they take place and the high demands these sports place on vision, they differ in terms of terrain, race duration, and technique. Nordic skiing is practiced on flatter terrain with gently rolling undulating hills on tracks that are often narrow and grooved, while alpine terrains are significantly steeper and less predictable.[63] Nordic skiing also requires sustained visual and physical performance for a much longer period of time compared to alpine skiing, as nordic races can go on for several minutes, but alpine races are usually over in less than two minutes. As there are considerable technical differences between the sports, it is likely that relationships between vision and performance are also unique to each sport; as such these relationships should be investigated separately.

The purpose of this experiment was to investigate the MDC in both Para nordic and Para alpine skiing. The results of this project will help to inform the development of evidence-based, sports-specific classification systems in Para nordic and Para alpine skiing. It was hypothesized that the current MDC do not represent the impairment levels at which the performance in each of the non-adapted skiing sports is affected significantly. We also expect that the minimum vision impairment level affecting performance will be different between Para nordic and Para alpine skiing.

2.3 Materials and Methods

Two separate studies were conducted to investigate the MDC in Para nordic and Para alpine skiing. These studies used within-subjects, repeated measures experimental designs, where each participant's habitual skiing performance was compared to their skiing performance with different levels of simulated vision impairments. Informed consent was obtained from all participants, and the studies adhered with the tenets of the Declaration of Helsinki. This study was reviewed by and received ethics clearance through a University of Waterloo Research Ethics Committee.

2.3.1 Participants

Experienced adult international and national level able-sighted skiers, guides, and coaches, both male and female, who had the technical skill to complete on competition-style ski courses were recruited for this study. Nordic participants were recruited during 2018 Para Nordic World Cup events at Oberried, Germany and Alpine participants were recruited during a training camp at National Sports Center for the Disabled, Winter Park, USA. Participants were excluded if they had a binocular habitual best-corrected VA worse than 0.4 logMAR or if they had visual field (VF) defects. Participants were also excluded if they had a history of active ocular disease and/or were undergoing ocular disease treatment that could impact their vision at the time of the study. Twenty-two nordic skiers and 11 alpine skiers participated in the studies. Participation was voluntary, and all athletes participated without any monetary benefit.

2.3.2 Procedure

The studies involved two visits per participant: visual function was assessed in visit one, and skiing trials with the simulated impairments were completed in visit two. All skiing trials took place on short nordic or GS alpine courses that were specially designed to mimic the demands of full-length courses in each sport.

2.3.2.1 Visit 1

The procedures conducted during the first visit were the same for both the nordic and alpine studies. During this visit, participants completed a short questionnaire (Appendix A) about their sport experience and ocular history. Participants' VA, CS, and VF were assessed binocularly with their habitual correction. The visual function assessments were repeated with 1) Cambridge simulation filters (sim-specs, 8 levels; Cambridge Simulation Specs, Cambridge, UK) that impaired visual acuity and contrast sensitivity simultaneously and 2) bespoke goggles (6 levels; University of Waterloo, Canada) that restricted the peripheral visual field progressively.[64] Bespoke goggles were painted to simulate binocular peripheral VF constrictions in incremental steps. Appendix B provides further detail on the sim-specs and the bespoke goggles used in these studies.

VA is a measure of how well participants can see black letters on a white background on an externally illuminated chart (395 +/- 10% lux). VA was measured using the Early Treatment Diabetic Retinopathy Studies (ETDRS) chart at 4m or 1m, and/or the Berkeley Rudimentary Vision Test (BRVT) at 0.25m to 1m. Both the ETDRS and BRVT charts measure visual acuity in logMAR units and a per-letter scoring system was used for each chart.[65,66] To ensure visual acuity could be calculated across the limits of measurement of each chart (i.e. where both charts overlap), the single-letter BRVT tumbling E targets were each presented 5 times as there are 5 letters per line on the ETDRS charts.

CS is a measure of how well participants see letters that decrease in contrast as the test progresses. The letters in the test have varying levels of grey and become fainter as the test progresses. The Mars letter contrast sensitivity chart was used for testing CS according to the standardized procedures and recorded in logCS units.[67] The chart was illuminated uniformly, with illuminance on the chart ranging from 189 to 377 lux at a viewing distance of 50 cm (20 inches) from the patient.

Participants' VF were assessed using an Arc perimeter with a Goldmann size IV target, recorded manually on Goldman VF recording sheets, and scored using Esterman's binocular VF scoring grids out of 120 points (Figure 2-1). The measurement procedures were modified to make it viable to measure the binocular VFs.[68] The Arc perimeter was placed in front of the participants such that their midline was centered on the Arc perimeter, and chin was comfortably resting on the chin rest. VF assessment was performed by the examiner moving a size IV Goldmann (6mm) target from the non-seeing area into a seeing area at about 3-5 degrees per second starting with the horizontal axis. Once the horizontal axis was marked, the arc axis was changed, and the entire 360^{o} visual field was tested similarly in 45^{o}intervals. The participants were given time to rest whenever they showed signs of fatigue or indicated a need to rest. If there were inconsistencies in the responses, or if the fixation was poor, participants were reinstructed and retested.

Esterman scores were converted to percentages [i.e., (Esterman score/120) *100].[68,69,70] Nordic and alpine participants VFs were also scored using two unbiased modified AMA scoring methods (AMA 7E and AMA 6E) designed by Mann and Ravensbergen as described in Appendix E and the analysis was repeated using these scores.[71]

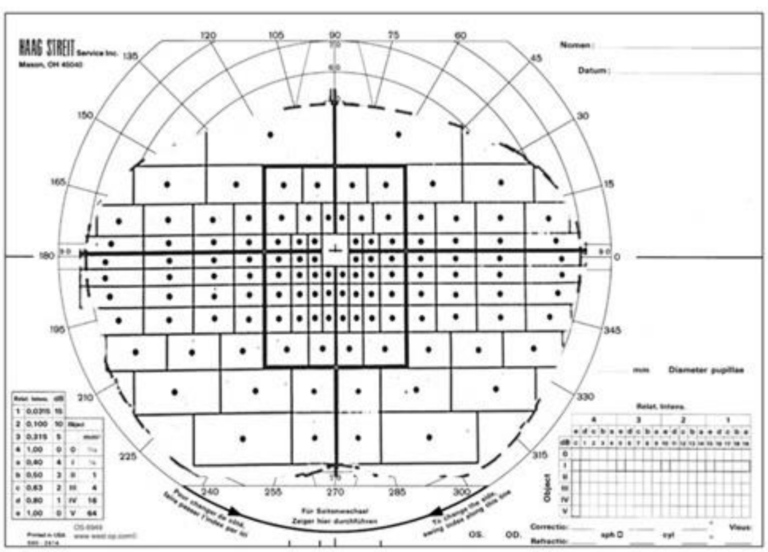

Figure 2-1: The Esterman grid used to overlay on the VF recording sheets for functionally scoring the VF of participants. Reprinted from Ophthalmology, 82/11, Esterman, B, Functional scoring of the binocular field, 1226-34, Copyright (1982), with permission from Elsevier (Appendix F).

2.3.2.2 Visit 2

During the second visit, all participants were asked to ski short racecourses while wearing either clear goggles (habitual vision; controls) or vision impairment simulating goggles on top of their habitual optical correction. The nordic ski courses were approximately 400 to 500 m long with at least one corner, an uphill, and a downhill. The alpine ski courses were short ten-gate GS courses, resembling an ordinary GS course in terms of the slope and the gate settings. In order to reduce the amount of time participants spent riding a chair lift between trials, two short GS courses were set on a single ski slope, one after the other. The two courses were separated from each other and timed as separate trials. GS courses were chosen for the Para alpine study, as GS is one of the disciplines with the most number of competitors and combines both technical and speed skills.[24] All courses were designed after consultation with subject experts such as World Para Nordic Skiing and World Para Alpine Skiing officials, coaches, and guides. Full-length ski courses were not used, as investigators wanted to ensure that testing could be completed in a reasonable amount of time and that there was minimal impact of fatigue on performance.

A total of 18 skiing trials for nordic and 20 skiing trials (10 on each course) for alpine were completed in the second study visit. Before starting the skiing trials, participants were allowed to ski through the courses untimed to become familiar with the course. During the trials, participants were asked to try to maintain a consistent, challenging pace (70-80% of their regular race pace) across all the trials. Skiers were not asked to ski at 100% exertion (race pace) because it was felt race pace would not be sustainable across the number of trials needed to complete the study visit. It was unlikely skiers could sustain their race pace due to fatigue which would introduce variability into the data collected and increase the potential risks involved in these studies. If participants felt the simulated impairment that they were asked to wear was unsafe to ski with, they were given options either to continue in the study by being reassigned to a lower level of impairment or to completely withdraw from the study. Interestingly, all of the participants in this study were confident to ski with every simulated vision impairment provided. Participants used their own skiing equipment to reduce the risk of unfamiliar gear. Since the purpose of these studies was to examine the impact of impairments on the un-adapted forms of the sports, participants always skied without a guide. Participants' times to complete the courses were recorded for each trial and used as the measure of performance.

All participants wore clear goggles during the first and last ski trials on each course to account for the variations in weather, lighting, snow conditions, and fatigue. In the nordic study, the middle 16 trials included skiing with 14 simulated vision impairments and two additional clear goggle trials to monitor the effect of fatigue across the trials. All alpine study participants completed a total of 20 skiing trials (10 in each course). Similar to the nordic study, all participants wore clear goggles during the first and last ski trials on each course. Apart from the first and last clear goggle trials on each course, the order of the goggles (simulated impairment and clear goggle controls) were randomized across both courses. The middle clear goggle trials were not equally distributed between the two courses due to this randomization.

2.3.3 Data analysis

2.3.3.1 <u>Descriptive analysis</u>

Kolmogorov-Smirnov and Shapiro-Wilk tests were used to investigate the normality of the distribution of data in addition to the skewness and kurtosis values, Q-Q plots, histograms, and residual plots.[72] The nordic and alpine data were not normally distributed therefore non-parametric tests were used for further analysis.

2.3.3.2 <u>Baseline skiing performance</u>

Baseline performance was calculated as the average time to complete all four habitual vision control ski trials for the nordic study to account for variation in race times that could occur due to learning or fatigue. Using only the first and final trials in, similar to what was done in alpine (see below), was considered in nordic, but when only the first and final trials were used, the variation around the average race times (mean variation: 1.87 s) was slightly higher than the variation calculated using all four habitual vision trials (mean variation: 1.78 s). Thus, the decision was made to use all four habitual vision race times in the baseline calculation for the nordic data analysis.

The habitual vision control trials were not equally distributed between the two courses in the alpine study because of the randomization across both courses, thus only the first and last clear goggle trials were considered while calculating baseline performance for each alpine ski course to keep the calculations the same on both courses.

Race times with the simulated vision impairments were normalized as a percentage of the participant's baseline performance {i.e., *Normalised race time = 100 - [(Individual race time - Baseline race time average) ÷ Baseline race time average] × 100}.*

2.3.3.3 *Fatigue and order effects*

Nordic and alpine participants completed four, and six habitual vision ski trials respectively. The effects of physical fatigue on participants' skiing performance was examined by comparing the race times of the clear goggle trials for each course. Overall order effects were examined by comparing the race times for all participants in the order that the trials were completed in for each course. Friedman's two-way ANOVA was used to determine the statistical significance of fatigue and order effects ($p<0.05$).[73]

2.3.3.4 *Simulated impairment effects on skiing performance*

The impacts of VA, CS, and VF impairments on performance were investigated by plotting the race times in the order of the severity of simulated impairments. Friedman's two-way ANOVA was used to determine the statistical significance of the simulated impairments as well ($p<0.05$).[73] VA and CS impairments measured in this study were not independent (due to the method of simulation chosen), however for the purposes of analysis each type of impairment was considered separately.

ROC curve analysis and the Youden's J index were conducted to examine the VA, CS, and VF cut-off points at which optimal sensitivity and specificity for discriminating below expected performance were achieved.[74] Each participant's race times in the habitual vision conditions were used to establish a margin for 'normal' or expected skiing performance. The upper margin of the 99% CI of all habitual vision race times for each participant was used as the level above which a race time would be 'below expected' performance.

To assess the MDC based on a combination of VA, CS, and VF, decision tree analysis (IBM SPSS Modeler, C 5.0 algorithm) was used. In particular, the C 5.0 algorithm was used in a training set data to create a model, and the accuracy of that model was assessed using the test data. The C 5.0 algorithm builds a decision tree by splitting the sample based on the field that provides the maximum information gain. The best split, in this case, is the split that leads to two nodes that are most 'homogeneous,' meaning that they optimally separate 'expected' or 'below-expected' performances. After the first split, the same process was continued until the subsamples could not be split any further.

Once a large tree overfitting the data is formed, the algorithm post-prunes the tree by removing the nodes and branches that do not contribute significantly to the value of the model.[75,76]

2.4 Results

Twenty-two nordic skiers (twelve coaches, five guides, four ski students, and one physiotherapist) and 11 male alpine skiers from (three coaches, five racers, and three masters racers) participated in the studies (Table 2-1). All nordic and alpine participants had good habitual vision.[77]

Table 2-1: Descriptive statistics of the visual function parameters and other characteristics assessed in nordic and alpine participants, including Mean ± SD and ranges.

Variable	Nordic participants (n=22)	Alpine participants (n=11)
Age	28.1 ±9.7 years (16 to 50)	37.9 ±18.9 years (17 to 64)
Gender	16 male, 6 female	11 male
Number of nations	11	2
Years of experience	21.6 ±10.9 years (5 to 44)	29.9 ±14.9 years (15 to 58)
Hours of skiing in a week	8.9 ±4.7 hours (1 to 20)	22.5 ±13.6 hours (6 to 43)

2.4.1 Habitual vision and vision with simulated impairments

The habitual and simulated VA, CS, and VF values of all our nordic and alpine participants are provided in Table 2-2 and Table 2-3, respectively. The progressive increase in the simulation levels of the sim-specs resulted in systematic simultaneous decrease of VA and CS in both the nordic and alpine participants; the decrease in participants' VA and CS were consistent with previously published data.[78] Progressive increases in impairment levels resulted in overall average VA reductions of 0.19 ± 0.05 logMAR (median: 0.18 logMAR) and 0.21 ± 0.13 logMAR (median: 0.21 logMAR) for nordic and alpine studies respectively, and the median values of the VA and CS reductions were close to the mean values in both nordic and alpine participants. Similarly, increasing levels of sim-specs resulted in overall average CS reductions of 0.19 ± 0.08 logCS (median: 0.20 logCS) and 0.21 ± 0.12 logCS (median: 0.20 logCS) for nordic and alpine studies, respectively. Simulated VA and CS impairments also demonstrated strong significant correlations in both nordic (ρ=-0.95, $p<0.001$) and alpine (ρ=-0.97, $p<0.001$). However, the VA reduction with impairment levels 3 and 5 of the sim-specs were noticeably higher in the alpine participants compared to the nordic participants, despite habitual VA being similar between groups. At sim specs level 3, alpine and nordic participants' VA reductions were 0.38±0.12 logMAR and 0.23±0.10 logMAR, respectively. At sim specs level 5, alpine and nordic participants' VA reductions were 0.39±0.11 logMAR and 0.22±0.06 logMAR, respectively.

Similarly, the impact of CS impairments with level 3 of the sim-specs was significantly higher in the alpine participants (average reduction: 0.39±0.10 logCS; median) compared to the nordic participants (average reduction: 0.25±0.10 logCS), despite habitual CS being similar between groups. Interestingly, the impact of VA and CS impairments with levels 7 and 8 of the sim-specs were significantly lower in the alpine participants compared to nordic participants. At sim-specs levels 7 and 8, alpine participants' average VA and CS were approximately 0.05 logMAR and 0.08 logCS worse than the previous levels. Nordic participants' average VA and CS at sim-specs levels 7 and 8 were approximately 0.16 logMAR and 0.22 logCS worse than the previous levels.

Increasing the level of the VF impairment simulation goggles resulted in systematic decrease in VF extent in both nordic and alpine participants, and the reduction in VF extent was similar between both nordic and alpine participants. Each increasing level of simulated VF goggle resulted in a mean reduction of 13.0 ± 3.3 % and 13.4 ± 3.1 % in the functional visual fields of nordic and alpine participants respectively. Appendix B provides further detail on the impact of simulated impairments on the visual functions of nordic and alpine participants.

Table 2-2: Visual function of the 22 nordic participants.

	VA (logMAR)				**CS (logCS)**				**VF (Esterman scoring %)**			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Habitual	-0.15	0.16	-0.30	0.32	1.88	0.05	1.76	1.92	100.0	0.0	100.0	100.0
Level 1	-0.02	0.20	-0.22	0.48	1.77	0.03	1.72	1.88	83.1	2.1	80.0	89.2
Level 2	0.14	0.19	-0.06	0.56	1.70	0.05	1.56	1.80	74.6	1.9	70.0	78.3
Level 3	0.37	0.17	0.14	0.74	1.46	0.12	1.28	1.68	63.0	4.1	55.8	71.7
Level 4	0.64	0.14	0.36	0.90	1.26	0.14	1.00	1.60	50.3	6.4	38.3	60.8
Level 5	0.85	0.10	0.66	1.02	0.95	0.11	0.76	1.16	33.4	4.9	25.0	42.5
Level 6	1.05	0.12	0.86	1.30	0.77	0.12	0.52	1.04	22.0	4.4	15.0	30.8
Level 7	1.21	0.10	1.04	1.42	0.53	0.11	0.28	0.76				
Level 8	1.37	0.11	1.18	1.60	0.34	0.12	0.16	0.52				

Table 2-3: Visual function of the 11 alpine participants.

	VA (logMAR)				CS (logCS)				VF (Esterman scoring %)			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Habitual	-0.14	0.11	-0.26	0.14	1.89	0.04	1.80	1.92	100.0	0.0	100.0	100.0
Level 1	-0.02	0.17	-0.18	0.42	1.76	0.03	1.68	1.80	85.7	3.9	82.5	95.8
Level 2	0.19	0.15	0.06	0.58	1.62	0.11	1.32	1.72	76.2	2.1	74.2	80.0
Level 3	0.56	0.13	0.38	0.80	1.21	0.14	0.92	1.36	59.6	3.5	53.3	66.7
Level 4	0.81	0.14	0.60	1.00	0.92	0.16	0.68	1.16	47.6	3.4	42.5	55.0
Level 5	1.20	0.07	1.06	1.34	0.60	0.11	0.36	0.76	30.5	3.8	25.8	37.5
Level 6	1.39	0.08	1.24	1.48	0.39	0.09	0.24	0.52	19.9	4.1	15.0	28.3
Level 7	1.46	0.07	1.34	1.54	0.28	0.08	0.20	0.44				
Level 8	1.50	0.06	1.42	1.58	0.22	0.10	0.12	0.44				

2.4.2 Fatigue and order effects

One of the nordic participants had a comparatively high variability (SD = 10.69 s) in their habitual race times compared to the rest of the participants (average SD = 1.16 s). As such, this participant was determined to be an outlier in the nordic data and was removed from the data before any analyses related to skiing performance were done. There were no outliers in the alpine data.

There were no significant differences and/or trends in the habitual race times for any of the participants in either the nordic (p=0.94) or alpine study (course one p=0.72 and course two p=0.52). There was also no significant ski trial order effect for nordic (p=0.20) or alpine on course 1 (p=0.10). However, the average race times were significantly higher (p=0.001) during the 5th and 9th ski trials on alpine course 2. Further investigation revealed that on these two trials, the number of participants wearing a more severe visual impairment simulation (VA and CS level 5 and higher; VF level 4 and higher) were greater (63.6% severe impairments on each trial) compared to all of the other ski trials (≤45.5% severe impairments each trial) on course 2. Thus, the order effect observed on course 2 was due to the greater proportion of severe impairment simulations on trials 5 and 9. Appendix C provides further detail on the fatigue and order effects analyses.

2.4.3 Effect of simulation goggles on skiing performance

2.4.3.1 *Static visual acuity and contrast sensitivity*

Nordic and alpine skiing performances gradually decreased with increasing levels of VA and CS impairments (Figure 2-2) and this decrease was statistically significantly from impairment level 5 for both nordic (2.44 ± 2.19s, $p<0.001$) and alpine participants (4.26 ± 4.01s, $p<0.001$).

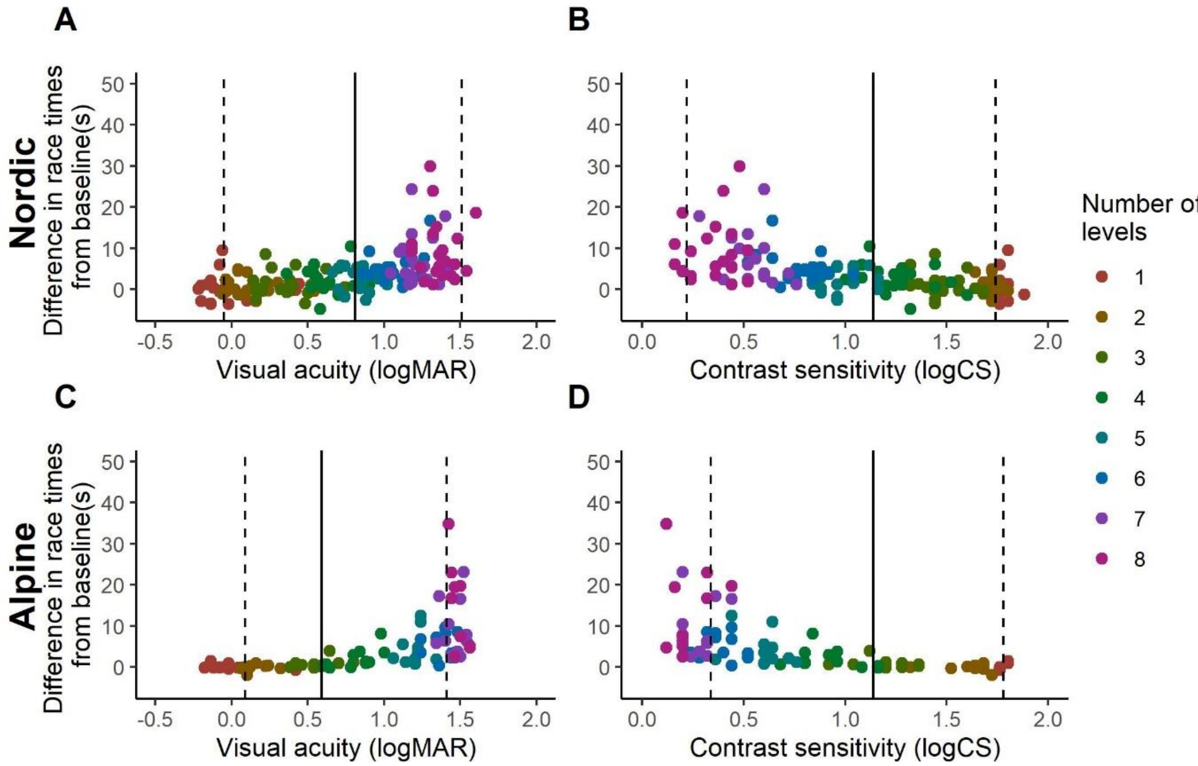

Figure 2-2: Skiing performance as a function of VA (A & C) and CS (B & D) for nordic and alpine participants. The x-axes show the level of visual function of the participants for each impairment level. Lower logMAR values represent better VA and higher logCS values represent better CS. The y-axis shows the difference in the race times from the baseline race time in seconds. The solid vertical line represents the Youden's J and the dashed vertical lines maximum sensitivity and maximum specificity.

2.4.3.2 *Visual field*

The differences in race times from baseline gradually increased with increasing level of visual field impairment, and the decrease was statistically significant from impairment level 5 for both nordic (2.43 ± 2.85s, $p<0.001$) and alpine (2.99 ± 5.69s, $p<0.001$) participants (Figure 2-3).

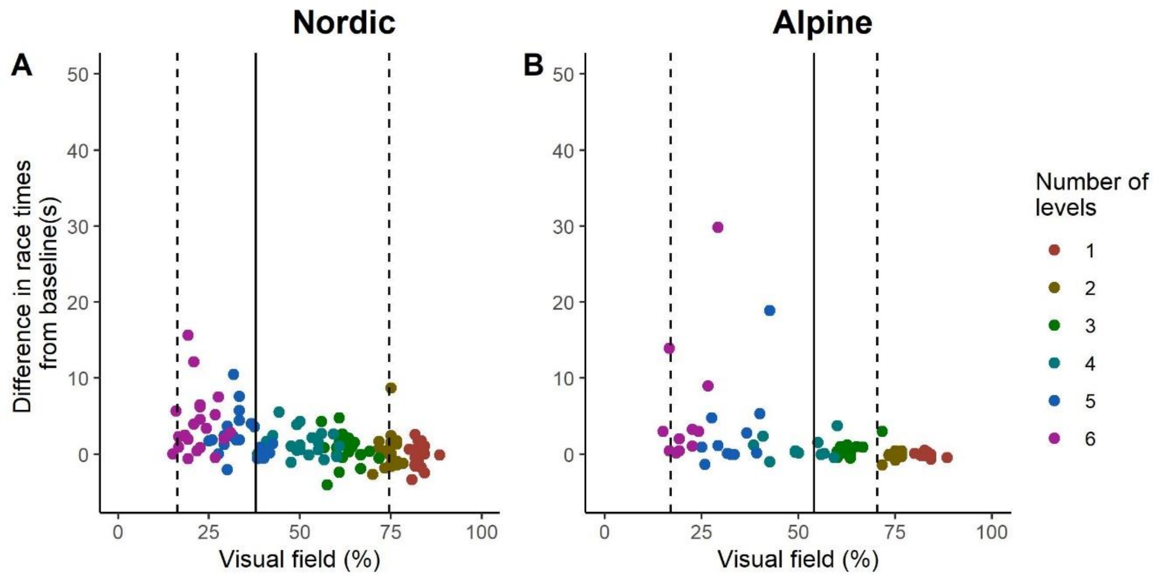

Figure 2-3: Skiing performance as a function of VF for (A) nordic and (B) alpine participants. The x-axes show the level of visual function achieved by each of the participants with each of the six VF impairments. Higher percentages of VF represent better VF. The y-axis shows the difference in the race times from the baseline race time in seconds. The solid vertical line represents the Youden's J and the dashed vertical lines maximum sensitivity and maximum specificity.

2.4.4 ROC analyses

2.4.4.1 Nordic skiing

The AUC for VA was 0.86 ± 0.03 ($p < 0.001$ to reject the null hypothesis that the AUC is 0.5; 95% confidence interval for the AUC = 0.80 – 0.92), demonstrating that VA has high discriminative ability to differentiate participants with above and below expected levels of performance (Figure 2-4A). Maximum sensitivity was achieved with a VA of -0.05 logMAR, though at this point, specificity was poor as many participants with an expected level of performance would be included (Figure 2-4B). Maximum specificity was at 1.47 logMAR, though this resulted in poor sensitivity, with a large proportion of nordic participants with below-expected levels of performance being excluded. A maximal Youden's J value of 0.59 was observed at 0.81 logMAR, indicating that this cut-off correctly classifies 59% of nordic participants, with a sensitivity of 0.88 and specificity of 0.71. Since the Youden's J curve did not have a sharp peak in the plot, a second maximum Youden's J was examined. The second maximum Youden's J (0.58) in the nordic data was at a VA of 0.76 logMAR, which was similar to the optimum cut-off value. The second maximum Youden's J had a sensitivity of 0.89 and specificity of 0.69.

In contrast to the optimum cut-off value identified here, the current cut-off criteria specified in the sport rules (MDC = VA of 1.00 logMAR), had a Youden's J of 0.52, indicating that this cut-off criteria correctly classifies 52% of nordic participants, with a sensitivity of 0.68 and specificity of 0.84.

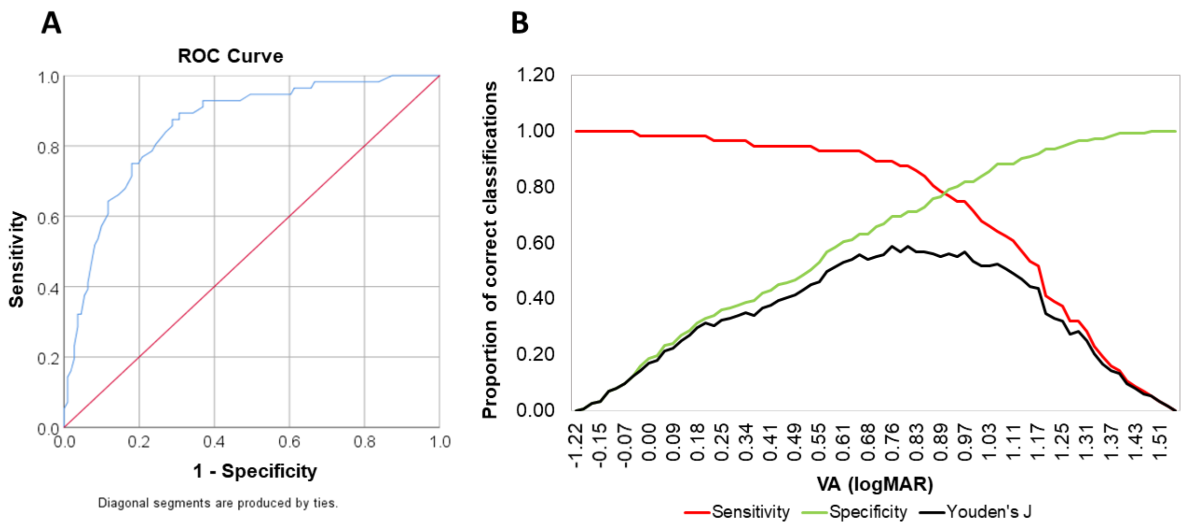

Figure 2-4: Receiver Operating Characteristic curve of VA (A) and the plot showing the sensitivities and specificities of the VA cut-off points (B) classifying 'expected' or 'below-expected' nordic skiing performance.

Contrast sensitivity also demonstrated good discrimination ability for differentiating nordic participants with expected and below expected levels of performance (AUC = 0.86 ± 0.03; $p < 0.001$, 95% confidence interval = 0.80–0.91; Figure 2-5A). The cut-off level of CS that would achieve maximum sensitivity was 1.74 logCS, for maximum specificity was 0.22 logCS, and for the maximum Youden's J (0.60) was at 1.14 logCS with a sensitivity of 0.91 and specificity of 0.69 (Figure 2-5B). Since the Youden's J curve did not have a sharp peak in the plot, a second maximum Youden's J was examined. The second maximum Youden's J (0.59) possible for the nordic data was at a CS of 1.10 logCS, which was similar to the optimum cut-off value. The second maximum Youden's J had a sensitivity of 0.89 and specificity of 0.69.

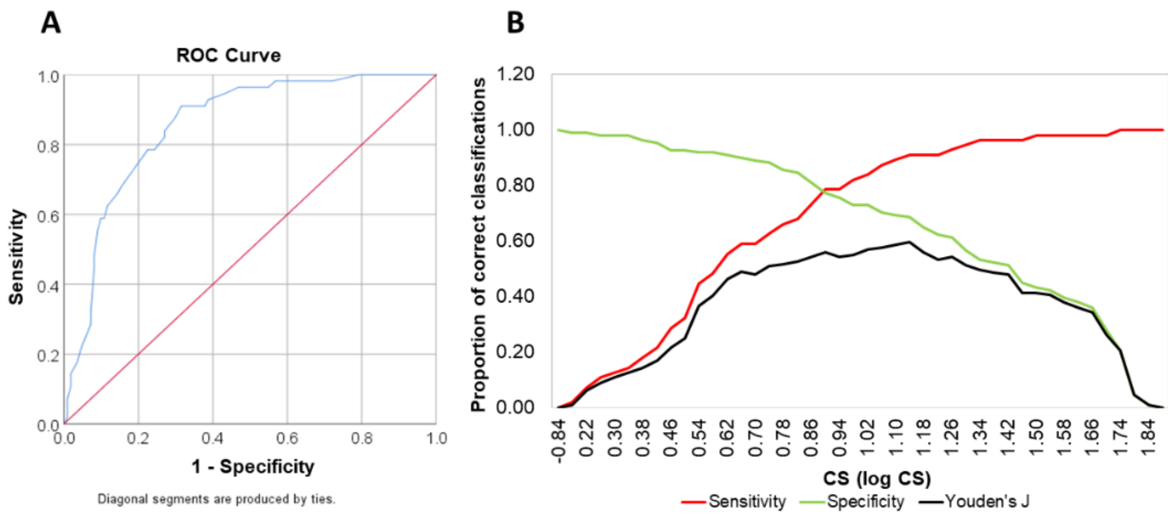

Figure 2-5: Receiver Operating Characteristic curve of CS (A) and the plot showing the sensitivities and specificities of the CS cut-off points (B) classifying 'expected' or 'below-expected' nordic skiing performance.

Finally, the ROC curve for VF indicated good discrimination between nordic participants with expected and below expected levels of performance (AUC = 0.80 ± 0.05; $p < 0.001$, 95% confidence interval = 0.70–0.88; Figure 2-6A). The cut-off level of VF that would achieve maximum sensitivity was 74.6%, for maximum specificity was 16.3%, and for the maximum Youden's J (0.50) was at 37.9% with a sensitivity of 0.71 and specificity of 0.79 (Figure 2-6B). An Esterman VF score of 40% corresponds to a VF radius of approximately 30º (Table 2-4). Since the Youden's J curve did not have a sharp peak in the plot, a second maximum Youden's J was examined. The second maximum Youden's J (0.48) possible for Esterman scoring for the nordic data was at 38.8%, which was similar to the optimum cut-off value. The second maximum Youden's J had a sensitivity of 0.78 and specificity of 0.71.

In contrast to the optimum cut-off value identified here, the current cut-off criteria specified in the sport rules (MDC = VF with a 20º radius) corresponds to a VF of 21.7% (Table 2-4). The Youden's J value of a 21.7% VF was 0.16, indicating that this cut-off correctly classifies only 16% of nordic participants, with a sensitivity of 0.21 and specificity of 0.95.

Table 2-4: Esterman VF scores at various levels of peripheral VF constrictions and the corresponding VF radii in degrees.

VF radius (degrees)	Esterman (%)
10	5.8
20	21.7
30	40.0
40	54.2
50	69.2
60	85.0
70	88.3
80	100.0

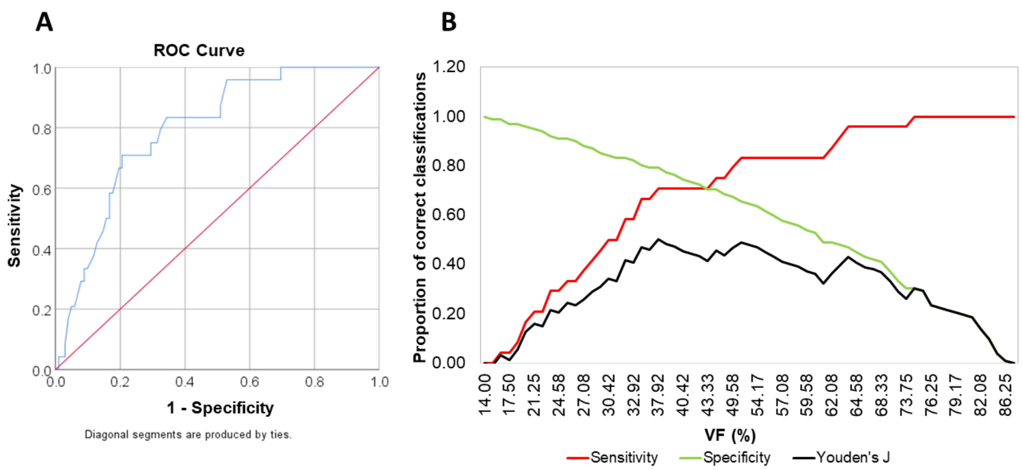

Figure 2-6: Receiver Operating Characteristic curve of VF (A) and the plot showing the sensitivities and specificities of the VF cut-offs (B) classifying 'expected' or 'below-expected' nordic skiing performance.

2.4.4.2 Alpine skiing

The AUC for VA (Figure 2-7A) was 0.96 ± 0.02 ($p < 0.001$ to reject the null hypothesis that the AUC is 0.5; 95% confidence interval for the AUC = 0.92 – 0.99), demonstrating that VA has high discriminative ability to differentiate participants with above and below expected levels of performance. The performances of the different cut-off values were compared by plotting the sensitivities and specificities (Figure 2-7B). Maximum sensitivity was achieved with a VA of 0.09 logMAR, though at this point, specificity was poor as many participants with an expected level of performance would be included. Maximum specificity was at 1.43 logMAR, though this resulted in poor sensitivity, with a large proportion of alpine participants with below-expected levels of performance being excluded. A maximal Youden's J value of 0.81 was observed at 0.59 logMAR, indicating that this cut-off correctly classifies 81% of alpine participants, with a sensitivity of 0.93 and specificity of 0.88. The second maximum Youden's J (0.79) possible for the alpine data was at a VA of 0.67 logMAR, which had a sensitivity of 0.86 and specificity of 0.93.

In contrast to the optimum cut-off value identified here, the current cut-off criteria specified in the sport rules (MDC = VA of 1.00 logMAR) has a Youden's J value of 0.70, indicating that this cut-off correctly classifies 70% of nordic participants, with a sensitivity of 0.73 and specificity of 0.98.

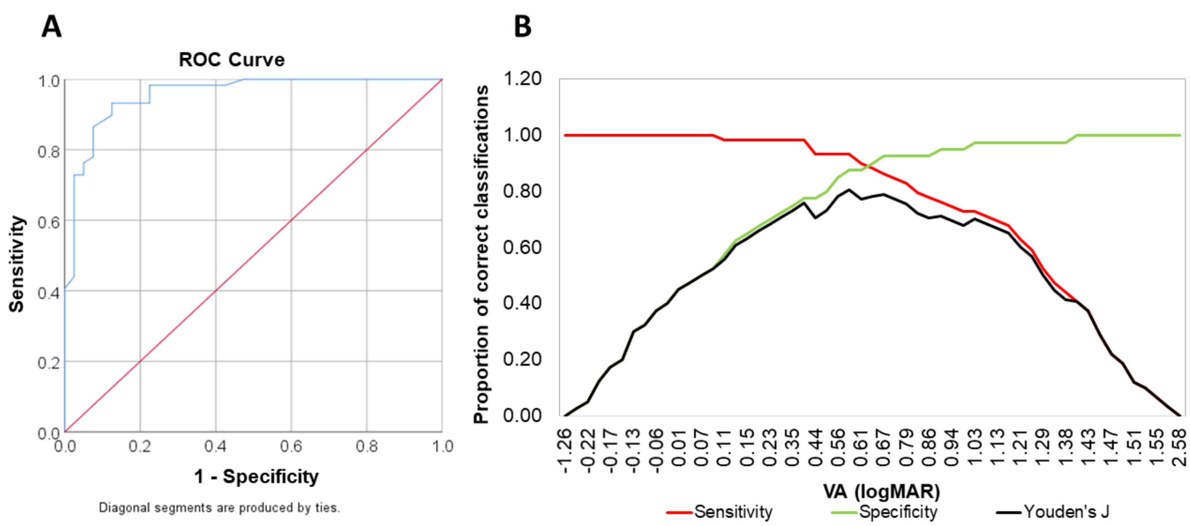

Figure 2-7: Receiver Operating Characteristic curve of VA (A) and the plot showing the sensitivities and specificities of the VA cut-offs (B) classifying 'expected' or 'below-expected' alpine skiing performance.

The ROC curve for CS (Figure 2-8A) indicated similarly good discrimination ability between alpine participants with expected and below-expected levels of performances (AUC = 0.95 ± 0.02; $p < 0.001$, 95% confidence interval = 0.91–0.99). The cut-off level of CS that would achieve maximum sensitivity was 1.78 logCS, for maximum specificity the cut-off was for 0.34 logCS, and the maximum Youden's J (0.78) was 1.14 logCS (Figure 2-8B), with a sensitivity of 0.88 and specificity of 0.90. The second maximum Youden's J (0.77) possible for alpine data was at a CS of 1.24 logCS, which was close to the optimum cut-off value, with a sensitivity of 0.93 and specificity of 0.85.

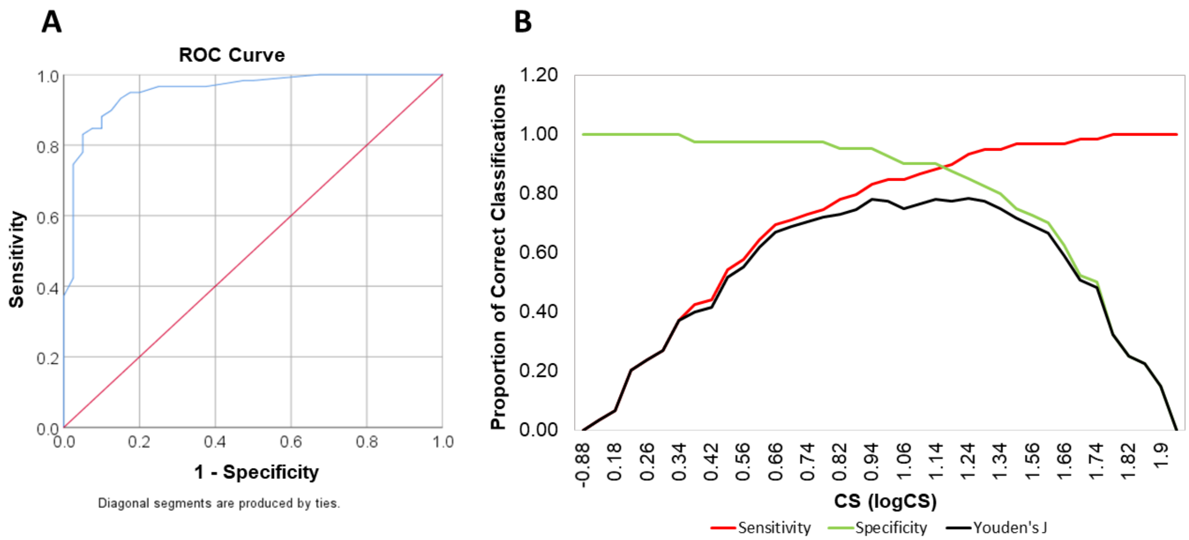

Figure 2-8: Receiver Operating Characteristic curve of CS (A) and the plot showing the sensitivities and specificities of the CS cut-offs (B) classifying 'expected' or 'below-expected' alpine skiing performance.

The ROC curve for VF (Figure 2-9A) also indicated good discrimination between alpine participants with expected and below-expected levels of performance (AUC = 0.83 ± 0.05; $p < 0.001$, 95% confidence interval = 0.73–0.93). The cut-off level of VF that would achieve maximum sensitivity is 70.0%, for maximum specificity is 17.0%, and for the maximum Youden's J (0.59) is at 54.0% of VF (Figure 2-9B) with a sensitivity of 0.88 and specificity of 0.71. Esterman VF score of 54.2% corresponds to a VF radius of 40º (Table 2-4). The second maximum Youden's J (0.58) possible for Esterman scoring for the nordic data was at 57.5%, which was close to the optimum cut-off value, with a sensitivity of 0.92 and specificity of 0.67.

In contrast to the optimum cut-off value identified here, the current cut-off criteria specified in the sport rules (MDC = VF with a 20º radius), which corresponds to a VF of 21.7% (Table 2-4), the Youden's J value was 0.20, indicating that this cut-off correctly classifies only 16% of nordic participants, with a sensitivity of 0.25 and specificity of 0.95.

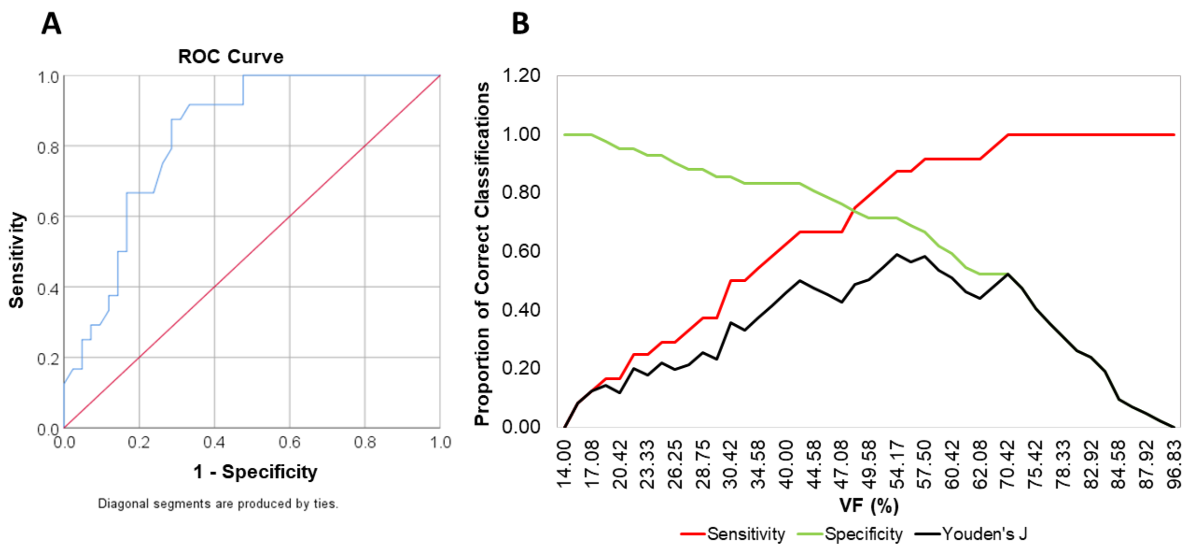

Figure 2-9: Receiver Operating Characteristic curve of VF (A) and the plot showing the sensitivities and specificities of the VF cut-offs (B) classifying 'expected' or 'below-expected' alpine skiing performance.

2.4.5 Decision tree analyses

2.4.5.1 Nordic skiing

When a decision tree was built with VA, CS, and VF in the model, the first binary split was made using a cut-off for a VA of 0.97 logMAR. This cut-off maximized the differentiation of the expected and below-expected performance scores, respectively, below and above the cut-off value. A VA cut-off of 0.97 logMAR had a sensitivity of 0.75 and specificity of 0.82 (Youden's J of 0.57) based on the ROC analysis results. When VA was ≤ 0.97 logMAR, the next best predictor of poor performance was VF ≤ 37.9% (same as the optimum VF cut-off value from ROC analysis), which had a sensitivity of 0.71 and specificity of 0.79 (Youden's J 0.50). The splitting process continued until the stopping criterion was met, reaching a maximum of five splits. The optimum VA cut-off for the nordic data based on just the ROC analysis was 0.81 logMAR. Considering both ROC and decision tree analysis, the VA cut-off value in the middle of 0.81 logMAR and 0.97 logMAR was 0.90 logMAR, which had a sensitivity of 0.79 and specificity of 0.77 (Youden's J: 0.55) based on the ROC analysis.

2.4.5.2 *Alpine skiing*

When a decision tree was built with VA, CS, and VF in the model, the first binary split was made using a cut-off for VF of 54.2% (same as the optimum VF cut-off value from ROC analysis), which had a sensitivity of 0.71 and specificity of 0.79 (Youden's J 0.59) based on the ROC analysis. This cut-off maximized the differentiation of the expected and below-expected performance scores above and below the cut-off value. When the visual field extent was ≤ 54.2%, the next best predictor of poor performance was static visual acuity ≤ 0.59 logMAR (same as the optimum VA cut-off value from ROC analysis), which had a sensitivity of 0.93 and specificity of 0.88 (Youden's J 0.81). The process of splitting continued until the stopping criterion was met, reaching a maximum of three splits.[*]

2.5 Discussion

This project aimed to determine the minimum levels of vision impairment that negatively affected performance of participants in the non-adapted forms of nordic and alpine skiing. The study investigated the impact of simultaneous VA and CS impairments (8 levels) and VF impairments (6 levels) on participants' skiing performance. The average values and ranges of habitual VA, CS, and VF were similar between the nordic and alpine participants, suggestive of comparable habitual vision between skiers in both sports. Consistent with previous reports, the progressive increase in simulated impairment produced by the sim-specs resulted in linear reductions in both VA and CS (details in Appendix B).[38,79] Although the reductions were linear, the average VA obtained in the nordic study participants were slightly better, and the average VA obtained in the alpine study participants were slightly worse, compared to the reported average VA by Goodman-Deane et al.[80] A linear reduction in VF extent was also achieved in this study.

[*] Following the completion of the VF analyses using an Esterman scoring grid presented in this thesis, IPC recommended using an AMA scoring grid for VF data instead. Appendix E contains a comparison of all three VF analysis methods examined (Esterman, AMA 6E, and AMA 7E). The ROC and decision tree analyses for nordic and alpine skiing were repeated with both the AMA 6E and AMA 7E scores, and these results are also presented in Appendix E. In brief, the VF cut-off criteria found with the AMA 7E scoring method were comparable to those found using Esterman scoring method, and the cut-off criteria found using AMA 6E scoring method were slightly larger than those found using the Esterman scoring method. However, all three scoring methods resulted in similar visual field cut-off criteria when the VF extent percentage scores were converted back to degrees of visual field.

It is worth nothing that the alpine participants had substantially higher VA reductions with sim-specs level 3 and level 5, and higher CS reductions with sim-specs level 3 than the nordic participants, although the overall mean and median of the VA and CS reductions in both groups were similar. Interestingly, the VA and CS reductions with sim-specs levels 7 and 8 were lower in alpine participants compared to nordic participants. One of the reasons for these observed differences could be the higher proportion of elderly participants in the alpine data compared to nordic data. All the nordic participants were below 50 years old, whereas 36% (n=4) of the alpine participants were older than 50 years (maximum age was 64 years). Healthy individuals over 50 years old are known to have reduced CS and VA compared to younger individuals due to the age related lens sclerosis[81] and retinal changes[82]. In addition, advanced age is also found to have adverse effects on the binocular summation of high spatial frequency contrast information.[83] Therefore, it is possible that the impact of sim-specs on the VA and CS of individuals vary depending on the age related ocular changes even though there are no published data available.

Other reasons for these reported difference between nordic and alpine participants could be the inherent variability in the data and interparticipant variations. A pilot study investigating VA in the presence of defocus and astigmatism (not sim specs) concluded that the effects of age on the simulated VA in their study participants were masked by the interparticipant variations in factors such as pupil size, refractive error, and corneal aberrations.[84] Thus, it is possible that factors outside the scope of these current studies such as inter ocular differences in VA and CS or the refractive status of participants might also have contributed to these observed differences in the simulated VA and CS between the nordic and alpine participants.

Inter-observer differences and variations in measurement conditions such as the external illumination, testing distances, and test termination criteria are also known to affect the outcomes of VA and CS assessments.[85,86] However, these factors are less likely to have contributed to the observed differences between the nordic and alpine participants' VA and CS since both these studies were conducted by the same examiners and the testing conditions were as similar as possible between the studies. In addition, the variability in the VA measurements among nordic and alpine participants with level 5 to level 8 sim-specs were lower than the previously reported variability in VA measurements with level 6 sim-specs (0.13 logMAR)[80], suggesting that the chances of having measurement errors within the nordic and alpine VA data are slim.

Both the nordic and alpine studies were of within-subjects design, in which each participant's performance with simulated impairments were compared against their baseline performance (without any simulated impairments). Therefore, the ROC and decision tree analyses results of nordic and alpine studies were independent of each other, and the between groups VA and CS differences could not have affected any of the within-subject results.

The simulated VA and CS values among both nordic and alpine participants were highly correlated, consistent with previous reports,[87] thereby making it impossible to determine the impact of independent reductions in VA and CS on skiing performance, despite conducting the ROC analyses separately. The independent VA and CS impairment results presented here are likely slightly higher than they would be if the impairments could be simulated individually, because both visual functions were affected simultaneously. Practically speaking however, most ocular conditions that impair VA also impair CS to some degree, so the independent analyses conducted here still give a good approximation of the functional impact of VA and CS impairments on performance.

There was no significant impact of fatigue or trial order on either nordic or alpine participants' skiing performance. The skiing performances of both the nordic and alpine participants were affected significantly from sim-specs level 5, at which the mean VA and CS impairments were approximately 0.90 logMAR and 1.00 log CS in nordic and corresponded with approximately a 2.5 second slower race time. In alpine the mean VA and CS impairments were approximately 1.20 logMAR and 0.60 log CS, which corresponded with more than a 4.0 second increase in race time. The VF impairments also had significant impact on performance from level 5, which corresponded to approximately 30% VF extent in both nordic and alpine. In nordic, this VF reduction resulted in an approximately 2 second increase in race time, whereas alpine participants skied approximately 3 seconds slower with this impairment.

It is important to note though that, not all participants' performances decreased before the level 5 simulated impairments; some participants' performances remained 'above-expected' despite higher levels of impairment. In an ideal scenario, participants would have been asked to ski at race pace (100% exertion) for all the trials, however this was not feasible in the study design because of the large number of skiing trials that were conducted. Skiing at race pace would have led to skier fatigue, thereby increasing the risk of injury and introducing an additional source of variability into the data. To minimize fatigue, all our participants were asked to try to maintain about 70-80% of their race pace. It is possible that the skiers who continued to perform 'above-expected' were exceptional athletes who were adjusting their strategies to compensate for any impact of the impairment on their performance (e.g. skiing faster on uphill sections to make up for time lost elsewhere). These additional sport-context factors are not captured by the statistical analysis of the data but cannot be ignored when final decisions on eligibility criteria are made for the sports. Since the skiers were not asked to ski at their race pace, it is also possible that the optimum cut-off levels of VI from these studies might be slightly more conservative than the actual values. While it is possible that not skiing at race pace resulted in conservative estimates of the levels of VI affecting skiing performance, the increased risk and complicated logistics (such as testing over multiple days) that would be involved in conducting skiing trials at maximum exertion with simulated impairments exceed the benefits that could be gained using a maximum exertion method. The 70-80% race pace method used here provided the best compromise between risk and benefit to conduct these studies and assess the minimum levels of VI affecting skiing performance.

The optimum cut-off values for VA, CS, and VF based on the ROC analyses were lower (better visual function) than the mean simulated level 5 vision impairments (Nordic: VA = 0.81 logMAR (59% correct classification), CS = 1.14 logCS (60% correct), VF = 37.92% (50% correct); Alpine: VA = 0.59 logMAR (81% correct classification), CS =1.14 logCS (78% correct), VF = 54% (59% correct). However, none of the Youden's J curves generated had single sharp peaks and there was no obvious single maximum value to the Youden's J curves, indicating that determining the decision cut-off based on just the maximum Youden's Js might not be ideal in these studies. Thus, second maximum values for the Youden's J for each of the visual functions were also looked at in both the studies, assuming that if the first and second maximum were similar, the true maximum was also likely similar to these two maxima in such cases. The second maximum Youden's J's observed for VA, CS, and VF were fairly similar to the optimum cut-off criteria observed, especially in nordic, thereby suggesting that the Youden's J calculations provided a reasonably accurate estimate of the cut-off points. In recognition of the limitations of the ROC analysis identified above, decision tree analyses were also conducted and the final recommendations for the cut-off criteria made in this Chapter were based on consideration of both the ROC and decision tree analyses. Both the ROC and decision tree analyses were consistent with observations made during the studies that skiing performance worsened for many participants at lower levels of impairment.

The decision tree analysis results supported the optimum cut-off criteria derived from the ROC analyses for VF in the nordic data and both VA and VF in the alpine data. Therefore, the optimum cut-off values obtained through the ROC analyses for VF were chosen as the MDC for both nordic and alpine studies and the optimum cut-off value obtained through the ROC analysis for VA was chosen as the MDC for alpine. The decision tree analysis cut-off for VA in the nordic data was at 0.97 logMAR while the ROC cut-off was 0.81logMAR; in consideration of both the ROC and decision tree analysis, a cut-off value in middle of 0.90 logMAR was chosen for the nordic VA MDC.

The decision trees also helped us to identify which visual functions best predict the changes in skiing performance. With regards to contrast sensitivity, the decision tree analyses demonstrated that the best predictors of performance in nordic skiing were VA, followed by VF, while in alpine skiing the best predictors of performance were VF, followed by VA. CS did not stand out as a strong predictor of performance in either decision tree. The finding that CS was not a strong independent predictor of performance in either sport was supported by the ROC analyses which demonstrated that the discriminating ability of VA was stronger than the discriminating ability of CS in both sports. However, these findings do not suggest that CS was not important for performance in either of these sports; rather these findings suggest that VA just appeared to be a better predictor of performance when a single cut-off value needs to be chosen. It is worth noting that the VA and CS of all participants, in both the habitual and simulated conditions demonstrated strong correlations, which could have masked the effect that CS had on skiing performance as well.

The findings of this research indicate that the current MDC cut-off criteria specified in the sport rules (VA of 1.00 logMAR as well as VF of 21.7% Esterman's score) do not represent the levels of impairments that significantly impact nordic or alpine skiing performance. The current cut-off criteria for VA and VF had lower Youden's J values, lower sensitivities, and higher specificities compared to the optimum cut-off levels recommended here, indicating that the current cut-off criteria are conservative for both the Para nordic and Para alpine VI sports. Thus, the current MDC ensure that athletes with visual impairments that do not impact their performances are not included in the Paralympics, even though some athletes with vision impairments affecting performance might be excluded. Currently, CS is not included in the MDC, which is supported by the decision tree analyses conducted in these studies. Both the nordic and the alpine decision trees suggested that VA and VF are better predictors of the skiing performances compared to CS. Thus, including VA and VF as eligibility criteria would be sufficient to identify Para skiers with whose vision significantly impacts their performances. An additional CS eligibility criterion does not need to be added. If the sports decide to use cut-off levels that equally maximize sensitivity and specificity, VA cut-off levels of 0.90 logMAR (midpoint between 0.8 logMAR and 0.97 logMAR in nordic) and 0.60 logMAR (alpine) and VF cut-off levels of 38% (nordic) and 54% (alpine) could be used.

When deciding on the final eligibility criteria for each sport, it will be important to consider the research findings in the context of the sport. High-speed sports, especially sports like alpine skiing can have hundredths of seconds separating gold medalists from four place finishers, so 3 and 4 second differences in performance have a much larger contextual significance in the sports themselves. Despite skiing performances decreasing statistically significantly different from the level 5 impairments onwards, skiing performance worsened for many participants at lower levels of impairment, while other participant's performance remained 'above-expected' despite higher levels of impairment.

Moderate to high levels of VA impairments have been reported to affect sports performance. Basketball shooting performances were reported to be significantly reduced only when VAs were worse than 1.10 logMAR.[88] Basketball free throw, as well as golf putting performances, were reported to be significantly affected only below a VA level of 1.90 logMAR.[89,90] Conversely, performances in more challenging sports tasks such as hitting a fast-moving cricket ball are reported to be affected with lesser levels of impairment in VA (0.50 to 0.80 logMAR).[91,92] Allen et. al. (2016) reported that performance in non-adapted forms of shooting could be correctly classified 78% with a VA cut-off of 0.53 logMAR and 74% with a CS cut-off of 0.83 logCS.[38] In our studies, we have shown that the performance in visually challenging sports like nordic and alpine skiing was also affected by moderate levels of VA, CS, and VF impairments. The levels of VA impairments affecting nordic and alpine skiing are comparable to highly dynamic sports tasks like cricket batting or visually demanding aiming sports like shooting. Interestingly, the VA and VF impairments simulated in this study significantly affected alpine performance at a lower level compared nordic performances, which may be a reflection of the higher competition speeds, and potentially higher visual demands, in alpine compared to nordic.

The athlete classification code mandates that to be eligible, the Para athlete should have a defined type and severity of impairment, which has an impact on performance in the unadapted form of the sport. From a Paralympic eligibility point of view, a criterion with low specificity could result in the inclusion of more athletes who do not have impairments that negatively impact performance, while a criterion with low sensitivity could result in the exclusion of more athletes who do have genuine impairment that negatively impacts performance. A test criterion with maximum sensitivity and specificity values (1.0) would be highly unlikely in real-life situations. Thus, the governing body of the sport should decide on prioritizing either the sensitivity or specificity of a cut-off criterion.

One of the limitations of this study was that it was done with simulated impairments. Participants only had approximately 5 minutes to familiarize themselves with the simulated impairments during the first visit before being asked to ski while wearing them. An argument could be made that without time to fully adapt to the simulated impairments, the impact of the impairment on performance could have been over estimated. However, a counterargument that could be made is that the controlled exposure to the simulated impairments before skiing with them limited participants' abilities to develop unique adaptation strategies, which may provide additional insight into understanding the impact of the impairment on performance. If participants had time develop unique adaptation strategies for the impairments, it is possible the impact of the impairment on performance could have been underestimated. The overall performances of Para athletes depend not only on their vision, but also on the training that they receive, thus, if new MDC are to be established based on these results, follow-up on the performance of the new MDC will be essential and differences in adaptation and training conditions of the study populations will need to be taken into consideration.

Another limitation of these studies was the relatively small sample sizes, particularly in the alpine study. However, considering the technical difficulties involved in conducting 20 skiing trials for each alpine participant in consistent environmental conditions, and the consistency in the performance data collected, the researchers feel the sample size was adequate.

Finally, the nordic study had both male (72.7%) and female (27.3%) participation, whereas the alpine study had only male participants. Every effort was made to recruit athletes of both genders for both studies; unfortunately, no females chose to participate in the alpine study. While not ideal, the lack of female participation in the alpine study probably had a minimal effect on the study results since gender is not a predictive factor for an individual's VA, CS, or VF.[93–95] It is possible that gender may be predictive of how CS, VA, and VF impairments affect skiing performance, however more research would need to be done to determine if this was the case or not. Normalising each participants impairment performance data to their own individual baseline, as was done in this study, would help to reduce the impact that the gender differences between the sports could have as well.

In conclusion, both nordic and alpine skiing performance appear to be negatively affected by moderate levels of VI. The findings of this research suggest that the current eligibility criteria for Para nordic and Para alpine skiing are conservative and may result in the exclusion of Para nordic and Para alpine skiers whose vision impairments have a significant impact on their skiing performance. The final decision on whether or not to change the current eligibility criteria for both Para nordic and Para alpine skiing will need to be made by the sport governing bodies, as the results of this research are only one piece of evidence. Other sport performance, legal, and logistical factors will also need to be considered and rigorous follow-up studies are required to assess the performance of current cut-off criteria considering all the limitations of these studies.

2.6 Thesis progress I

Minimum disability criteria	
Para nordic •Static VA: 0.90 logMAR, VF: 38%	**Para alpine** •Static VA: 0.60 logMAR, VF: 54%

Figure 2-10: Thesis progress I outlining the main objectives and conclusions of Chapter 2.

The findings from the Chapter 2 suggest that moderate levels of VA and CS impairments negatively affect nordic and alpine skiing performance.

Chapter 3
Visual function assessments predictive of Para nordic and Para alpine skiing performances

3.1 Chapter summary

Introduction: The current International Paralympic Committee (IPC) classification criteria for skiers with vision impairment competing in Para sports are based only on the static visual acuity (Static VA) and visual field (VF) radius of the better eye, and do not account for the dynamic vision demands of sports. Prospective observational studies were conducted to identify the vision tests to be included in classification by examining the relationships of a wide range of vision functions with Para nordic and Para alpine skiing performance.

Methods: Elite Para nordic skiers (n=26) and Para alpine skiers (n=15) were recruited at the 2017 Para Nordic Skiing World Championships, 2018 Para Nordic World Cup, and 2017 Para Alpine Skiing World Championships events. Static VA, light sensitivity, glare sensitivity, glare recovery, dynamic VA, CS, translational and radial motion perception, and VF were assessed binocularly in all skiers. Skiing performance was assessed using modified World Para Nordic Skiing and World Para Alpine Skiing points systems based on skiers' raw times. Performance on the vision function tests were compared with skiing performances using Kendall's correlations (with Bonferroni-Holm corrections) and linear multivariable regressions ($p<0.05$ considered significant).

Results: None of the vision variables were significantly correlated with performance in Para nordic or Para alpine skiing after the Bonferroni-Holm corrections were applied. Prior to applying the corrections, VF extent (ρ= -0.41, p= 0.004) and static VA (ρ=0.26, p=0.066) demonstrated the strongest correlations with Para nordic skiing performance, but neither of these variables independently predicted the variance in Para nordic skier's performance. Prior to applying the corrections in Para alpine skiing, static VA (ρ=0.54, p=0.046), dynamic VA (ρ=0.593, p=0.04) and CS (ρ=-0.50, p=0.06) demonstrated the strongest correlations with downhill skiing performance. Static VA and CS also demonstrated the strongest correlations with Super G (Static VA: ρ=0.50, p=0.007, CS: ρ=-0.51, p=0.017) and giant slalom (Static VA: ρ=0.57, p=0.01, CS: ρ=-0.46, p=0.017) performance, and showed trends towards significance in slalom (Static VA: ρ=0.35, p=0.074, CS: ρ=-0.37, p=0.06). VF was significantly associated with slalom performance (ρ=-0.43, p = 0.029). Static VA found to be a significant predictor of giant slalom [($F(3,11)=24.71$, $p<0.001$), with an R of 0.87], Super G [($F(3,9)=17.34$, p=0.002), with an R of 0.85], and slalom [($F(3,11)=11.8$, p=0.002), with an R of 0.80] performance, but CS and VF

were not. Interestingly, static VA and CS were highly correlated in both Para nordic ($\rho=-0.60$, $p<0.001$) and Para alpine ($\rho=-0.80$, $p<0.001$) skiers.

Conclusions: Of all the vision variables, only static VA independently predicted skiing performance (Para alpine only). VF (Para nordic and Para alpine) and CS (Para alpine) also appear to be associated with skiing performance but were not predictive. Considering both the correlation and regression analyses, static VA and VF should be included as measures of visual function in the classification systems.

3.2 Introduction

In order to develop evidence-based, sport-specific classification systems for Para nordic and Para alpine skiing, it was of primary importance to determine which visual functions were associated with skiing performance. Following discussions with experts in the sport and on-site observations at the 2015 World Para Alpine Championships (WCH), Panorama, Canada, a number of different aspects of vision were identified as being important to consider for future testing. The aspects of vision identified included:1) resolving high and low contrast details such as the position of gates or changes in the snow while moving, 2) judging depth and contours of the hill while moving, 3) identifying peripheral visual information, 4) adapting to changing light conditions, 5) tracking the guide, and 6) resolving the colour of gates.[59]

As a next step, preliminary studies were conducted with Para nordic and Para alpine skiers during the 2015-2016 season using a test battery that included assessments associated with the vision aspects mentioned above. Tests of binocular static visual acuity (VA), binocular contrast sensitivity (CS), binocular dynamic VA, binocular low contrast VA, monocular glare sensitivity (GLS), monocular glare recovery (GLR), and binocular colour vision were included in the battery.[60] The skiing performance metric used in each of these studies were unfactored WPNS and WPAS points that were re-calculated based on skiers' raw race times. The relationships between the Para nordic and Para alpine skiing performances and the assessed visual functions were explored using correlation and regression analyses in two separate studies. None of the visual functions tested were individually predictive of Para nordic skiing performance; however there was a trend towards static VA appearing to be predictor of Para alpine skiing performance.[33]

In addition to examining the relationships between visual functions and skiing performance, this preliminary study was also used to assess the feasibility of testing each of the individual visual function measures in the Para nordic and Para alpine populations. Feasibility was assessed by the number of participants who were able to complete a particular test. Most visual functions assessed were feasible to test in the Para nordic and Para alpine populations except for measuring CS with the Pelli-Robson chart due to the limitations in letter size as well as the spatial frequency range.[60,33] In addition, GLS and GLR could only be measured monocularly in this study. Thus, it was concluded that the test battery needed to be refined further to be used in classification research.[33,60,61] Finally, these initial studies had participants with a broad range of experience, from novice to expert skiers, and the varying skill levels could have confounded the true performance-impairment relationships.[33,60,61]

As the colour vision error scores did not capture the functional differences in colour vision between skiers, the decision was made to remove colour vision testing from the revised test battery for future studies. As low contrast VA was highly significantly correlated with static and dynamic VAs and CS, but was not significantly correlated with skiing performance, it was also removed from the preliminary test battery because it did not add any additional information regarding the skiers' visual function.[60,33]

Following the preliminary study described above, prospective observational studies were designed and conducted separately in Para nordic and Para alpine elite skiers using a refined test battery to re-examine the relationships of a wide range of visual functions with skiing performance. This chapter presents the analyses conducted during these secondary studies to identify which visual function assessments should be included in the classification research. The data collected in these secondary studies were also used to determine the sports classes (Chapter 4).

3.3 Materials and Methods

This project used an observational research design and adhered with the tenets of the Declaration of Helsinki. All international level Para nordic and Para alpine skiers eligible to participate in the study were given the opportunity to participate, and informed consent was obtained from all participants. This study was reviewed by and received ethics clearance through a University of Waterloo Research Ethics Committee.

3.3.1 Participants

Elite Para nordic and Para alpine skiers were recruited with the help of the International Paralympic Committee (IPC) at the 2017 Para nordic World Championships (WCH, Finsterau, Germany), 2018 Para nordic World Cup (WC, Oberried, Germany), and the 2017 Para alpine WCH (Tarvisio, Italy). A total of 35 Para nordic skiers (21 from WCH and 14 from WC) and 15 Para alpine skiers participated in the studies. WCH events are the most prestigious Para nordic and Para alpine events next to the Paralympic Games, with only the elite, most competitive skiers as participants. By recruiting from WCH events, it was made sure that the study participants have comparable levels of skiing skills and training. Of the 14 skiers recruited at the 2018 WC event, only the six additional Para nordic skiers who were eligible to participate in the WCHs were included in this study. 72.4% of Para nordic skiers and 65.2% of Para alpine skiers who were part of the 2017 WCH events participated in the study. Although small, these samples were representative of the elite Para nordic and Para alpine skiers' populations.

3.3.2 Procedure

This study consisted of a single study visit. During the study visit, participants completed a questionnaire (Appendix D) about their skiing experience, which included questions about their vision impairment and skiing history as well as their current average annual training routine both on- and off-snow. Participants' visual functions were assessed using a test battery that was determined based on the previous feasibility studies conducted by the research team. The test battery included binocular tests of static VA, dynamic VA, CS, translational motion perception (TMP), radial motion perception (RMP), GLS, GLR, light sensitivity (LS) and VF. The participants' performances on the visual function assessments were compared with their skiing performances; the skiing performance metric used is described in more detail below.

Static VA was measured using an Early Treatment Diabetic Retinopathy Study (ETDRS) chart at 1m and/or the Berkeley Rudimentary Vision Test (BRVT) at 0.25 to 1m.[65] Standard measurement procedures with letter-by-letter scoring were incorporated during the static VA assessments using ETDRS.[96,97] To ensure visual acuity could be calculated at the borders near the limits of measurement of both charts (i.e. where both charts overlap), the single-letter BRVT tumbling E targets were each presented 5 times as there are 5 letters per line on the ETDRS charts, and letter-by-letter scoring was used.[98]

Dynamic VA was measured using the computer program moV& (V&mp Vision Suite, Waterloo, Canada) which used moving single Tumbling E letter that moved in a random walk trajectory at a speed of 1 m/s, and was presented on a high definition television screen (50” or 60” display, 60 Hz refresh rate and 1920x1080 resolution, illuminance at 130-150 lx) at a distance of 1m.[99] The initial size of the letter presented was 0.60 log units bigger than the participant’s static VA to make sure that the subject started the test from a suprathreshold level, and the maximum letter size presentable on this screen was 2.60 logMAR at a distance of 1 m. Each target was presented 5 times, and the display time was set to be unlimited to ensure adequate time to respond to the direction of the letter E. Dynamic VA was also recorded in logMAR units, using a per letter scoring system.[100]

Contrast sensitivity was measured using a relatively new method called as the quick CSF (contrast sensitivity function) procedure on an Adaptive Sensory Technology platform (AST, Germany). The AST platform consisted of a 46" NEC P463 screen with 1920x1080 resolution, calibrated to 90cd/m^2 background luminance. At a viewing distance of 1m, the screen allowed a display of stimuli in a spatial frequency range of 0.35 to 9 cycles per degree. It was possible to present contrast levels down to 0.2% reliably.[101] Three letters were presented horizontally during a trial with the left and middle letters displayed at four and two times the contrast of the right letter, respectively. A CSF was calculated after 25 trials. The area under the log CSF curve (AULCSF, logCS units) calculated by the software was used as the summary statistic for the CS assessments for this study.[102,103]

Random dot kinematograms consisting of 100 individual, full contrast, local dots that were equivalent to the size of the target detail of a 2.00 logMAR letter were used to assess two types of global motion tasks: translational (up and down) motion (TMP) and radial (in and out) motion (RMP).[104] Stimuli were presented on high definition television screens (50” or 60” displays, 60 Hz refresh rate and 1920x1080 resolution, illuminance at 130 - 150lx). On each TMP and RMP trial, the stimulus was presented for a maximum of 16 seconds, and participants were asked to identify the motion direction of the signal dots. The testing followed a staircase method, which was terminated after 8 reversals and the threshold was calculated by averaging the last 6 reversals.

A novel device (D&zzle, V&mp Vision Suite, University of Waterloo), was used to measure GLS and GLR. GLS was estimated by measuring the static VA of participants immediately after introducing a bright, binocular glare source in the line of sight. Glare recovery was measured by re-testing the static VA 1 minute after the glare source was removed. Static VA in the presence of, and after removing the glare source were compared to the baseline static VA (no glare) to determine the GLS and GLR, respectively. LS was assessed by measuring the static VA of participants at increased light levels (approximately 1900 lux, both in the surround as well as on the chart). Static VA in the presence of the bright light as compared to the baseline static VA to determine LS in logMAR units. GLS was calculated using the following formula: $GLS = Static\ VA\ in\ the\ presence\ of\ glare - Static\ VA$. GLR and LS were also calculated similarly. Positive logMAR values for GLS, GLR, and LS indicated that visual acuity worsened compared to baseline.

VF was binocularly assessed using an Arc perimeter and recorded following the standardized protocol, which was modified to allow binocular measurement.[68] VF assessments were performed by the same examiner (AS), moving a 6 mm target from non-seeing areas in the far periphery to the seeing areas at a speed of approximately 3-5 degrees per second. Once the VF boundary was identified, the target was moved continuously along each axis towards the central fixation point to identify any scotomas, if present. The edges of scotomata were reassessed until the response was consistent and reliable. Testing always started with the horizontal axis, and once the horizontal axis was marked, the arc was rotated to test the entire 360 degree VF in 30-degree intervals.[68] A binocular Esterman scoring grid, which scores different parts of the field in proportion to their functional value to the participant, was used for scoring VF extents. The maximum possible VF score was 120, and the scores were converted into percentages for analysis and interpretation. To make the results of these studies translatable to those in other Para sports studies, all the analyses were repeated with re-scored VF extents using a modified AMA scoring method (Appendix E).

3.3.3 Skiing performance measure

Choosing the raw race times from one particular race as a performance metric might not have be representative of the participants' overall performance due to confounding factors such as fatigue, jetlag, weather conditions, anxiety, or a temporary sickness affecting performance on a particular day for an elite skier. Therefore, we calculated overall performance points for each participant based on the World Para Nordic Skiing (WPNS) and World Para Alpine Skiing (WPAS) scoring systems, which are based on the International Ski Federation (FIS) formula for calculating points in able-bodied ski competitions. The skiers with VI compete for one medal during Para skiing competitions, and the IPC uses factored race times based on the skier's assigned class so that the skiers with most severe impairments receive a maximum time bonus, unlike the FIS points, which are based on raw race times.

However, the FIS formula with the raw race times were used for the current studies to calculate the race points of Para nordic and Para alpine skiers without adjusting for their impairments. The raw race times were used instead of factored race times in order to obtain a performance measure independent of the current classification systems.

The FIS formula for calculating race points was $P = \left(\left(\frac{Tx}{T0}\right) - 1\right) * F$, where P= race points, T_X= raw race time of competitor in seconds, T_0= raw race time of the overall gender best performer in seconds, and F= discipline factor (determined by FIS or the IPC and re-evaluated once in every two years based on competition results). This formula calculates race points relative to the race time of the overall best performer in each race, for each gender. Normalising the performance points to the best performance in each gender allowed researchers to compare performance data between genders. Race penalties are added to adjust the performance points based on the quality of a competition and to make the points in one competition comparable to the other as no two ski races are the same.

Each participant's overall performance points in a race are then calculated as the sum of the FIS race points and the race penalty. Thus, the formula for determining overall performance points was: *performance points = FIS points + race penalty*. Skiers who perform better will have lower performance points. Thus, the best skier in the race in each discipline will have 0 points.[57,25,24]

The F value (discipline factor) is evaluated every second year based on the last two years competition results in PWG, WCH and World Cups by the respective sports governing bodies for both Para nordic and Para alpine skiing. For Para nordic skiing, the F value used for calculating overall performance points was 600 irrespective of the competition event (sprint, middle distance or long distance). The average of a competitor's best five performance points during the validity period were used for the calculation of their raw-WPNS points or skiing performance. The validity period used for the calculation of raw-WPNS points used for this study was from 1 April 2016 to 31 March 2018. Since the IPC calculates WPNS points based on two-year validity period, this study also used a two-year validity period for the points calculation. Nine Para nordic participants (one from the WCH and 8 from WC) had participated in less than five races during the validity period, and their data was excluded from the analysis.

For Para alpine skiing, the F values were specific for each discipline (DH: 1330, GS: 870, SG: 1060, and SL: 610). Performance points in Para alpine were only compared within each discipline, not between disciplines. Since the same F values were used for every participant within each individual discipline, these F values act as a constant in the equation and do not induce any additional variability into the results. If there were less than three competitors with WPAS points in any single event, the competition was not considered. The IPC calculates the WPAS points for Para alpine skiers as the average of their best two race points in a validity period of 15 months. Similarly, the average of a participants' best two results in each discipline during the validity period from 1 January 2016 to 31 March 2017 were used for the calculation of their WPAS in the Para alpine study.[24]

3.3.4 Data analysis

The analysis conducted here focused on 1) understanding the relationships among the various visual function assessments, 2) determining the associations between skiing performance with vision-related and non-vision related variables such as skiers' age, age started skiing, age of onset of impairment, total lifetime hours of skiing, and the number of races completed in the period that the skiing performance points were calculated for, and 3) identifying the visual function assessments, which could be predictive of skiing performances taking into account the non-vision variables. Kendall τ correlations and linear multivariable regressions ($p<0.05$ considered significant) were used to assess the relationships between variables (SPSS for Windows, version 25.0, SPSS, Inc.). Bonferroni-Holm corrections were used to account for multiple comparisons in the correlation analyses.[105] Any variables that demonstrated significant ($p<0.05$) or near significant ($p<0.1$) correlations with skiing performance were included in the multivariable regression models, conducted using enter method. In Para alpine, each discipline (downhill (DH), super G (SG), giant slalom (GS), and slalom (SL)) was analyzed separately.

Since seven Para nordic and two Para alpine participants had no quantifiable static VA, values of 3.8 logMAR and 4.2 logMAR were arbitrarily assigned for participants with LP and NLP vision, respectively, to include them in the correlation and regression analysis on the same continuous scale as the other static VA measurements. Similarly, values of 0.00 log CS and 0.0% were assigned for these participants' CS and VF measures, respectively, since these participants had no quantifiable CS or VF. Dynamic VA has been shown to be between 0.20 to 0.30 logMAR worse than the static VA in individuals with normal vision,[99] but it was impossible to predict how much worse dynamic VA would be relative to static VA for each individual with vision impairment, therefore, it was not appropriate to assign the same, or adjusted, arbitrary values for dynamic VA for the participants with LP or NLP vision. Assigning 0.0 logMAR values for GLS, GLR, or LS for these participants would indicate that their static VA did not change with glare or increased light intensity rather than they were unable to do the task. Similarly, assigning 100% value for their TMP and RMP would indicate that they were able to perceive the motion at 100% coherence, not that they were unable to do the task. To avoid these incorrect assumptions, no values were substituted for the dynamic VA, GLS, GLR, LS, TMP, or RMP in the Para nordic and Para alpine participants with LP or NLP vision.

3.4 Results

Twenty-six Para nordic skiers from 13 NPCs and 15 Para alpine skiers from 10 NPCs participated in these studies (Table 3-1). Summary visual function data for each sport can be found in Tables 3-2 and 3-3. The arbitrarily assigned values for static VA, CS, and VF were not included in the calculation of means and standard deviations presented in these summary tables because they were not actual measured values of the participants. The arbitrary values were only included in the correlation and regression analyses.

Among the Para nordic participants, 5 had no light perception (NLP) and 2 had light perception (LP) vision. Among the Para alpine participants, 1 had NLP and 1 had LP vision. One Para alpine participant also had very good static visual acuity (-0.04 logMAR), however this participant qualified for competition based on the extent of their visual field (7.5º radius).

A comparison of the study sample sizes with the number of currently registered skiers and the number of WCH eligible skiers competing when the research was conducted is in Table 3-4.

Table 3-1: Participant details and summary statistics of their non-vision variables by sport. The summary statistics presented in this table include the Mean ± Standard Deviation of all the athletes.

	Nordic	Alpine
Number of athletes	26	15
Gender	18 Male; 8 Female	8 Male; 7 Female
Number of nations	13	10
Age (years)	26.0 ± 6.3	28.1 ± 11.6
Age range (years)	18 to 43	16 to 58
Age started skiing (years)	12.8 ± 8.2	16.2 ± 8.2
Age of onset of impairment (years)	6.8 ± 8.1	5.3 ± 7.1
Total lifetime hours of skiing	4545.5 ± 3883.5	4239.3 ± 4094.0
Number of races during the validity period	12.2 ± 4.9	DH: 6.8 ± 2.1 (N=9) GS: 8.9 ± 3.4 (N=15) SG: 7.4 ± 3.4 (N=13) SL: 13.7 ± 5.0 (N=15)

Table 3-2: Summary of visual function assessments of Para nordic skiing participants. Only the participants' data with measurable results on each test are included. The data presented do not include participants with LP or NLP vision.

Visual Function Tests	N	Mean± SD	Median	Range
Static Visual Acuity (logMAR)	19	1.71 ± 0.40	1.60	1.18 to 2.68
Dynamic Visual Acuity (logMAR)	16	1.80 ± 0.31	1.80	1.20 to 2.20
Contrast Sensitivity (logCS)	19	0.21 ± 0.26	0.12	0.00 to 0.82
Translational motion perception (%)	15	59.8 ± 26.9	61.8	19.2 to 100.0
Radial motion perception (%)	15	62.8 ± 28.5	61.2	26.5 to 100.0
Glare Sensitivity (change in logMAR)	19	0.20 ± 0.31	0.10	-0.19 to 0.98
Glare Recovery (change in logMAR)	19	0.06 ± 0.20	0.00	-0.20 to 0.79
Light sensitivity change in logMAR)	19	0.00 ± 0.09	0.00	-0.15 to 0.16
Visual field (%)	19	56.5 ± 25.7	63.3	10.0 to 100.0

Table 3-3: Summary of visual function assessments of Para alpine skiing participants. Only the participants' data with measurable results on each test are included. The data presented do not include participants with LP or NLP vision.

Visual Function Tests	N	Mean± SD	Median	Range
Static Visual Acuity (logMAR)	13	1.20 ± 0.51	1.40	0.04 to 1.64
Dynamic Visual Acuity (logMAR)	11	1.48 ± 0.57	1.40	0.50 to 2.20
Contrast Sensitivity (logCS)	13	0.53 ± 0.59	0.40	0.00 to 1.90
Translational motion perception (%)	12	56.4 ± 31.9	53.3	9.3 to 100.0
Radial motion perception (%)	12	56.8 ± 29.0	55.3	12.8 to 100.0
Glare Sensitivity (change in logMAR)	13	0.19 ± 0.17	0.14	0.02 to 0.54
Glare Recovery (change in logMAR)	13	0.05 ± 0.08	0.02	-0.06 to 0.18
Light sensitivity change in logMAR)	10	0.09 ± 0.14	0.04	-0.08 to 0.34
Visual field (%)	13	46.9 ± 33.2	52.5	0.0 to 89.2

Table 3-4: Comparison of the numbers of skiers currently registered with the samples of studies. Para nordic participants were recruited at two different events (2017 WCH, 2018 WC), whereas Para alpine participants were recruited only at one event (2017 WCH).

		Registered and WCH eligible	Participated in the event		Participated in the study
			(2017)	(2018)	
Para nordic	B3	16	8	5	4
	B2	19	15	4	14
	B1	11	6	4	8
Total		***46***	***29***	***13***	***26***
Para alpine	B3	13	10		6
	B2	19	11		7
	B1	2	2		2
Total		***34***	***23***		***15***

3.4.1 Types of visual impairments among skiers

Both the Para nordic and Para alpine skiers had a broad range of ocular pathologies (Table 3-5). Ocular diseases affecting the central retina, peripheral retina, and total retina were most common among Para nordic and Para alpine skiers. 62% of the Para nordic participants and 53% of Para alpine participants had onset of VI after age 2. Forty percent (40%) of the Para nordic and 63% of the Para alpine skiers had VI conditions that were progressive. The most common VF defect among both Para nordic and Para alpine skiers was a peripheral VF constriction. Further details on the types of VF defects can be found in Table 3-6.

Table 3-5: Summary of ocular pathology diagnoses of Para nordic and Para alpine participants.

Ocular Pathology	Para nordic (N=26)	Para alpine (N=15)
Central Retina	Stargardt's disease (2), macular degeneration (1), viteliform macular dystrophy (1), central retinal degeneration (2)	Stargardt's disease (2), macular degeneration (1), achromatopsia (2)
Peripheral Retina	X linked retinoschisis (1), Leber's congenital amaurosis (2), retinitis pigmentosa (1), exudative genetic retinopathy (1), vitreo-choreo-retinal peripheral degeneration (1), peripheral retinal degeneration (1)	Retinitis pigmentosa (3)
Optic Nerve	Congenital optic nerve pathology (5)	Congenital coloboma of optic nerve (1), optic nerve atrophy (1)
Total Retina	Central and peripheral retinal dystrophy (2), retinal abiotrophy (1)	Retinopathy of prematurity (1), retinal dysplasia (1), retinal detachment (1), retinoblastoma (1)
Anterior Segment	Mature cataract (1), aphakia (1)	
Total Globe	Microphthalmos (1), albinism (1), trauma (1)	Microphthalmos (1)

Table 3-6: Summary of types of VF defects among Para nordic and Para alpine participants.

Type of visual field defect	Para nordic (N=26)	Para alpine (N=15)
Peripheral VF defect without central scotoma	80.8%	60%
Peripheral VF defect with scattered peripheral scotomata	7.7%	Nil
Peripheral VF defect with central scotomata	7.7%	20.0%
Peripheral VF defect with ring scotomata	Nil	6.7%
Tunnel vision (<10^0 radius)	Nil	13.3%
Peripheral island of vision	3.8%	Nil
Central scotoma without peripheral VF defect	Nil	Nil
Full field with absolute scotoma in the central (30°) VF	Nil	Nil
Quadrantanopia (partial/complete) without central scotoma	Nil	Nil
Partial hemianopia without central scotoma	Nil	Nil
Asymmetric central VF with scattered scotomata	Nil	Nil

3.4.2 Skiing performance

The average raw-WPNS points of Para nordic participants was 58.73 ± 52.44 (range: 0.00 to 172.07, N=26). The average raw-WPAS points of Para alpine participants for DH discipline was 155.81 ± 66.36 (range: 33.99 to 254.19, N=9), GS was 226.98 ± 212.13 (range: 51.11 to 854.02, N=15), SG was 336.20 ± 341.34 (range: 50.09 to 1299.41, N=13), and SL was 193.40 ± 185.03 (range: 66.77 to 722.13, N=15).

3.4.3 Associations among visual functions

In the Para nordic data (Table 3-7), consistent with previous study results,[33,60,61] static VA was significantly correlated with dynamic VA, CS, and Esterman scoring of VF. Contrast sensitivity and dynamic VA were also significantly correlated. Glare recovery was well correlated with other light and glare related measurements such as GLS and LS. Light Sensitivity was also correlated with TMP and RMP. Translational motion perception and RMP were also significantly correlated.

In the Para alpine data (Table 3-8), also consistent with previous study results,[33,60,61] static VA was significantly associated with dynamic VA, CS, and TMP. Contrast sensitivity and dynamic VA were also significantly correlated. Glare sensitivity was well correlated with LS and GLR. Translational motion perception was also well correlated with dynamic VA and CS. However, RMP and VF did not correlate significantly with any other visual functions in the Para alpine data.

3.4.4 Associations of visual functions and skiing performance

In the Para nordic and Para alpine data, all p-values were adjusted using the Bonferroni-Holm correction method. None of the correlations in the Para nordic or Para alpine data were significant after applying the Bonferroni-Holm correction. The only visual function that was close to being significantly correlated with raw-WPNS points was VF. The summary of the correlation analyses of the vision-related variables with the adjusted, Bonferroni-Holm corrected, p-values in the Para nordic and Para alpine data are provided in Table 3-9. The unadjusted or uncorrected p-values are provided in Table 3-10.

Without accounting for the Bonferroni-Holm corrections in Para nordic skiing, participants' raw-WPNS points were significantly correlated to the Esterman scoring of VFs ($p = 0.004$). There were also trends towards significance for static VA ($p = 0.066$) being correlated with raw-WPNS points.

Table 3-7: Summary of correlations among visual functions in the Para nordic data. Significant correlations among the vision variables are bolded. Sample sizes of each comparison are provided in brackets.

Variable	Static VA	Dynamic VA	CS	TMP	RMP	GLS	GLR	LS	VF
Static VA (logMAR)	τ_b = 1.00 (26)	**τ_b = 0.64, p=0.001 (16)**	**τ_b = -0.71, p<0.001 (26)**	τ_b = 0.57, p=0.098 (13)	τ_b = 0.35, p=0.770 (15)	τ_b = -0.02, p=0.915 (19)	τ_b = -0.14, p=0.770 (19)	τ_b = -0.21, p=0.216 (19)	τ_b = 0.35, p=0.770 (15)
Dynamic VA (logMAR)	**τ_b = 0.64, p=0.001 (16)**	τ_b = 1.00 (16)	**τ_b = -0.64, p=0.001 (16)**	τ_b = -0.01, p=0.960 (15)	τ_b = 0.02, p=0.545 (15)	τ_b = -0.18, p=0.350 (16)	τ_b = -0.22, p=0.262 (16)	τ_b = -0.14, p=0.490 (16)	τ_b = -0.02, p=0.927 (16)
CS (logCS)	**τ_b = -0.71, p<0.001 (26)**	**τ_b = -0.64, p=0.001 (16)**	τ_b = 1.00 (26)	τ_b = -0.12, p=0.551 (15)	τ_b = -0.25, p=0.211 (15)	τ_b = -0.01, p=0.943 (19)	τ_b = -0.08, p=0.642 (19)	τ_b = 0.03, p=0.859 (19)	**τ_b = 0.55, p<0.001 (26)**
TMP (%)	τ_b = 0.57, p=0.098 (13)	τ_b = -0.01, p=0.960 (15)	τ_b = -0.12, p=0.551 (15)	τ_b = 1.00 (15)	**τ_b = 0.53, p=0.008 (15)**	τ_b = -0.17, p=0.410 (15)	**τ_b = 0.42, p=0.039 (15)**	**τ_b = 0.43, p=0.034 (15)**	τ_b = 0.03, p=0.881 (15)
RMP (%)	τ_b = 0.35, p=0.770 (15)	τ_b = 0.02, p=0.545 (15)	τ_b = -0.25, p=0.211 (15)	**τ_b = 0.53, p=0.008 (15)**	τ_b = 1.00 (15)	τ_b = -0.03, p=0.876 (12)	τ_b = 0.28, p=0.177 (15)	**τ_b = 0.44, p=0.029 (15)**	τ_b = -0.20, p=0.315 (15)
GLS (change in logMAR)	τ_b = -0.02, p=0.915 (19)	τ_b = -0.18, p=0.350 (16)	τ_b = -0.01, p=0.943 (19)	τ_b = -0.17, p=0.410 (15)	τ_b = -0.03, p=0.876 (12)	τ_b = 1.00 (19)	**τ_b = 0.37, p=0.036 (19)**	τ_b = 0.27, p=0.132 (19)	τ_b = -0.17, p=0.318 (19)
GLR (change in logMAR)	τ_b = -0.14, p=0.770 (19)	τ_b = -0.22, p=0.262 (16)	τ_b = -0.08, p=0.642 (19)	**τ_b = 0.42, p=0.039 (15)**	τ_b = 0.28, p=0.177 (15)	**τ_b = 0.37, p=0.036 (19)**	τ_b = 1.00 (19)	**τ_b = 0.59, p=0.001 (19)**	τ_b = -0.11, p=0.544 (19)
LS (change in logMAR)	τ_b = -0.21, p=0.216 (19)	τ_b = -0.14, p=0.490 (16)	τ_b = 0.03, p=0.859 (19)	**τ_b = 0.43, p=0.034 (15)**	**τ_b = 0.44, p=0.029 (15)**	τ_b = 0.27, p=0.132 (19)	**τ_b = 0.59, p=0.001 (19)**	τ_b = 1.00 (19)	τ_b = -0.04, p=0.832 (19)
VF (%)	τ_b = 0.35, p=0.770 (15)	τ_b = -0.02, p=0.927 (16)	**τ_b = 0.55, p<0.001 (26)**	τ_b = 0.03, p=0.881 (15)	τ_b = -0.20, p=0.315 (15)	τ_b = -0.17, p=0.318 (19)	τ_b = -0.11, p=0.544 (19)	τ_b = -0.04, p=0.832 (19)	τ_b = 1.00 (26)

Table 3-8: Summary of correlations among visual functions in the Para alpine data. Significant correlations among the vision variables are bolded. Sample sizes of each comparison are provided in brackets.

Variable	Static VA	Dynamic VA	CS	TMP	RMP	GLS	GLR	LS	VF
Static VA (logMAR)	τ_b = 1.00 (15)	**τ_b = 0.69, p=0.004 (11)**	**τ_b = -0.83, p<0.001 (15)**	**τ_b = 0.72, p=0.001 (12)**	τ_b = 0.34, p=0.112 (12)	τ_b = 0.16, p=0.459 (13)	τ_b = -0.03, p=0.902 (13)	τ_b = -0.16, p=0.528 (10)	τ_b = -0.30, p=0.122 (15)
Dynamic VA (logMAR)	**τ_b = 0.69, p=0.004 (11))**	τ_b = 1.00 (11)	**τ_b = -0.59, p=0.015 (11)**	**τ_b = 0.69, p=0.007 (12)**	τ_b = 0.26, p=0.317 (10)	τ_b = 0.40, p=0.096 (11)	τ_b = 0.23, p=0.340 (11)	τ_b = 0.42, p=0.164 (8)	τ_b = 0.06, p=0.813 (11)
CS (logCS)	**τ_b = -0.83, p<0.001 (15)**	**τ_b = -0.59, p=0.015 (11)**	τ_b = 1.00 (15)	**τ_b = -0.61, p=0.007 (12)**	τ_b = -0.38, p=0.086 (12)	τ_b = -0.33, p=0.125 (13)	τ_b = -0.17, p=0.425 (13)	τ_b = -0.02, p=0.928 (10)	τ_b = 0.22, p=0.272 (15)
TMP (%)	**τ_b = 0.72, p=0.001 (12)**	**τ_b = 0.69, p=0.007 (12)**	**τ_b = -0.61, p=0.007 (12)**	τ_b = 1.00 (12)	τ_b = 0.31, p=0.166 (12)	τ_b = 0.13, p=0.577 (12)	τ_b = 0.14, p=0.532 (12)	τ_b = 0.00, p=1.000 (9)	τ_b = -0.30, p=0.189 (12)
RMP (%)	τ_b = 0.34, p=0.112 (12)	τ_b = 0.26, p=0.317 (10)	τ_b = -0.38, p=0.086 (12)	τ_b = 0.31, p=0.166 (12)	τ_b = 1.00 (12)	τ_b = 0.34, p=0.128 (12)	τ_b = 0.33, p=0.147 (12)	τ_b = 0.00, p=1.000 (9)	τ_b = -0.20, p=0.372 (12)
GLS (change in logMAR)	τ_b = 0.16, p=0.459 (13)	τ_b = 0.40, p=0.096 (11)	τ_b = -0.33, p=0.125 (13)	τ_b = 0.13, p=0.577 (12)	τ_b = 0.34, p=0.128 (12)	τ_b = 1.00 (13)	**τ_b = 0.53, p=0.014 (13)**	**τ_b = 0.54, p=0.037 (10)**	τ_b = 0.25, p=0.244 (13)
GLR (change in logMAR)	τ_b = -0.03, p=0.902 (13)	τ_b = 0.23, p=0.340 (11)	τ_b = -0.17, p=0.425 (13)	τ_b = 0.14, p=0.532 (12)	τ_b = 0.33, p=0.147 (12)	**τ_b = 0.53, p=0.014 (13)**	τ_b = 1.00 (13)	τ_b = 0.23, p=0.365 (10)	τ_b = -0.04, p=0.854 (13)
LS (change in logMAR)	τ_b = -0.16, p=0.528 (10)	τ_b = 0.42, p=0.164 (8)	τ_b = -0.02, p=0.928 (10)	τ_b = 0.00, p=1.000 (9)	τ_b = 0.00, p=1.000 (9)	**τ_b = 0.54, p=0.037 (10)**	τ_b = 0.23, p=0.365 (10)	τ_b = 1.00 (10)	τ_b = 0.25, p=0.321 (10
VF (%)	τ_b = -0.30, p=0.122 (15)	τ_b = 0.06, p=0.813 (11)	τ_b = 0.22, p=0.272 (15)	τ_b = -0.30, p=0.189 (12)	τ_b = -0.20, p=0.372 (12)	τ_b = 0.25, p=0.244 (13)	τ_b = -0.04, p=0.854 (13)	τ_b = 0.25, p=0.321 (10)	τ_b = 1.00 (15)

Without accounting for the Bonferroni-Holm corrections in Para alpine, static VA was significantly associated with raw-WPAS points in DH ($p = 0.046$), GS ($p = 0.010$), and SG ($p = 0.007$), and had a trend towards significance in the SL discipline ($p = 0.074$). TMP was significantly associated with raw-WPAS points in SG ($p = 0.041$) and VF was significantly associated with raw-WPAS points SL ($p = 0.029$). TMP also demonstrated a trend towards significance with raw-WPAS points in DH ($p = 0.095$) and GS ($p = 0.084$). CS was significantly associated with raw-WPAS points in GS ($p = 0.017$) and SG ($p = 0.017$). CS also showed trend towards significance with raw-WPAS points in DH ($p = 0.06$) and SL ($p = 0.06$).

Table 3-9: Summary of correlations of visual functions with skiing performances. The adjusted p-values based on the Bonferroni-Holm corrections are presented in the table with sample sizes. None of the values retained significance after applying the Bonferroni-Holm corrections.

Variable	Raw-WPNS points	DH Raw-WPAS points	GS Raw-WPAS points	SG Raw-WPAS points	SL Raw-WPAS points
Static VA (logMAR)	τ_b = 0.26, p=0.792 (26)	τ_b = 0.54, p=0.598 (9)	τ_b = 0.50, p=0.140 (15)	τ_b = 0.57, p=0.098 (13)	τ_b = 0.35, p=0.77 (15)
Dynamic VA (logMAR)	τ_b = -0.22, p=1.000 (16)	τ_b = 0.59, p=0.616 (8)	τ_b = 0.25, p=1.000 (11)	τ_b = 0.46, p=0.90 (9)	τ_b = -0.06, p=1.000 (11)
CS (logCS)	τ_b = -0.23, p=1.000 (26)	τ_b = -0.50, p=0.72 (9)	τ_b = -0.46, p=0.221 (15)	τ_b = -0.51, p=0.221 (13)	τ_b = -0.37, p=0.708 (15)
TMP (%)	τ_b = -0.10, p=1.000 (15)	τ_b = 0.44, p=1.000 (9)	τ_b = 0.39, p=0.96 (12)	τ_b = 0.49, p=0.492 (11)	τ_b = 0.23, p=1.000 (12)
RMP (%)	τ_b = -0.24, p=1.000 (15)	τ_b = 0.03, p=1.000 (9)	τ_b = 0.08, p=1.000 (12)	τ_b = -0.04, p=1.000 (11)	τ_b = -0.02, p=1.000 (12)
GLS (change in logMAR)	τ_b = 0.18, p=1.000 (19)	τ_b = 0.31, p=1.000 (9)	τ_b = 0.21, p=1.000 (13)	τ_b = -0.02, p=1.000 (11)	τ_b = 0.08, p=1.000 (13)
GLR (change in logMAR)	τ_b = 0.21, p=1.000 (19)	τ_b = 0.48, p=1.000 (9)	τ_b = -0.01, p=1.000 (13)	τ_b = -0.13, p=1.000 (11)	τ_b = 0.12, p=1.000 (13)
LS (change in logMAR)	τ_b = -0.06, p=1.000 (19)	τ_b = -0.20, p=1.000 (7)	τ_b = -0.21, p=1.000 (10)	τ_b = -0.33, p=1.000 (8)	τ_b = -0.16, p=1.000 (10)
VF (%)	τ_b = -0.41, p=0.056 (26)	τ_b = 0.06, p=1.000 (9)	τ_b = -0.25, p=1.000 (15)	τ_b = -0.30, p=1.000 (13)	τ_b = -0.43, p=0.406 (15)

Table 3-10: Summary of correlations of visual functions with skiing performances. The unadjusted p-values are presented in the table with sample sizes and significant correlations are provided in bolded text.

Variable	**Raw-WPNS**	**DH Raw-WPAS points**	**GS Raw-WPAS points**	**SG Raw-WPAS points**	**SL Raw-WPAS points**
Static VA (logMAR)	τ_b = 0.26, p=0.066	**τ_b = 0.54, p=0.046 (9)**	**τ_b = 0.50, p=0.010 (15)**	**τ_b = 0.57, p=0.007 (13)**	τ_b = 0.35, p=0.074 (15)
Dynamic VA (logMAR)	τ_b = -0.22, p=0.238	τ_b = 0.59, p=0.044 (8)	τ_b = 0.25, p=0.306 (11)	τ_b = 0.46, p=0.092 (9)	τ_b = -0.06, p=0.813 (11)
CS (logCS)	τ_b = -0.23, p=0.124	τ_b = -0.50, p=0.061 (9)	**τ_b = -0.46, p=0.017 (15)**	**τ_b = -0.51, p=0.017 (13)**	τ_b = -0.37, p=0.059 (15)
TMP (%)	τ_b = -0.10, p=0.728	τ_b = 0.44, p=0.095 (9)	τ_b = 0.39, p=0.084 (12)	**τ_b = 0.49, p=0.041 (11)**	τ_b = 0.23, p=0.299 (12)
RMP (%)	τ_b = -0.24, p=0.317	τ_b = 0.03, p=0.917 (9)	τ_b = 0.08, p=0.731 (12)	τ_b = -0.04, p=0.876 (11)	τ_b = -0.02, p=0.945 (12)
GLS (change in logMAR)	τ_b = 0.18, p=0.301	τ_b = 0.31, p=0.206 (9)	τ_b = 0.21, p=0.357 (13)	τ_b = -0.02, p=1.000 (11)	τ_b = 0.08, p=0.759 (13)
GLR (change in logMAR)	τ_b = 0.21, p=0.225	τ_b = 0.48, p=0.075 (9)	τ_b = -0.01, p=0.951 (13)	τ_b = -0.13, p=0.583 (11)	τ_b = 0.12, p=0.668 (13)
LS (change in logMAR)	τ_b = -0.06, p=0.724	τ_b = -0.20, p=0.543 (7)	τ_b = -0.21, p=0.417 (10)	τ_b = -0.33, p=0.262 (8)	τ_b = -0.16, p=0.528 (10)
VF (%)	**τ_b = -0.41, p=0.004**	τ_b = 0.06, p=0.835 (9)	τ_b = -0.25, p=0.196 (15)	τ_b = -0.30, p=0.158 (13)	**τ_b = -0.43, p=0.029 (15)**

3.4.5 Associations of non-vision related variables and skiing performance

None of the correlations in the Para nordic or Para alpine data were significant after applying the Bonferroni-Holm correction. The summary of the correlation analyses of the non-vision variables with the adjusted p-values in the Para nordic and Para alpine data are provided in Table 3-11. Without accounting for the Bonferroni-Holm corrections (Table 3-12), participants' number of races during the point calculation period was significantly correlated with the raw-WPNS points (p= 0.010) and SG raw-WPAS points (p= 0.031). There were also trends towards significance for total hours of skiing in lifetime (p = 0.098) being correlated with raw-WPNS points.

Table 3-11: Summary of correlations of non-vision variables with skiing performances. The adjusted p-values based on the Bonferroni-Holm corrections are presented in the table with sample sizes. None of the values retained significance after applying the Bonferroni-Holm corrections.

Variable	Raw-WPNS points (N=26)	DH Raw-WPAS points (N=9)	GS Raw-WPAS points (N=15)	SG Raw-WPAS points (N=13)	SL Raw-WPAS points (N=15)
Age (years)	τ_b = 0.05, p=1.000	τ_b = 0.06, p=1.000	τ_b = 0.17, p=1.000	τ_b = 0.12, p=1.000	τ_b = 0.39, p=0.611
Age started skiing (years)	τ_b = 0.19, p=1.000	τ_b = 0.31, p=1.000	τ_b = 0.17, p=1.000	τ_b = 0.03, p=1.000	τ_b = 0.31, p=1.000
Age of onset of impairment (years)	τ_b = -0.06, p=1.000	τ_b = -0.03, p=1.000	τ_b = -0.17, p=1.000	τ_b = -0.28, p=1.000	τ_b = 0.08, p=1.000
Total hours of skiing	τ_b = -0.23, p=1.000	τ_b = -0.06, p=1.000	τ_b = -0.11, p=1.000	τ_b = -0.18, p=1.000	τ_b = 0.03, p=1.000
Number of races	τ_b = -0.37, p=0.130	τ_b = -0.12, p=1.000	τ_b = -0.19, p=1.000	τ_b = -0.46, p=0.403	τ_b = -0.17, p=1.000

Table 3-12: Summary of correlations of non-vision variables with skiing performances. The unadjusted p-values are presented in the table with sample sizes and significant correlations are provided in bolded text.

Variable	Raw-WPNS points (N=26)	DH Raw-WPAS points (N=9)	GS Raw-WPAS points (N=15)	SG Raw-WPAS points (N=13)	SL Raw-WPAS points (N=15)
Age (years)	τ_b = 0.05, p=0.707	τ_b = 0.06, p=0.833	τ_b = 0.17, p=0.371	τ_b = 0.12, p=0.581	**τ_b = 0.39, p=0.047**
Age started skiing (years)	τ_b = 0.19, p=0.422	τ_b = 0.31, p=0.249	τ_b = 0.17, p=0.371	τ_b = 0.03, p=0.903	τ_b = 0.31, p=0.112
Age of onset of impairment (years)	τ_b = -0.06, p=0.657	τ_b = -0.03, p=0.914	τ_b = -0.17, p=0.411	τ_b = -0.28, p=0.218	τ_b = 0.08, p=0.681
Total hours of skiing	τ_b = -0.23, p=0.098	τ_b = -0.06, p=0.835	τ_b = -0.11, p=0.586	τ_b = -0.18, p=0.393	τ_b = 0.03, p=0.882
Number of races	**τ_b = -0.37, p=0.010**	τ_b = -0.12, p=0.669	τ_b = -0.19, p=0.343	**τ_b = -0.46, p=0.031**	τ_b = -0.17, p=0.371

3.4.6 Visual functions predictive of skiing performances

Multivariable regression analysis was used to look at whether or not skiing performances could be predicted based on any of the individual visual functions measured. Based on the correlation analyses, static VA, VF, number of races, and total hours of skiing were included in the modelling for Para nordic skiing performance, and a significant regression equation was found $F(4, 21) = 7.12$, $p = 0.001$, $R^2 = 0.58$. Para nordic predicted raw-WPNS points were equal to 130.484 – 3.981(Number of races) – 0.006 (Total hours of skiing). In other words, a participant's Para nordic skiing performance improved by 3.981 points for each race competed by the participant during the points calculation period and by 0.006 points for each hour of skiing.

Static VA, dynamic VA, CS, TMP, and VF showed a significant association or trend towards a significant association with performance in one or more of the Para alpine disciplines and were considered for inclusion in the multivariable regression. Static VA had strong significant correlations with skiing performances in most of the Para alpine disciplines and static VA was also strongly correlated with dynamic VA, CS, and TMP. To prevent multicollinearity and a high variation inflation factor in the multivariable regression model, static VA was chosen for inclusion in the model as the most representative visual function of these four visual functions. Thus, the final regression model for Para alpine included static VA, VF, skier's age, and the number of races.

There was no significant regression equation for DH ($F(4,4) = 0.46$, $p=0.76$, $R^2 = 0.32$). For GS, a significant regression equation was found $F(4,10) = 14.36$, $p<0.001$, $R^2 = 0.85$. Para alpine participants' predicted GS raw-WPAS points were equal to -74.472 + 166.991(Static VA) + 5.557 (Age), where static VA was measured in logMAR units and age was measured in years. Participants' Para alpine GS skiing performance points deteriorated by 166.991 points for each 1.00 logMAR increase in static VA (worsening) and by 5.557 points for an increase in each year of age.

For SG, a significant regression equation was found $F(4,8) = 8.71$, $p=0.05$, $R^2 = 0.81$. Para alpine participants' predicted SG raw-WPAS points were equal to 13.714 + 217.007(Static VA), where static VA was measured in logMAR units. Participants' Para alpine SG skiing performance points deteriorated by 217.007 points for each 1.00 logMAR increase in static VA.

Similar to the GS results, a significant regression equation was found $F(4,10) = 14.66$, $p<0.01$, $R^2 = 0.85$ for SL performance points. Para alpine participants' predicted SL raw-WPAS points were equal to -164.532 + 145.066(Static VA) + 5.739(Age), where static VA was measured in logMAR units and age was measured in years. Participants' Para alpine SL skiing performance deteriorated by

145.066 points for each 1.00 logMAR increase in static VA and by 5.739 points for an increase in each year of age.

3.5 Discussion

These studies were conducted to identify the visual function assessments to be included in classification. Multiple factors such as training, skill development and coaching levels influence the performance of skiers in addition to various physical and psychological factors, which are unique to each individual. Ideally, a large study population would have been used to assess the significance of the broad range of vision functions on the skiing performance, as was done in this study, because the high variation in the other non-vision factors could mask the effects of vision on performance. However, the Para nordic and Para alpine skiers' populations in the world are unique and small, because of which, it is impossible to obtain large sample populations to study. However, these studies recruited 56.5% and 44.1% of the world's elite, World Championship eligible Para nordic and Para alpine populations competing at the time of the study, respectively. Only elite, World Championship eligible skiers were recruited for these studies to ensure that the variations in skill development, training, and coaching levels were as small as possible between participants. It is also noteworthy that 72.4% of the Para nordic participants and 65.2% of the Para alpine participants, who were present at the specific competition events where the research was conducted, participated in these studies. Data were also collected at a second Para nordic event, at which, 38.5% of the skiers who competed in the 2018 event participated. The skiers who participated in the 2018 event were not present at the initial 2017 event, and so had not had a prior opportunity to complete the study. Therefore, despite the small sample sizes, it can be seen that the study populations in these studies were actually very representative of the entire Para nordic and Para alpine populations.

The results of the Para nordic study suggests that even though static VA had possible associations and VF had strong associations with Para nordic skiing performance, individual vision function assessments were not predictive of Para nordic skiing performance. The number of races that the participants competed in and the total hours of skiing were the only predictive factors of Para nordic skiing performance when both vision and non-vision variables were taken into account. That is not to say that static VA and VF do not impact performance. Rather, the training variables seem to have a more significant impact on skiing performance than vision.

In Para alpine, better static VA was predictive of better GS, SG, and SL performances, which require more technical skill and less speed than DH. Though not predictive, better VF was also associated with better SL performances (prior to applying Bonferroni-Holm corrections). Slalom is the most technical alpine discipline, requiring athletes to sometimes look several gates ahead and shift their gaze frequently between different gate positions.[49] The need to attend to multiple gates might be the reason behind the association of VF with the SL performance. It is also worth noting that SL and GS are the two most popular alpine disciplines, with participation from skiers with the most severe impairments (B1 class). DH had the least number of participants and did not have participation from skiers in B1 class, probably due to the increased speed (maximum speed of 150km/h) and high visual demands involved in DH.[106] Additionally, downhill courses are steeper and longer compared to the other alpine courses, which limits their availability for training. The limited availability of well-groomed DH courses for training might also have reflected in the reduced participation. It is also reported that DH is the alpine discipline that is reported to have the highest injury incidence rates.[107]

Considering both the correlation and regression analyses, static VA and VF appear to be associated with Para nordic skiing performance and should be included as visual functions in Para nordic classification. Performance in the Para alpine technical disciplines, which have participation from skiers with a wide range of visual impairments, seems to be predicted by the static VA and associated with VF. Even though dynamic VA, CS, and TMP were associated with the performance in some Para alpine disciplines, they are also strongly associated with static VA and do not need to be included as separate tests in classification. This decision is supported by the IPC joint position stand on classification research, which clearly states that a test can be incorporated into the classification only if its addition improves the ability of classification system to minimize the impact of impairments on the outcome of competition. Thus, these studies concluded that static VA and VF should be considered as the measures of visual function used in Para nordic and Para alpine classification systems going forward.

3.6 Thesis progress II

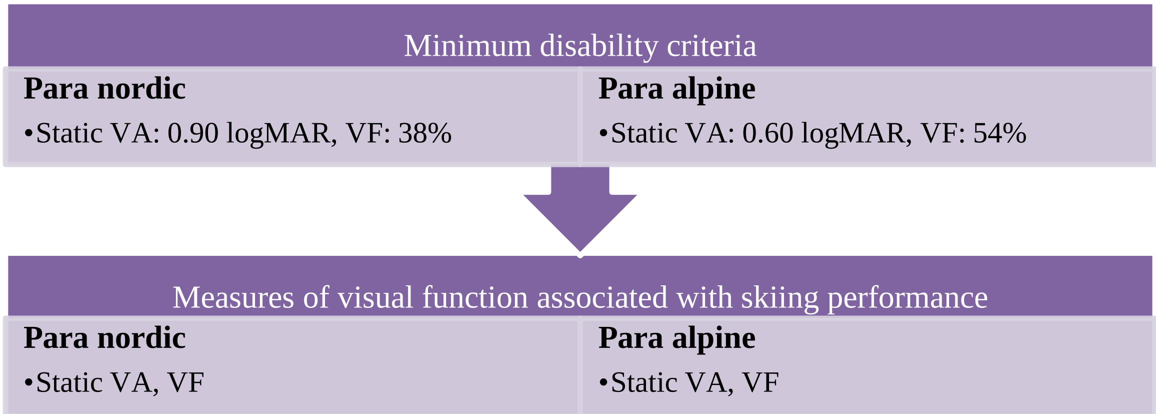

Figure 3-1: Thesis progress II outlining the main objectives and conclusions of Chapter 2 and Chapter 3. The findings from the Chapter 3 suggest that static VA and VF are the only visual functions associated with Para nordic and Para alpine skiing performance.

Chapter 4
Investigation of sports class allocation criteria in Para nordic and Para alpine skiers with visual impairments

4.1 Chapter summary

Introduction: The current International Paralympic Committee classification criteria allocate skiers with vision impairment to classes based only on the static visual acuity and visual field radius of their better eye. Prospective observational studies were conducted to investigate whether or not a broad range of visual functions were different among groups of skiers who were found to have different levels of skiing performance.

Methods: Elite Para nordic skiers (n=26) and elite Para alpine skiers (n=15) were recruited at the 2017 Para Nordic Skiing World Championships, a 2018 Para Nordic World Cup, and the 2017 Para Alpine Skiing World Championships. Static and dynamic visual acuities, light sensitivity, glare sensitivity, glare recovery, contrast sensitivity, translational and radial motion perception, and visual field were assessed binocularly in all participants. Skiing performances were calculated using modified Para nordic and Para alpine skiing points systems based on participants' raw times. Clusters of participants with similar performances were identified for both sports and the vision and non-vision variables were examined using cluster analysis to determine significant differences between performance groups.

Results: Para nordic clusters 1 and 2 had participants with better skiing performances, better static visual acuities and larger visual fields compared to participants in cluster 3. Cluster 1 participants also had a significantly higher number of races in the 2016-2018 seasons compared to cluster 3 participants. The Para alpine downhill discipline had two clusters differing significantly in terms of the participants' dynamic visual acuity. In Para alpine giant slalom, super-G, and slalom, the average static visual acuity among the clusters were significantly different. In slalom, the cluster with better performance also had a significantly larger visual field.

Conclusions: We recommend that participants with light perception or no light perception vision should be allocated a different class than participants with measurable vision in both Para nordic and Para alpine skiing.

4.2 Introduction

The purpose of classification systems in the Paralympics is to encourage individuals with disabilities to participate in sports by reducing the effect of their impairments on the sports performance outcome.[7] The International Paralympic Committee (IPC) tries to fulfil this purpose by allocating eligible athletes to classes or groups such that the level of impairments is similar within each class. The current sports class allocation systems in the visually impaired (VI) category of most Para sports are based only on two measures of visual function: static visual acuity (VA) and visual field (VF) of the athlete's better eye. Athletes with the most severe impairments with static VAs worse than 2.6 logMAR, as well as athletes with and without light perception vision are allocated into the B1 class. Athletes with static VAs ranging from 1.5 logMAR to <2.6 logMAR or a VF radius of less than or equal to 5 degrees are classified as B2 and have moderately severe vision impairments. The B3 class, with the least severe vision impairments, has athletes with static VAs ranging from 1.0 logMAR to <1.5 logMAR or a VF radius of less than or equal to 20 degrees.[11] Impairments in other visual functions such as contrast sensitivity (CS) or colour vision (CV), which could affect sports performance are not taken into consideration currently.

A four-round Delphi study completed with 25 VI sports experts to identify classification research priorities concluded that new classification systems should be designed as the current ones take neither the unique visual demands nor the performance environments of each sport into consideration.[31] A joint position stand published by Mann and Ravensbergen[32] suggested that all the visual functions significantly affecting sports performance should be taken into account while designing new classification systems specific to each sport. They also recommended that the sports performance environment, as well as specific adaptations used in some Para sports, must also be taken into consideration. For example, some Para sports are performed monocularly (e.g., shooting Para sport), while some are performed binocularly (e.g., Para swimming), and some sports rules allow the appointment of assistants to help with the orientation and mobility of athletes (e.g., guides in Para skiing, tappers in Para swimming). Finally, Mann and Ravensbergen[32] recommended that testing the athletes' visual functions at varying light levels might be useful since varying light levels affect the performance of athletes with certain eye conditions (e.g., albinism).

Myint et al.[37] reported that shooting Para sport athletes rely on auditory information from the aiming devices emitting sound based on the proximity of target more than visual information. It was concluded that the severity of the visual impairment does not affect rifle-shooting performance, and one competition class was sufficient for fair competition in shooting Para sport.[37,21] However, in other more dynamic sports, preliminary research suggests that more than one competition class might be necessary. Malone et al.[40] reported that the swimming performances of athletes in the B2 and B3 classes were better than athletes in the B1 class even though swimming performance also depends on various non-visual forms of feedback such as proprioception, vestibular contributions, and instructions from guides or coaches.[40,42] In Judo, athletes are currently classified based only on their body weight in the assumption that starting the fight having a grip on each other eliminates the need for having visual information to succeed in the fight.[17] However, Krabben et al.[44] reported that the number of medals won by the B1 athletes was significantly lower compared to that of the athletes in B2 and B3 classes. Separate Delphi studies conducted with experts in VI Para swimming, VI judo, and VI Para athletics concluded that the current classification systems are not sufficient. Extensive research is ongoing to develop classification systems in those Para sports.[34–36]

Our laboratory has been conducting studies to identify the visual aspects and related visual functions associated with Para nordic and Para alpine skiing performance since March 2015. In general, both Para nordic and Para alpine skiing have vision demands at far distances and skiers have to process visual information while moving at high speeds.[50] Skiers have to make quick decisions in response to visual information about their speed, direction, and body position. The vision demands involved in skiing suggest that visual functions such as VA, CS, and depth perception might be crucial for competitive skiing.[53,51,52] Since skiers often move at high speeds, it is also necessary to assess the significance of static and dynamic measures of these visual functions whenever possible.

Skiing is thought to depend more on central vision than the peripheral vision and skiers need to process information from larger visual spaces than most of the other sports like tennis or swimming, which suggests that there are also peripheral vision demands while skiing.[53] In fact, one of the earliest studies conducted on alpine skiers in 1955 reported that the occlusion of peripheral vision caused marked deterioration in the motor control of skiers, compared to occlusion of central vision.[54] Furthermore, skiers are exposed to glare from snow and bright sunlight in their environment, as well as shadows cast by the trees; skiers visibility can be greatly altered by changes in the weather, lighting conditions, and the conditions of snow, especially while moving from sunny to shady parts of courses.[53]

There are three main individual competition events in Para nordic skiing: sprint, middle distance, and long distance, which differ in terms of the length of the ski courses. There are four major disciplines in Para alpine skiing. Downhill (DH) is a speed event, where skiers are timed as they race down a long, steep course that may include a few gates, turns, and jumps. Slalom (SL) is a technical event with shorter courses and a higher number of gates compared to the other Para alpine disciplines. Giant slalom (GS) is also a technical event with longer courses and fewer wider and smoother turns than SL. Super G (SG) combines the speed of DH with the turns of GS. Thus, it could be considered an event requiring speed as well as technical skill.

While nordic and alpine skiing are similar in terms of the high demands they place on vision and the challenging environments competitions take place in, they differ in aspects related to the terrain and skiing techniques. Although both nordic and alpine skiing are physically demanding, Stöggl et. al reported that the energy spent by a skier during an hour of nordic skiing is equivalent to that spent during 2.5 hours of alpine skiing.[108] However, due to the speed involved, the risk of injuries are higher in Para alpine skiing, compared to Para nordic skiing.[109] Nordic skiing is practiced on groomed trails on flatter and often tree-laden terrains, which are in loops, with uphills, gentle downhills, and curves.[63] Skiers race only downhill in alpine skiing, and the groomed courses are shorter, steeper and wider compared to the nordic courses. There could be multiple skiers on the nordic course in some events, while alpine courses will never have more than one skier competing at a time,[25] therefore nordic skiers might need to utilize visual information from a wider field to avoid collision with other skiers or to look around trees or curves, compared to the alpine skiers. However, alpine skiers might need faster processing of visual information to make quicker decisions on adjusting their speed and positions, compared to nordic skiers. Considering these unique demands of both sports, the levels of impairments in visual function affecting the performance need to be explored separately in Para nordic and Para alpine skiing.

Based on expert opinions and observations, our laboratory research team conducted initial studies using a test battery that included a range of visual function assessments such as static VA, CS, dynamic VA, low contrast VA, glare sensitivity (GLS), glare recovery (GLR), and colour vision, which were expected to be associated with Para nordic and Para alpine skiing performances. These studies were focused on assessing the feasibility of measuring a wide range of visual functions in the Para skier populations with varying levels of low vision, and the studies concluded that most of the visual function assessments were feasible to be used on these populations. However, the Pelli-Robson chart for measuring CS was found to have poor feasibility due to its limited spatial frequency and contrast range, which were not suitable for the wide range of impairments tested. Also, no binocular measurement techniques/ tools were available at the time of the study to measure GLS, GLR, and VF (Chapter 3).[33,60,61]

Therefore, the purpose of this study was to design new criteria to allocate Para nordic and Para alpine skiers into sports classes based on visual functions that significantly affect skiing performance. This purpose was achieved by examining for the existence of clusters, or groups of skiers with similar skiing performances, within currently classified elite Para nordic and Para alpine populations, and by comparing vision and non-vision related variables among these groups in each sport. The Para nordic competition events of different distances were examined as a pooled group because the three individual Para nordic competition events are very similar in terms of the visual demands they require. These events mainly differ in terms of the distance of courses involved. The four Para alpine disciplines were examined separately as the visual demands might be significantly different among them due to the differences in terrain, gate settings, and skiing techniques involved. A refined test battery was used to assess the visual functions, based on the previous studies (Chapter 3).[33,60,61]

4.3 Materials and Methods

This chapter describes the second analysis of the data presented in Chapter 3. The participants, visual function assessments conducted, and the skiing performance points calculated were as described in Chapter 3. The refined test battery included binocular tests of static VA, dynamic VA, CS, GLS, GLR, LS, TMP, RMP, and VF and skiing performance was assessed using the recalculated, raw-WPNS and raw-WPAS points. The non-vision related performance variables accounted for in this analysis included age, age started skiing, age of onset of impairment, total lifetime hours of skiing, and number of races during the validity period.

4.3.1 Data analysis

Data analysis was conducted using SPSS for Windows (version 25.0, SPSS, Inc.) and SPSS modeler (version 18.2.1). The raw-WPNS and raw-WPAS points were not normally distributed, and non-parametric tests were used for further analysis in two steps. Initial data analysis was focused on identifying the visual functions associated with and predictive of skiing performances using Kendall τ correlations (with Bonferroni-Holm correction) and multiple linear regression analyses (Chapter 3).[105] This initial analysis concluded that only static VA and VF were associated with Para nordic and Para alpine skiing performances. This chapter includes the results of the second analysis conducted on this data set to identify natural clusters of data within the Para nordic and Para alpine participants based on similarities in skiing performance using hierarchical clustering. Once clusters were identified, comparisons of vision and non-vision related variables among different performance clusters were done using the Kruskal-Wallis test with the Dunn-Bonferroni post hoc test when there were more than two clusters, or a Mann-Whitney U post hoc test when there were only two clusters. The Dunn-Bonferroni or Mann-Whitney U post hoc tests were carried out for each pair of groups to calculate the adjusted significance when Kruskal Wallis tests were found to be significant.

Clustering is one of the simplest and yet comprehensive data mining techniques. The agglomerative hierarchical clustering algorithm was used to determine the clusters based on the performance points, which starts the process by considering each participant as a separate cluster. In each subsequent step, the two clusters that were most similar were combined to form a single cluster. This process continued until all clusters were combined finally to form one large cluster. For the analysis completed here, clusters were identified solely on the participants' skiing performance points, which means that all participants, even those who did not have measurable CS or DVA, were included in the analysis. Arbitrary values were assigned for the static VA and 0 values were assigned for the CS and VF of participants with LP or NLP vision as detailed in Chapter 3, to include them in the cluster comparisons. The missing or unmeasurable dynamic VA, GLS, GLR, LS, TMP, or RMP data did not affect the clusters formed because the clusters were formed based only on performance points, which all athletes had. The summary data presented in the cluster comparison tables do not include the arbitrarily assigned values of VA, CS, or VF of participants with LP or NLP vision, and include only actual measured values.

Ward's linkage criterion was used to determine the similarity of each cluster and identified the two most similar clusters by assessing the sum of squares of distances between the clusters. Ward's method is known to produce clusters with the same shape and roughly the same number of observations.[110] The cluster solution obtained prior to a large change in the coefficient of distances between the clusters was chosen as the best solution.

The nearest neighbour criterion was used initially to identify potential outliers and the average linkage criterion was used to check the consistency of the results obtained through Ward's linkage. The nearest neighbour method defines the similarity between clusters as the shortest distance from any object in one cluster to any object in the other. Thus, any single participant cluster which stays as separate until the last step of the clustering could be considered as a potential outlier and examined.[111] Average linkage is another commonly used clustering method, in which the distance between two clusters is defined as the average distance between all pairs of the two clusters' members. As the cluster results are known to occasionally vary depending on the distance measure used, the cluster analyses were repeated using the average linkage method to assess the consistency of the cluster results.

In addition to the cluster analysis, a decision tree analysis was used in the Para nordic data to identify the best predictor of skiing performances in addition to the hierarchical clustering. Expected performance was defined as the average raw-WPNS points of the cluster with least (best) raw-WPNS points.[112] Decision trees differ from hierarchical clustering as decision trees are created to maximize the leaf purity of skiing performances. There is no such target for the cluster tree, which groups the clusters based on the similarity between each cluster. Therefore, both hierarchical clustering, as well as decision trees, were considered to identify the sports class criteria in Para nordic data. Due to fewer participants in the Para alpine study and unequal cluster sizes as generated by the hierarchical cluster analysis, decision trees were not possible in the Para alpine data.

4.4 Results

A total of 26 Para nordic skiers (18 male, 8 female; age 26.0 ± 6.3 years, range: 18 to 43 years) from 13 nations and 15 Para alpine skiers (8 male, 7 female; age 28.1 ± 11.6 years, range 16 to 58 years) from 10 nations participated in these studies. The demographics, as well as the summary of visual functions of participants from each sport, are provided in Tables 3.1 to 3.3 of Chapter 3.

4.4.1 Skiing performance

The average raw-WPNS points of Para nordic participants was 58.73 ± 52.44 (range: 0.00 to 172.07, N=26). The average raw-WPAS points of Para alpine participants for DH discipline was 155.81 ± 66.36 (range: 33.99 to 254.19, N=9), GS was 226.98 ± 212.13 (range: 51.11 to 854.02, N=15), SG was 336.20 ± 341.34 (range: 50.09 to 1299.41, N=13), and SL was 193.40 ± 185.03 (range: 66.77 to 722.13, N=15).

4.4.2 Para nordic skiing performance clusters

No outliers were identified in the Para nordic or Para alpine data based on the nearest neighbour criterion. Both the Ward's linkage and average linkage methods generated the same performance clusters, which suggests that the cluster results obtained through Ward's linkage method are consistent. Therefore, none of the cluster conclusions would have changed if the average-linkage method had been used instead of the Ward's linkage criterion.

The cluster analysis in the Para nordic data resulted in three distinct clusters based on the WPNS points ($p<0.001$) (Figure 4-1A). Raw-WPNS points of participants based on their current classes are also provided for comparison purposes as Figure 4-1B. There was an overall significant difference among the skiers' performance based on their current class ($p=0.002$). Post hoc analyses suggested that the performances of B1 skiers were significantly different from that of B2 skiers ($p = 0.001$).

The summary statistics of the vision and non-vision variables in each cluster are shown in Table 4-1. In addition to the performance points, static VA, VF, and the number of races were significantly different among the clusters (Static VA $p = 0.041$; VF $p = 0.004$; number of races $p = 0.044$). The first cluster had participants with the best performance (least average performance points), better static VAs, and larger VF extents. Cluster 3 had participants with the worst average performance and cluster 2 had performance points in between clusters 1 and 3. The average static VA and VF between clusters 1 and 3 (adjusted significance values: Static VA $p= 0.029$; VF $p = 0.002$), and between 2 and 3 (adjusted significance values: Static VA $p= 0.030$; VF $p = 0.010$) were significantly different. The average number of races in cluster 3 was significantly different from cluster 1 (adjusted significance: $p = 0.015$), but clusters 2 and 3 were not significantly different (adjusted significance: $p = 0.492$). Cluster 1 and 2 were not significantly different in any vision or non-vision related aspects except in the raw-WPNS points.

Based on the current classification system defined in the existing sport rules, the Para nordic population had 15.4% of participants classified as B3, 53.9% classified as B2, and 30.8% classified as B1. The 1st Para nordic cluster with the best skiing performance, static VA, and VF had 10.0% of B3 and 90.0% of B2 participants, respectively. The 2nd Para nordic cluster had 28.6% B3, 57.1% B2, and 14.3% B1 participants. The B1 participant in cluster 2 had light perception vision. The 3rd cluster had 11.1% of B3 and B2 skiers each and 77.8% of B1 participants. One of the B1 participants in cluster 3 had measurable static VA (2.50 logMAR) with 10.0% of Esterman VF extent, 1 had light perception, and 5 had no light perception.

Table 4-1: Summary statistics (mean±SD, median) of vision and non-vision related variables the Para nordic clusters. The values of variables that are significantly different among the clusters are bolded. The values of non-vision variables are italicized. The summary data include only actual measured values.

Variable	Cluster 1 (N=10)	Cluster 2 (N=7)	Cluster 3 (N=9)	P value (overall)
Raw-WPNS points	**6.50±7.21, 2.82 (10)**	**53.16±16.30, 57.16 (7)**	**121.14±22.72, 114.71 (9)**	**<0.001**
Static VA (logMAR)	**1.77±0.43, 1.60 (10)**	**1.61±0.21, 1.57 (6)**	**1.73±0.68, 1.50 (3)**	**0.041**
Dynamic VA (logMAR)	1.90±0.25, 2.00 (9)	1.82±0.36, 1.60 (5)	1.30±0.14, 1.30 (2)	0.091
AULCSF (logCS)	0.17±0.25, 0.06 (10)	0.19±0.22, 0.16 (6)	0.36±0.41, 0.28 (3)	0.189
TMP (%)	58.0±30.0, 62.7 (9)	59.3±18.3, 66.6 (4)	48.3±19.2, 48.3 (2)	0.744
RMP (%)	65.8±29.8, 67.7 (9)	43.6±17.2, 52.1 (4)	59.8±32.8, 59.8 (2)	0.411
LS (change in logMAR)	0.01 ± 0.08, 0.01 (10)	0.00 ± 0.11, 0.01 (6)	-0.02 ± 0.05, 0.00 (3)	0.816
GLS (change in logMAR)	0.13 ± 0.17, 0.06 (10)	0.23 ± 0.39, 0.10 (6)	0.36 ± 0.54, 0.10 (3)	0.813
GLR (change in logMAR)	0.01 ± 0.13, 0.00 (10)	0.04 ± 0.16, 0.01 (6)	0.27 ± 0.45, 0.02 (3)	0.454
VF (%)	**58.3±24.1, 63.8 (10)**	**64.4±25.8, 66.3 (6)**	**34.7±26.9, 30.8 (3)**	**0.004**
Age (years)	23.6±3.0, 24.5 (10)	29.0±8.6, 27.0 (7)	26.2±6.6, 26.0 (9)	0.340
Age started skiing (years)	13.6±4.5, 16.0 (10)	12.3±8.6, 15.0 (7)	16.0±8.9, 15.0 (9)	0.439
Age of onset of impairment (years)	5.5±4.5, 5.0 (10)	9.9±12.1, 8.0 (7)	5.9±7.6, 3.0 (9)	0.917
Total lifetime hours of skiing	5447.6±4383.9, 3796.0 (10)	4440.0±4378.2, 3064.0 (7)	3625.1±3023.9, 2620.0 (9)	0.447
Number of races during the validity period	**15.2±4.7, 16.5 (10)**	**11.0±4.4, 10.0 (7)**	**9.8±5.8, 7.0 (9)**	**0.044**
Current competition class	B3 (10.0%), B2 (90.0%)	B3 (28.6%), B2 (57.1%), B1 (14.3%)	B3(11.1%), B2 (11.1%), B1(77.8%)	

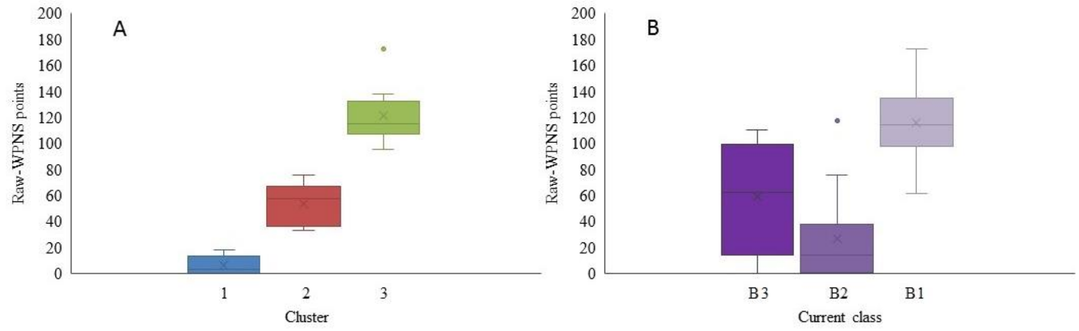

Figure 4-1: Raw-WPNS points for each cluster (A) and Raw-WPNS points for each current competition class (B) for the Para nordic participants.

Since all the three clusters were comparable in size and were distinct in terms of average raw-WPNS points, a decision tree analysis was used to determine the factors best predicting ‘expected’ and ‘below-expected’ performances (Figure 4-2). Expected performance was defined as the average raw-WPNS points in Cluster 1, and ‘below-expected’ performance was defined as any performance points that exceeded the upper 99% confidence interval around the average raw-WPNS of cluster 1. The decision tree analysis indicated that the participants who competed in more races were more likely to perform better. In participants with ≤14.5 races, the second most significant predictor of ‘below-expected’ performance was having a VF extent of ≤33.3%. Static VA >1.98 logMAR was a significant predictor of performance in participants with ≤14.5 races and >33.3% VF extents.

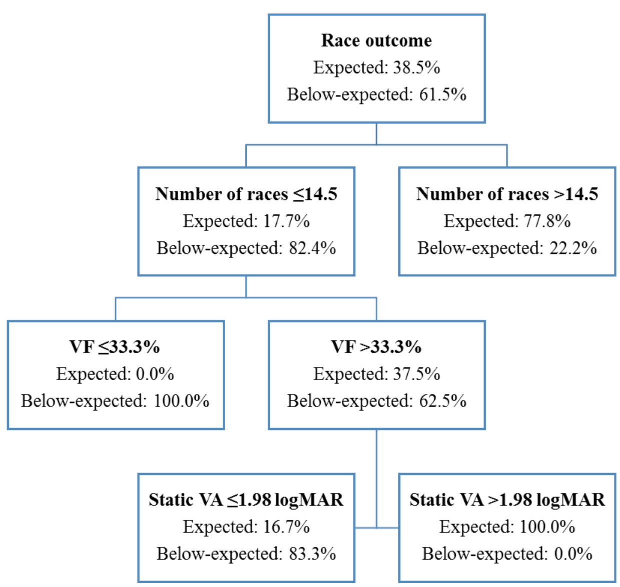

Figure 4-2: Decision tree analysis results using the C 5.0 algorithm for the Para nordic participants.

4.4.3 Para alpine skiing performance clusters

Hierarchical cluster analysis was conducted separately for each Para alpine discipline. Two distinct clusters were identified in the DH discipline based on the raw-WPAS DH points (p=0.016) (Figure 4-3A), which also differed significantly in terms of the participants' dynamic VA (p=0.029). Static VA, CS, and TMP were also nearly significantly different (p=0.063) between the clusters (Table 4-2). There were no study participants classed as B1 (>2.6 logMAR, LP or NLP VA) who competed in DH. 80% and 20% of participants in cluster 1 were currently classified as B2 and B3, respectively. 25% and 75% of participants in cluster 2 were presently classified as B2 and B3, respectively. The DH raw-WPAS points of participants based on their current classes are also included in Figure 4-3B for comparison purposes. There was no overall significant difference between the skiers' performance based on their current class (p=0.09).

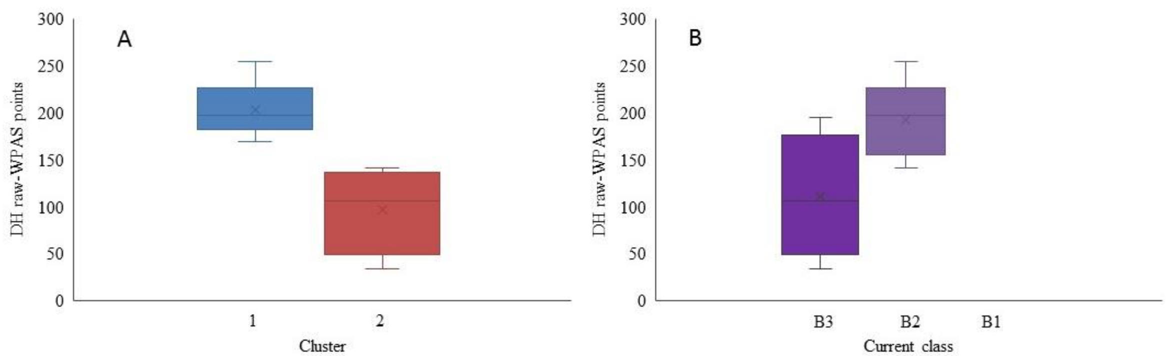

Figure 4-3: Raw-WPAS points for each cluster (A) and Raw-WPAS points for each current competition class (B) for the Para alpine DH participants.

Table 4-2: Summary statistics (mean±SD, median) of the vision and non-vision variable in Para alpine DH clusters. The values of variables that are significantly different between the clusters are bolded. The values of non-vision variables are italicized. The summary data include only actual measured values.

Time	Cluster 1 (N=4)	Cluster 2 (N=5)	P value (overall)
DH raw-WPAS points	**97.10±46.5, 106.6 (4)**	**187.55±21.6, 195.1 (5)**	**0.016**
Static VA (logMAR)	0.65±0.58, 0.67 (4)	1.38±0.23, 1.40 (5)	0.063
Dynamic VA (logMAR)	**0.88±0.29, 0.90** (4)	**1.80±0.33, 1.90** (4)	**0.029**
AULCSF (logCS)	1.16±0.66, 1.16 (4)	0.30±0.30, 0.20 (5)	0.063
TMP (%)	29.6±20.4, 25.7 (4)	65.0±22.7, 61.0 (5)	0.063
RMP (%)	47.8±38.0, 38.1 (4)	59.0±31.6, 55.5 (5)	0.556
LS (change in logMAR)	0.07±0.08, 0.04 (4)	0.07±0.16, 0.02 (3)	1.000
GLS (change in logMAR)	0.09±0.08, 0.08 (4)	0.15±0.03, 0.14 (5)	0.413
GLR (change in logMAR)	0.05±0.09, 0.01 (4)	0.07±0.05, 0.06 (5)	0.286
VF (%)	42.5±45.3, 43.3 (4)	50.1±25.2, 52.5 (5)	0.730
Age (years)	32.3±18.7, 26.5 (4)	27.4±11.9, 20.0 (5)	1.000
Age started skiing (years)	15.5±10.5, 11.5 (4)	18.0±8.9, 17.0 (5)	0.413
Age of onset of impairment (years)	9.3±11.6, 5.5 (4)	4.8±5.6, 3.0 (5)	0.730
Total lifetime hours of skiing	6136.5±5982.3, 5568.0 (4)	5243.2±4162.5, 4320.0 (5)	1.000
Number of races during the validity period	7.0±2.8, 8.0 (4)	6.6±2.0, 6.0 (5)	0.730
Current competition class	B3 (20.0%) & B2 (80.0%)	B3 (75.0%) & B2 (25.0%)	

Three distinct groups were identified in GS that performed significantly different in terms of the GS raw-WPAS points ($p<0.05$) (Figure 4-4A). The GS raw-WPAS points of participants based on their current classes are also provided for comparison purposes as Figure 4-4B. There was no overall significant difference among the skiers' performance based on their current class ($p=0.09$).

Static VA and CS were the only variables found to be significantly different between the clusters (static VA: $p=0.019$ and CS: $p = 0.043$). None of the other vision or non-vision variables were different between the clusters (Table 4-3). Post-hoc analysis showed that static VA was significantly different between clusters 2 and 3 (adjusted significance: $p=0.019$), but there was no difference in static VA between clusters 1 and 2 (adjusted significance: $p = 0.253$). Similarly, CS was significantly different only between clusters 1 and cluster 3 (adjusted significance: $p=0.041$). Only cluster 3 had participants with LP or NLP vision. 40% and 60% of participants in cluster 1 and 62.5% and 37.5% of participants in cluster 2 were currently classified as B2 and B3 respectively. The two participants in cluster 3 were classified as B1.

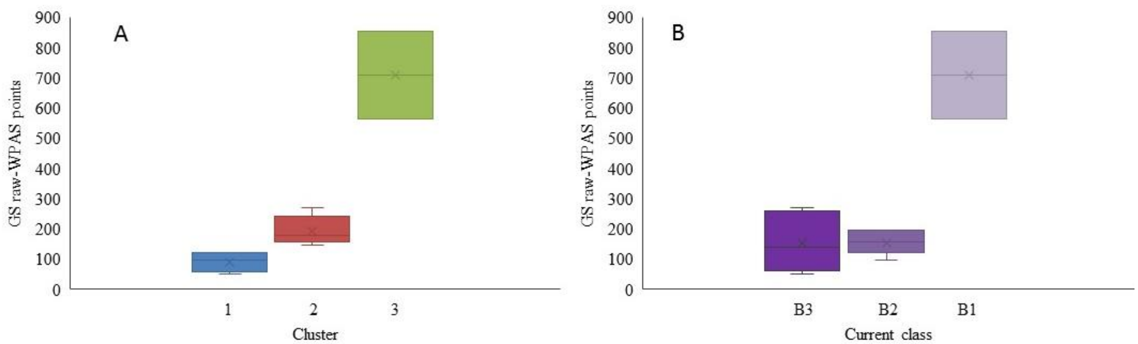

Figure 4-4: Raw-WPAS points for each cluster (A) and Raw-WPAS points for each current competition class (B) for the Para alpine GS participants.

Table 4-3: Summary statistics (mean±SD, median) of the vision and non-vision variables in Para alpine GS clusters. The values of variables that are significantly different among the clusters are bolded. N/M indicates that the particular variable was non-measurable. The values of non-vision variables are italicized. The summary data include only actual measured values.

Variable	Cluster 1 (N=5)	Cluster 2 (N=8)	Cluster 3 (N=2)	P value (overall)
GS raw-WPAS points	**90.34±32.70, 95.80 (5)**	**194.70±46.10, 187.17 (8)**	**563.66 & 854.02**	**0.003**
Static VA (logMAR)	**0.99±0.43, 1.06 (5)**	**1.34±0.53, 1.52 (8)**	**NLP and LP**	**0.019**
Dynamic VA (logMAR)	1.26±0.42, 1.20 (5)	1.67±0.64, 1.85 (6)	N/M	0.197
AULCSF (logCS)	0.72±0.50, 0.64 (5)	0.42±0.64, 0.19 (8)	N/M	0.043
TMP (%)	40.4±14.4, 43.8 (5)	67.9±36.8, 75.7 (7)	N/M	0.120
RMP (%)	50.2±37.3, 51.5 (5)	61.6±23.5, 55.5 (7)	N/M	0.416
LS (change in logMAR)	0.12±0.11, 0.10 (4)	0.08±0.16, 0.04 (6)	N/M	0.588
GLS (change in logMAR)	0.09±0.08, 0.08 (5)	0.24±0.19, 0.16 (8)	N/M	0.122
GLR (change in logMAR)	0.05±0.09, 0.02 (5)	0.04±0.08, 0.03 (8)	N/M	0.941
VF (%)	46.7±41.6, 55.0 (5)	47.1±30.0, 42.5 (8)	N/M	0.123
Age (years)	25.4±8.8, 20.0 (5)	29.1±14.6, 25.5 (8)	28.0 & 34.0	0.644
Age started skiing (years)	15.6±9.2, 12.0 (5)	16.3±8.2, 14.5 (8)	10.0 & 25.0	0.911
Age of onset of impairment (years)	9.0±10.0, 8.0 (5)	3.1±4.1, 1.0 (8)	9.0 & 0.0	0.403
Total lifetime hours of skiing	4842.8±3873.1, 4320.0 (5)	4380.0±4829.2, 1960.0 (8)	2816.0 & 1520.0	0.907
Number of races during the validity period	10.3±3.3, 12.0 (5)	8.0±3.0, 7.5 (8)	12.0 & 4.0	0.333
Current competition class	B3 (60.0%) & B2 (40.0%)	B3 (37.5%), B2 (62.5%)	B1 (100.0%)	

Based on the SG raw-WPAS points, four distinct groups were identified that performed significantly differently (p=0.038) (Figure 4-5A). Figure 4-5B also includes the SG raw-WPAS points of participants based on their current classes for comparison purposes. There was no significant difference among the skiers' performance based on their current class (p=0.09).

Only static VA was significantly different (p=0.039) between the clusters (Table 4-4). Cluster 2,3, and 4 had only one participant each. Participants in clusters 3 and 4 had NLP and LP vision, respectively (B1 class). 60% and 40% of participants in cluster 1 were currently classified as B2 and B3, respectively. The cluster 2 participant was classified as B3.

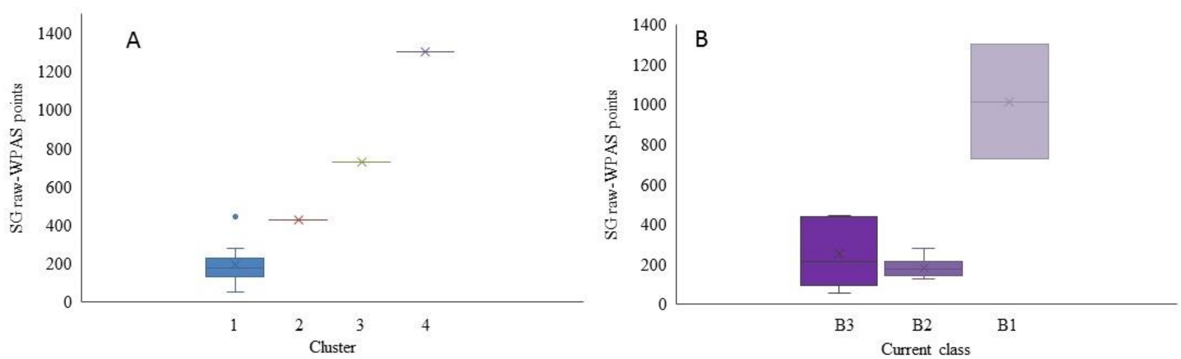

Figure 4-5: Raw-WPAS points for each cluster (A) and Raw-WPAS points for each current competition class (B) for the Para alpine SG participants.

Table 4-4: Summary statistics (mean±SD, median) of the vision and non-vision variables in Para alpine SG clusters. The values of variables that are significantly different among clusters are bolded. N/M indicates that the particular variable was non-measurable. The values of non-vision variables are italicized. *n/a indicates that statistical analyses could not be completed. The summary data include only actual measured values.

Variable	Cluster 1 (N=10)	Cluster 2 (N=1)	Cluster 3(N=1)	Cluster 4 (N=1)	P value (overall)
SG raw-WPAS points	**151.60±73.70, 155.5 (10)**	**425.90**	**727.51**	**1299.42**	**0.038**
Static VA (logMAR)	**1.11±0.53, 1.32 (10)**	**1.64**	**NLP**	**LP**	**0.039**
Dynamic VA (logMAR)	1.40±0.56, 1.40 (9)	N/M	N/M	N/M	*n/a
AULCSF (logCS)	0.66±0.62, 0.54 (10)	0.01	N/M	N/M	0.206
TMP (%)	54.8±30.8, 53.3 (10)	100.0	N/M	N/M	0.202
RMP (%)	56.6±32.0, 55.3 (10)	54.5	N/M	N/M	0.751
LS (change in logMAR)	0.07±0.10, 0.02 (7)	-0.08	N/M	N/M	0.118
GLS (change in logMAR)	0.11±0.07, 0.13 (10)	0.06	N/M	N/M	0.338
GLR (change in logMAR)	0.05±0.07, 0.02 (10)	-0.06	N/M	N/M	0.110
VF (%)	42.3±34.4, 41.7 (10)	32.5	0.0	N/M	0.254
Age (years)	29.3±13.6, 23.5 (10)	26.0	28.0	34.0	0.796
Age started skiing (years)	15.8±9.2, 12.5 (10)	22.0	10.0	25.0	0.563
Age of onset of impairment (years)	6.1±8.1, 3.0 (10)	0.0	9.0	0.0	0.614
Total lifetime hours of skiing	5556.2 ± 4460.7, 4560.0 (10)	2240.0	2816.0	1520.0	0.535
Number of races during the validity period	8.4±30.0, 8.5 (10)	2.0	7.0	3.0	0.137
Current competition class	B3 (40.0%) & B2 (60.0%)	B3 (100.0%)	B1 (100.0%)	B1 (100.0%)	

In SL, two distinct groups were identified that performed significantly differently (p=0.019) (Figure 4-6A). The SL raw-WPAS points of participants based on their current classes are also provided for comparison purposes as Figure 4-6B. There was no overall significant difference among the skiers' performance (p=0.07) based on their current class.

The performance groups differed significantly in terms of the number of races (p=0.038), static VA (p=0.019), CS (p=0.038) and VF (p=0.038) of the participants (Table 4-5). Cluster 2 had participants with LP or NLP vision (B1 class) only. 53.8% and 46.2% of participants in cluster 1 were currently classified as B2 and B3, respectively.

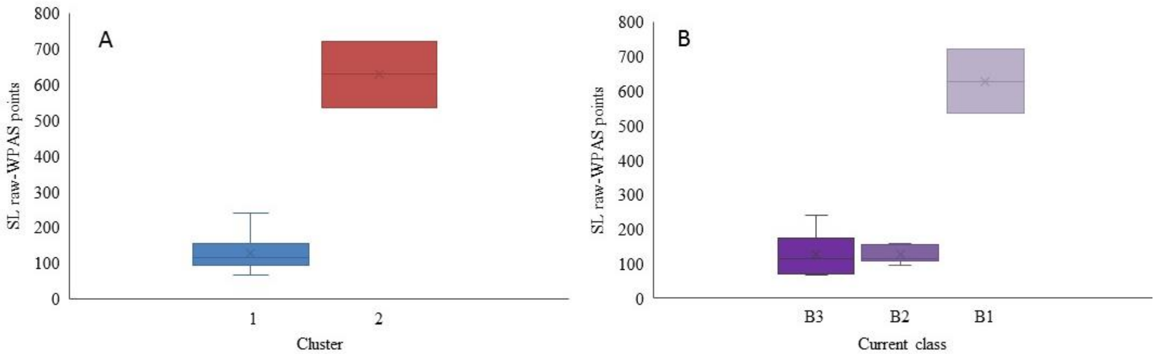

Figure 4-6: Raw-WPAS points for each cluster (A) and Raw-WPAS points for each current competition class (B) for the Para alpine SL participants.

Table 4-5: Summary statistics (mean±SD, median) of the vision and non-vision variables in Para alpine SL clusters. The values of variables that are significantly different between the clusters are bolded. N/M indicates that the particular variable was non-measurable. The values of non-vision variables are italicized. *n/a indicates that statistical analyses could not be completed. The summary data include only actual measured values.

Variable	Cluster 1 (N=13)	Cluster 2 (N=2)	P value (overall)
SL raw-WPAS points	**119.90±33.40, 129.1 (13)**	**534.74 & 722.13**	**0.019**
Static VA (logMAR)	**1.20±0.53, 1.40 (13)**	**NLP & LP**	**0.019**
Dynamic VA (logMAR)	1.50±.59, 1.40 (11)	N/M	*n/a
AULCSF (logCS)	0.55±0.62, 0.40 (13)	N/M	0.038
TMP (%)	58.8±32.2, 53.3 (12)	N/M	*n/a
RMP (%)	56.8±29.0, 55.3 (12)	N/M	*n/a
LS (change in logMAR)	0.09±0.14, 0.04 (10)	N/M	*n/a
GLS (change in logMAR)	0.18±0.17, 0.14 (13)	N/M	*n/a
GLR (change in logMAR)	0.05±0.07, 0.02 (13)	N/M	*n/a
VF (%)	43.4±32.0, 52.5 (13)	N/M	0.038
Age (years)	27.9±12.9, 25.0 (13)	28.0 & 34.0	0.381
Age started skiing (years)	16.0±8.6, 13.0 (13)	10.0 & 25.0	1.000
Age of onset of impairment (years)	5.3±7.7, 3.0 (13)	9.0 & 0.0	1.000
Total lifetime hours of skiing	4751.2±4452.6, 2240.0 (13)	2816.0 & 1520.0	0.800
Number of races during the validity period	**15.6±21.0, 11.0** (13)	**5.0 & 2.0**	**0.038**
Current competition class	B3 (46.2%) & B2 (53.8%)	B3 (100.0%)	

Decision tree analysis was not possible in the Para alpine data due to 1) non-comparable cluster sizes and 2) smaller sample sizes compared to Para nordic sample size.

4.5 Discussion

This project aimed at grouping Para nordic and Para alpine participants into clusters with highly similar skiing performances within each cluster, which at the same time were dissimilar to participants of different clusters. In Para nordic, three distinct clusters were identified based on the raw-WPNS points with comparable cluster sizes. Para nordic participants in clusters 1 and 2 had better skiing performances, better static VA, and larger VF compared to participants in cluster 3, which had most of the participants classified as B1 class. Cluster 1 participants also competed in a significantly higher number of races in the 2016-2018 season compared to cluster 3 participants. Cluster 1 and cluster 2 were not significantly different in any of the vision or non-vision aspects. The decision tree analysis also resulted in choosing the VF extent and static VA as the second and third best predictors of raw-WPNS points, respectively.

Among the Para alpine disciplines, DH is considered as a speed event, and GS, SG, and SL require progressively increasing technical skills compared to DH. The number of the Para alpine participants in each discipline also varies, with a high number of athletes participating in more technical events (N=15 in SL and GS, N=13 in SG) with less speed, compared to that in DH (N=9). There are also differences in the participation of skiers with most severe vision impairments among these disciplines. The Para alpine participants classified as B1 competed in all Para alpine events except the DH. Like Para nordic, the cluster analysis in Para alpine participants suggests that participants with better skiing performances also have better static VA, especially in the disciplines requiring more technical skill. SL is the most technical discipline, in which the worst-performing cluster had no measurable vision (i.e., NLP and LP visual acuity and 0.0% of VF extent). In DH, dynamic VA was significantly better in the group with better raw-WPAS points, which also had a higher number of participants classified as B3 (75%).

Considering the recommended sample sizes for population-based studies, the Para nordic and Para alpine studies had smaller sample sizes.[113,114] However, during the time period when this analysis was conducted, there were only 46 and 34 registered and active Para nordic and Para alpine skiers qualified to compete for the WCH events in the world, out of which 23.9%, 41.3%, and 34.8% of Para nordic and 5.9%, 55.9%, and 38.2% of Para alpine skiers are classified as B1, B2, and B3, respectively (Table 3-4). The Para nordic and Para alpine studies conducted in this thesis included 56.5% and 44.1% of the entire Para nordic and Para alpine skiers' populations, respectively. The percentages of participants classified as B1, B2 and B3 in this thesis were 30.8%, 53.9%, and 15.4% in the Para nordic studies and 13.3%, 46.7%, and 40.0% in the Para alpine studies. Therefore, considering the number and uniqueness of our population, the study samples were reasonably representative of the skiers' populations.

Although the studies had representation of participants from all three classes, one limitation of these studies is that in both the Para nordic and Para alpine studies, there was not much representation of participants with visual functions in the lower end of the B2 class and upper end of the B1 class. The Para nordic study sample had only one participant in the lower end of the B2 class static VA (i.e., static VA from 2.30 to 2.60) and one participant the upper end of the B1 class static VA (2.60 to 2.90 logMAR). No Para alpine participants who had static VA in these ranges participated in the study. Therefore, it was impossible to reach conclusions about this particular group of skiers based on these studies. It is also interesting to note that the nordic participant in the lower static VA end of B2 was in the worst-performing cluster, yet the nordic participant with static VA in the upper end of B1 was in the best-performing cluster despite having similar onset and hours of training and lower number of races compared to the B2 participant. Both these participants had acquired visual impairments, which were also progressive. However, the better performing B1 participant had an early onset of VI (5 years), compared to the B2 participant (11 years), which might indicate that the adaptation level of the participant to the VI could have played a role in the skiing performance.

The poorer performances (worst average raw-WPNS and raw-WPAS points) of the participants in B1 class in both Para nordic and Para alpine data were consistent with the reports of comparatively poor performances of B1 athletes in both Para judo and Para swimming, indicating that athletes with the most severe VI perform differently compared to partially sighted athletes in all these sports. The performances between B2 and B3 participants were not significantly different in either of the Para nordic or Para alpine studies, which suggests that Para nordic and Para alpine skiers with measurable vision do not differ significantly in terms of their skiing performances. The results of this study would suggest that Para nordic and Para alpine skiers with LP or NLP vision should be in one class and that the skiers with quantifiable static VA should be in a different class. Thus, there could be two distinct classes in both Para nordic and Para alpine skiing: 1) the eligible participants with static VA better than 2.60 logMAR and 2) participants with no quantifiable vision (LP and NLP). As the Para nordic study had only limited participation (N=2) and the Para alpine study did not have participation of skiers with static VAs ranging from 2.30 to 2.90 logMAR, follow up studies are essential to assess the performance of these new classification systems, especially in populations of skiers with static VAs in this range, if these recommendations are taken into consideration by the IPC for modifying the classification systems for Para nordic and Para alpine participants.

4.6 Thesis progress III

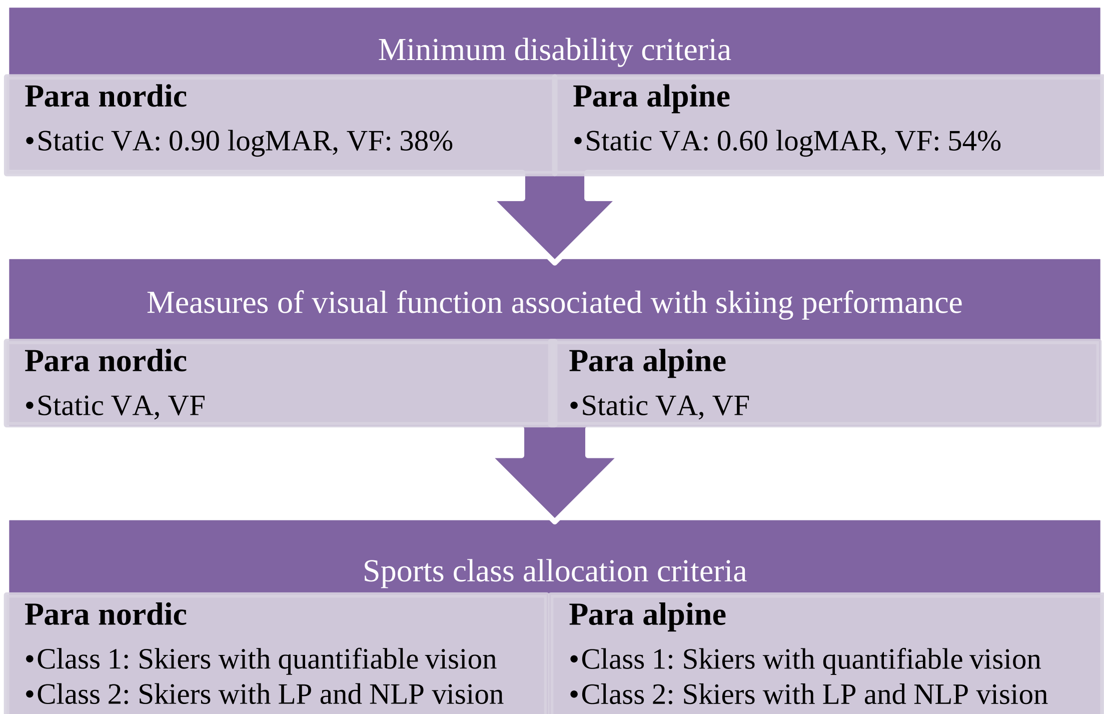

Figure 4-7: Thesis progress III outlining the main objectives and conclusions of Chapter 2 - 4.

The findings from the Chapter 4 suggest that once eligibility is determined, the Para nordic and Para alpine skiers could be classified in to one of the two classes.

Chapter 5
Do Blindfolds alter Para Nordic and Para Alpine Skiing Performance in Skiers with Severe Vision Impairments

5.1 Chapter summary

Introduction: Paralympic classification systems are designed to ensure that impairment levels are similar amongst competitors and that the competition is fair for all the athletes. In the most severe vision impairment category (B1 class) of Para nordic and Para alpine skiing, athletes are required to wear blindfolds while competing. The purpose of this study was to determine the impact of blindfolds on skiing performances in Para nordic and Para alpine skiers competing in the B1 class.

Methods: Four elite Para nordic skiers and one Para alpine skier were recruited to participate in this study at the 2018 Para Nordic Skiing World Cup in Oberried, Germany and the 2019 Para Alpine World Championships in Kranjska Gora, Slovenia. Participants were asked to ski short racecourses with and without their blindfolds in randomized orders. Participants skied the courses with their guides under both test conditions (with and without blindfold) and time taken to complete the courses (race times) were compared between conditions.

Results: The race times were not significantly different between the with and without blindfold conditions for both the Para nordic and Para alpine participants (Para nordic p=0.17, Para alpine p=0.11), but there was a trend towards race times being faster with the blindfold condition. When asked about their individual experiences, some Para nordic participants preferred skiing without the blindfolds, while others preferred skiing with the blindfolds; however, Para nordic participants did not ski faster during their preferred competition condition. The Para alpine skier did not have any preference regarding blindfolds.

Conclusions: Blindfolds do not appear to significantly improve or worsen performances in Para nordic and Para alpine skiers who are eligible to compete in the B1 class, although skiers do have different preferences for using blindfolds when skiing.

5.2 Introduction

International sports competitions such as the Paralympic Games enable athletes with physical, visual, and intellectual impairments to compete at the highest levels of sports. To ensure competition fairness and to keep the impairment effect on sports performance minimal, the International Paralympic Committee (IPC) classifies athletes based on their level of impairment.[115,116] Currently, the system classifies athletes with visual impairment (VI) into three different classes (B1, B2, and B3) based on the visual acuity (VA) and/ or visual field (VF) extent of their best-corrected eye. Athletes with the most severe visual impairments (monocular VA >2.6 logMAR in their better eye, including athletes with light perception (LP), and no light perception (NLP) are allocated to the B1 class for competition.[7]

In some sports, athletes in the B1 class are required to wear blindfolds or eyeshades such as blackened swimming goggles or opaque ski goggles, to equalize the impact of athletes' impairments within the class. The inside of these blindfolds or eyeshades must be completely black, and the athletes should not be able to see any light while wearing the goggles.[22] In goalball, a sport specifically designed for the athletes with visually impairments, all athletes are required to wear blindfolds. Similarly, outfield athletes playing football 5-a side are also required to wear blindfolds. In other sports such as skiing and swimming, only athletes in the most severe vision impairment class (B1) are required to wear blindfolds during competition.[23,25]

In a recent Delphi study focused on improving vision impairment classification across Paralympic sports, experts (coaches, guides, athletes, classifiers, researchers) were asked about whether or not the mandatory use of blindfolds was appropriate for use by athletes in the most severe impairment class during competition. On this particular topic, the group was unable to reach consensus. The majority of the panellists (96%) agreed that it is not appropriate for all the athletes to wear blindfolds because using blindfolds would limit athletes' abilities to use their residual vision while competing, thereby essentially increasing their disability. However, 77% of the panellists felt that wearing blindfolds might be required in some sports or some situations.[31] Currently, there is no evidence available on the effect blindfolds have on sports performance in individuals with severe vision impairments.[32]

During the Delphi study process, some experts argued that an athlete with some amount of vision or light perception might have an advantage over athletes with no light perception due to the visual cues that might help them during their training as well as competition. Other experts argued that the athlete's limited remaining vision might not be helpful during sport, and could impair the athlete's performance by distracting the athlete from the auditory information provided by the guide.[31] Therefore, the purpose of this project was to investigate the impact of blindfolds on skiing performance in Para nordic and Para alpine skiers classified as B1 (severe vision impairment).

5.3 Materials and Methods

This project used a within-subjects, experimental research design where observations were made in defined populations. Informed consent was obtained from all participants, and the studies adhered with the tenets of the Declaration of Helsinki. This study was reviewed by and received ethics clearance through a University of Waterloo Research Ethics Committee.

5.3.1 Participants

International level Para nordic and Para alpine skiers who were eligible to compete in the B1 class were recruited from the 2018 Para Nordic World Cup (WC) event at Oberried, Germany, and the 2019 Para Alpine World Championship (WCH) event at Kranjska Gora, Slovenia. A total of eight B1 athletes competed in the nordic event, and four of them participated in the study (three females, one male, and age 26 ± 2.6 years, range: 21 to 28 years). The only alpine skier who participated in that WCH event in the B1 class (male, 30 years old) participated in the alpine study.

5.3.2 Procedure

The study involved two short visits per participant. During the first visit, participants completed a short questionnaire (Appendix D) about their skiing experience, which included questions about when they started training and competing and what their average annual training routine involved both on- and off-snow. Participants' binocular VA was also measured during this visit using a Berkeley Rudimentary Vision Test and / or a transilluminator to determine light perception.

The second study visit took place outdoors, and participants were asked to ski either a short (approximately 500m) nordic ski course or a short ten gates giant slalom (GS) alpine course (depending on their sport) with and without their blindfolds. The courses were designed to mimic typical racecourses in each sport (i.e. terrain, gate settings). Participants were randomly assigned to ski with

(A) and without (B) their blindfolds in either an ABBA or BAAB sequence. Participants' time to complete each trial was recorded, and race times were compared between the two conditions. Participants were also asked whether they preferred to ski with or without their blindfolds.

5.3.3 Data analysis

Descriptive data analysis was conducted and the effect of skiing trial order on the race time was compared among all participants with a repeated measures ANOVA (all participants pooled). The effects of blindfolds on the performances were also assessed separately for the Para nordic and Para alpine participants using paired t-tests. Each Para nordic participant's race time with blindfold condition was paired with without blindfold condition (two pairs for each participant), and all eight pairs were analyzed as a pooled data. Similarly, Para alpine participant's data was also paired and analyzed (two pairs). The authors recognize that the utility of these statistical analyses is minimal due to this project's small sample size. However, the study population included 36.4% and 50.0% of world's entire population of elite B1 Para nordic (4 of 11 WCH eligible B1 skiers) and Para alpine (1 of 2 WCH eligible B1 skiers) skiers. Thus, the study sample was felt to be representative of the world's population, despite the small number of participants involved.

5.4 Results

Three of the Para nordic participants had NLP vision and one participant had a binocular VA of 2.50 logMAR units. The age of onset of the participants' VI varied from 6 months to 5 years of age (3.0 ± 1.9 years). Participants' average years of experience competing at a national or international level were 7.7 ± 3.4 years (range: 5 to 12 years), and the average number of hours they spent training during their lifetime was 5870.5 ± 1771.8 hours (range: 3424 to 7640 hours). The Para alpine participant who completed this study had NLP vision, with a VI diagnosed at nine years of age. This participant had 15 years of skiing experience and 2400 hours of training. None of the participants had a history of progressive vision loss.

Any systematic variation in skiing performance with increasing order of skiing trial would have indicated either an effect of fatigue on the participants' performance (if performance worsened) or a learning effect as participants became more familiar with the course (if performance improved). A one-way repeated measures ANOVA was conducted to compare the effect of order on the skiing performances of each participant; due to small sample size both the Para nordic and Para alpine participants were pooled for this analysis. There was no significant order effect (Wilks' lambda = 0.722, F(3,2) = 0.256, p = 0.854 (Figure 5-1). Race times improved with each trial for two nordic skiers and worsened for the other two nordic skiers. There was no systematic increase or decrease in race times for the alpine skier.

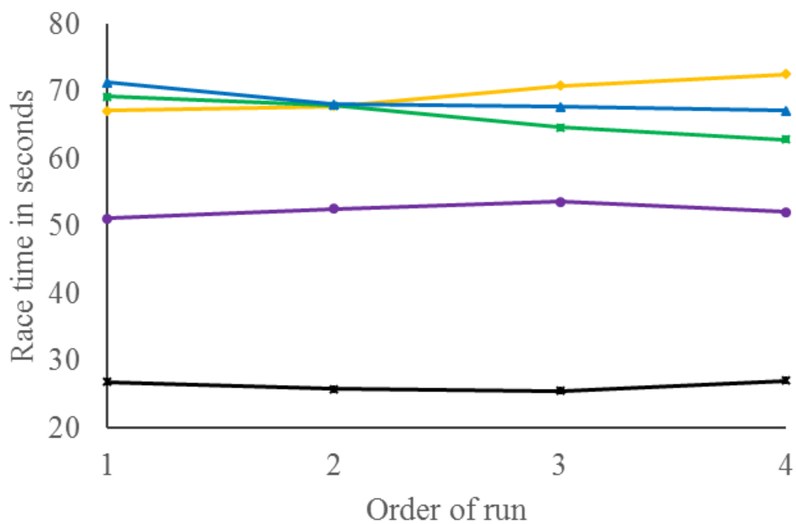

Figure 5-1: Order effect on Para nordic and Para alpine skiers' performance. Each line represents the actual race times for each participant based on the trial order. The coloured lines represent the Para nordic participants and the black line represents the Para alpine participant.

The average of race times with the blindfold condition of each Para nordic participant was slightly better than the average of the race times without blindfold, ranging from 0.19 s to 1.51 s improvement. On average, the Para alpine participant skied 1.30 s faster with the blindfold compared to without the blindfold. Paired-samples t-tests were conducted to compare the participants' race times in the with and without blindfold conditions in both nordic and alpine. There was no statistically significant difference in the Para nordic race times for the blindfold (Mean ± SD = 63.75 ± 7.82 s) and without blindfold (Mean ± SD = 64.62 ± 7.52 s) conditions; t(7) = 1.54, p = 0.17. Similarly, the difference in race times between the two blindfold conditions in the Para alpine participant was also not statistically significant (p=0.11). The average race times with and without blindfold for each participant are plotted in Figure 5-2.

One of the Para nordic participants preferred to ski with the blindfolds, one preferred skiing without them, and two participants had no preference. The Para alpine participant had no preference for either blindfold condition. There was no relationship observed between the preferences of participants and the variations in race times observed in the different blindfold conditions.

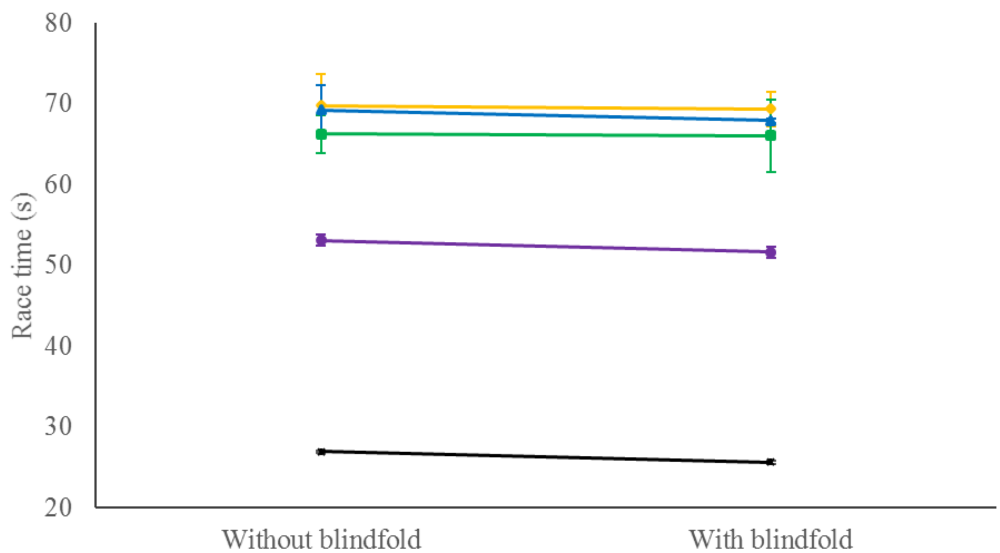

Figure 5-2: Effect of blindfolds on Para nordic and Para alpine skiers' performance. Average race time (with error bars representing the standard deviations) in both blindfold conditions are plotted for all five participants. The coloured lines represent the Para nordic participants and the black line represents the Para alpine participant.

5.5 Discussion

This study assessed the impact of blindfold use on skiing performance and considered the subjective preferences of participants regarding blindfolds. Blindfold condition (with or without blindfolds) did not have obvious impacts on Para nordic or Para alpine skiing performances. Participant's preference for wearing or not wearing a blindfold also did not seem to have an influence on skiing performances. It is interesting to note that the race times of the nordic participant who preferred to ski without blindfolds improved by 1.5 s when the skier was wearing the blindfold, compared to without it, and this was the maximum time difference between blindfold conditions out of all the participants.

Four Para nordic and one Para alpine skiers participated in these studies, which limited the data analysis that could be done. However, considering the total number of Para skiers classed as B1 available world-wide (11 Para nordic and 2 Para alpine skiers) we had a representative sample. It is also noteworthy that 50% of the Para nordic B1 skiers and the only Para alpine skier (100%) who competed at the events where the research was conducted participated in these studies. Considering the very small population of these skiers worldwide, collecting a larger sample size would be nearly impossible due to the prohibitive costs and logistics associated with getting all the athletes in one place or travelling to the athletes individually. Notwithstanding the relatively limited sample, the empirical findings in this study provide valuable insights into the effects of blindfold use on Para nordic and Para alpine skiing performance.

In consideration of skier's race times during the trials, observations regarding the participants' subjective preferences, and the associations between race time and subjective preferences, there does not appear to be any obvious impact of using blindfolds on either Para nordic or Para alpine skiers' performance. Individual athlete's levels of comfort while skiing with or without a blindfold may depend on other factors such as the skiers' adaptation levels and methods of training. It is possible that some athletes skied faster with the blindfold, only because it was a more familiar condition. Methods of training is also an important consideration for training and competition performance of these athletes, because their confidence levels could be affected by a change in blindfold condition between training and competition. If the athlete prefers to train without blindfolds, introducing blindfolds during competition could affect their comfort levels and vice versa. As such, athletes should ensure that they are comfortable training in the same conditions as they compete in under the current sport rules.

5.6 Thesis progress IV

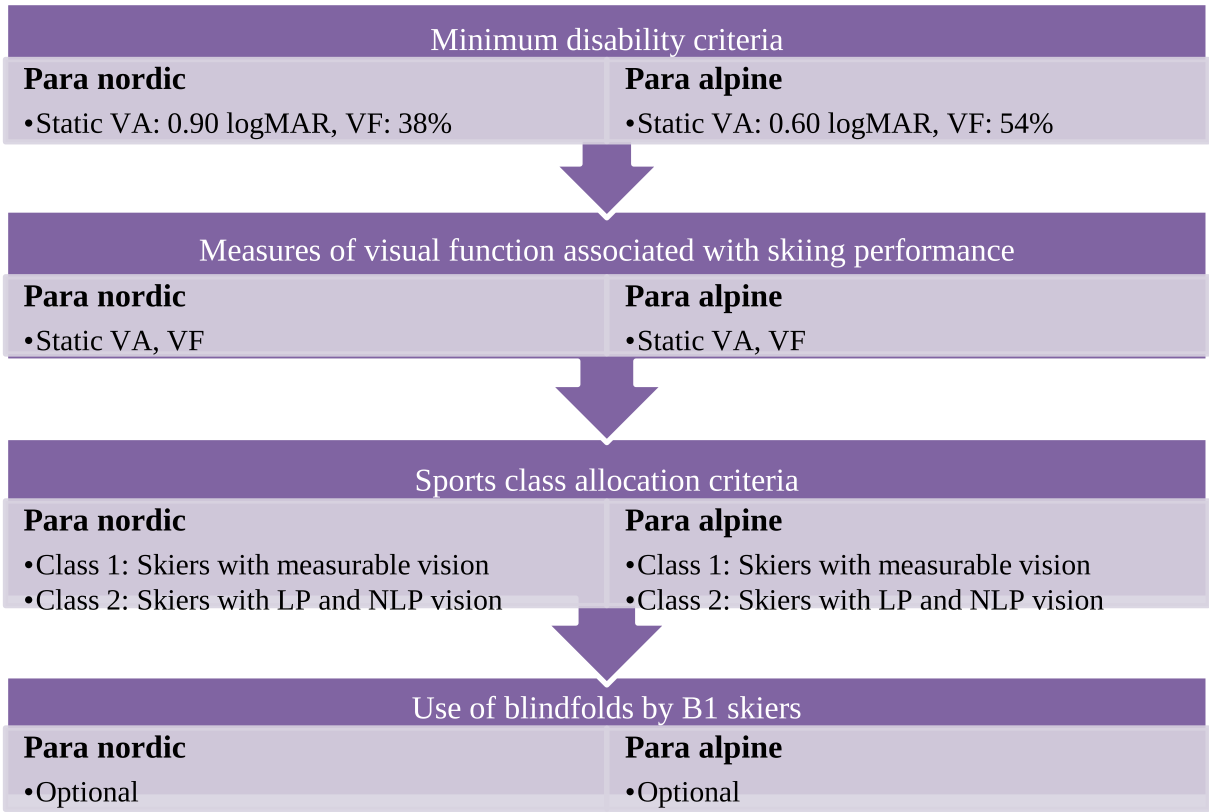

Figure 5-3: Thesis progress IV outlining the main objectives and conclusions of Chapter 2 to 5.

The findings from the Chapter 5 suggest that use of blindfold should be optional for both Para nordic and Para alpine skiers classified as B1.

Chapter 6
Validation of visual field measurements using an Arc perimeter: comparison with the Humphrey Field Analyzer in adults

6.1 Chapter summary

Introduction: The Arc perimeter is a simple and efficient way to assess the boundary of the visual fields of individuals. All the studies conducted as part of the Para nordic and Para alpine classification research used an Arc perimeter for the participants' visual field measurements. The purpose of this study was to compare the visual field measurements made using an Arc perimeter with measurements made using a Humphrey Field Analyzer in adult participants.

Methods: Fifteen adults with monocular or binocular visual field defects participated in this study. Visual acuity and visual field were assessed binocularly in all participants. The visual fields were measured using an Arc perimeter and a Humphrey Field Analyzer. The functional visual scores obtained using both instruments were non-parametrically compared, and the agreement between both methods was assessed using Bland-Altman plots.

Results: The visual fields measured using the Arc perimeter were larger than the ones measured using the Humphrey Field Analyzer (mean difference = 14.0%, $p < 0.001$). The mean difference between the visual field scores was smaller when an equivalent field scoring method was used (mean difference = 5.1%, $p = 0.02$). There was reasonable agreement between both the full field and equivalent field Arc perimeter and Humphrey Field Analyzer visual field scores.

Conclusions: We recommend that the functional scores obtained using an Arc perimeter could be used as an efficient and feasible way to assess visual fields for classification research purposes.

6.2 Introduction

The processing of information from the peripheral visual field (VF) is essential in any outfield sport to understand and anticipate the challenges in the sport. Previous research reported that athletes have larger VFs and better sensitivities in the central VF compared to non-athletes.[117,118] Skiing is a highly dynamic outfield sport, and in some skiing disciplines such as slalom, skiers need to look one to two gates ahead of their position in order to anticipate and respond accordingly due to the high speeds involved in the sport.[49] Craybiel et. al[54] reported that peripheral VF occlusion caused a significant reduction in slalom skiing performance, affecting the skiers' distance judgements. Therefore, VF was one of the most important visual functions that needed to be included in the test battery for the Para nordic and Para alpine classification research.

Visual functions such as visual acuity (VA) or contrast sensitivity (CS) can be measured using standardized charts like the Early Treatment of Diabetic Retinopathy Study (ETDRS) or Pelli-Robson charts that are relatively easy to transport and quick (2 to 6 minutes to test). Accurate, standardized instruments for assessing VF extents are not easily portable and or as fast (7 to 30 minutes for a full field screening test, depending on the VF defects). Quick VF screening methods such as confrontation visual fields are neither accurate, nor comparable to the measurements obtained through standardized perimeters. Currently, the Humphrey Field Analyzer (HFA) is the most commonly used automated perimeter and is considered as the most accurate and standardized instrument for measuring VFs. The HFA can be used to screen for visual field defects, to assist the diagnosis of early neurological conditions or glaucoma, and to monitor the progression of ocular diseases.[119] During the Para nordic and Para alpine classification research studies (described in the previous chapters), participants were recruited, and the vision assessments were conducted close to the nordic and Alpine skiing venues; HFAs could not be used in such situations because they could not be easily transported to the venues and testing would have taken too long to complete.

The Arc perimeter is an easy to use and portable perimeter constructed by Richard Foster in 1869 and was the first instrument designed to quantitatively assess full VFs. Arc perimetry was used to identify peripheral VF defects related to advanced glaucoma or neurological abnormalities in the late 1800s and early 1900s.[120,121] Arc perimeter measurements are made manually, using a kinetic stimuli, while the standardized instruments for measuring VFs today, such as HFA, are automated and use static stimuli for testing. Previous research reported that the sensitivity results across VFs vary between static and kinetic methods of perimetry.[122] In addition, due to potential changes in stimulus velocity, variability could be higher in Arc perimetry measurements compared to automated perimetry measurements.[123] Despite these limitations, the Arc perimeter still provides valuable information on the participant's VF boundary and is a good screening tool for identifying VF defects,[124] and has been used for research purposes even in the recent past to examine VFs of infants, neonates, and children.[125,126,127]

Currently, Goldmann, Humphrey, or Octopus perimeters are considered acceptable for use for VF measurements during classification by the IPC.[31] However, none of the perimeters mentioned above were feasible for use in the Para nordic and Para alpine studies due to the difficulties with instrument portability and the longer test durations. Therefore, an Arc perimeter was used to assess the VF extents of the nordic and alpine study participants in all the classification research studies conducted in this thesis.

There is little published literature on the validity of VF extents measured using an Arc perimeter since the Arc perimeter is no longer used for routine VF assessments. Hence, the validity of the VF measurements with the Arc perimeter should be determined before interpreting and implementing the results from the Para nordic and Para alpine classification research. Therefore, the purpose of this study was to compare the functional visual field scores measured using an Arc perimeter (manufacturer unknown) with those measured using the HFA III (Carl Zeiss Meditec, Inc) and to determine the validity of the Arc perimetry VF assessments conducted in the Para nordic and Para alpine classification research.

6.3 Materials and Methods

This project used an observational research study design and adhered with the tenets of the Declaration of Helsinki. This study was reviewed by and received ethics clearance through a University of Waterloo Research Ethics Committee. Fifteen participants (9 female, 6 Male; age 52.87±11.70 years; range 29 to 74 years) with a history of monocular or binocular VF defects were recruited from the patient database at the University of Waterloo Optometry clinic and attended one study visit. Informed consent was obtained from all participants.

6.3.1 Procedure

Each participant underwent binocular visual acuity measurements using the Early Treatment Diabetic Retinopathy Studies (ETDRS) chart using the standardized protocol.[65] Binocular VF measurements were conducted using an Arc perimeter as well as an HFA III for each participant. Participants wore their habitual correction and all the assessments were conducted by the same trained clinical investigator (A.S.). The VFs measured were functionally scored and converted to percentages using the modified American Medical Association (AMA) scoring method described below.

6.3.2 Arc perimeter

Binocular VF assessments were performed by the examiner moving a Goldman size IV target from the non-seeing area to the seeing area at a speed of approximately 3-5 degrees per second, with the participant's head centred on the Arc perimeter, supported by the chin rest. A size IV target (4.51 mm diameter) was chosen because this was the size of target used in all of our prior studies with Para skiers. The participants were instructed to report when they first saw the peripheral target while fixating on the central mirror. Testing always started with the horizontal axis, and once the horizontal axis was marked, the arc was rotated to test the entire 360-degree visual field in 30-degree intervals.[68] Once the VF boundary was identified, the target was moved continuously along each axis towards the central fixation point and participants were asked to report if the target disappeared anywhere to identify presence of any scotomas, if present. The edges of scotomata were reassessed until the response was consistent and reliable. When a scotoma was detected within the VF, the boundaries of the scotoma were marked by moving the target from both the periphery (seeing) in towards the centre (non-seeing) and the centre (non-seeing) out towards the periphery (seeing). The boundaries of the scotomas were rechecked for consistency in the participant's responses. If responses were inconsistent or fixation was poor, participants were reinstructed and re-tested. Responses were marked on a Goldmann VF recording sheet and functionally scored as described below.

6.3.3 Humphrey Field Analyzer III

Participants underwent a central VF screening method (C-80) as well as a full field screening method (FF246, also known as an Armaly VF) on the HFA with the participant's head centred in the instrument as much as possible so both fields could be measured binocularly. The chin rest was moved to the far-right position and the participant's chin was placed on the left chin cup so that the participant's midline was in the centre of the instrument. Participants' VFs were assessed using the C-80 (80 points across the central 30 degrees) and the FF246 (246 points across the central 60 degrees or full field) suprathreshold screening test patterns. We used a size IIIe stimulus (2.26 mm diameter) as this was the only stimulus size available for the HFA III FF246 program.[119,128] In addition, this is the most common target used for HFA VF measurements in routine practice and during Paralympic VI classifications. The standardized protocols for both the C-80 as well as the FF246 tests were followed.[119] The FF246 field was the primary outcome measure identified for this analysis; the C-80 field was only collected in case the central field needed to be examined in more detail. However, the FF246 outputs had all the necessary information needed to score the VFs using the modified AMA scoring grid, so additional analysis on the C-80 fields was not done. The automated fixation monitor could not be used for either field due to the fact that fields were tested binocularly, thus the examiner continuously monitored participant's fixation. If the participant did not fixate throughout the test, tests were repeated. Participants were also reminded to blink frequently and encouraged to ask for breaks if they felt tired. VFs were functionally scored as described below.

6.3.4 Functional scoring of VF

The AMA functional visual field scoring system was introduced in 1958, and uses a grid with ten meridians, each one at 25º, 65º, 115º, 155º, 195º, 225º, 255º, 285º, 315º, and 345º. Ten eccentricities are scored on each meridian, including five within the central 10º at 1º, 3º, 5º, 7º, and 9º, and five outside the central 10º at 15º, 25º, 35º, 45º, and 55º. VF are scored according to whether the target was seen or not seen at each position on the scoring grids. The maximum possible AMA score is 100, and the AMA score obtained can be converted to a percentage to describe the VF extent. A total of 50% of the possible AMA score is allocated to the central 10º VF radius and a total of 60% of the possible AMA score is allocated to the inferior VF to account for the importance of the central and inferior VFs in the daily visual tasks of individuals.[129]

Since there is little literature on the functional importance of various VF locations on skiing performance, a modified, unbiased AMA grid consisting of the same ten meridians as in the original AMA grid and six eccentricities on each meridian (5º, 15º, 25º, 35º, 45º, 55º) was used for scoring the data (Figure 6-1). Thus, the maximum modified AMA score possible was 60. The modified grid was chosen for use in this study because it removed any bias towards the central VFs for this analysis; multiple VF scoring methods were examined prior to deciding on this specific method for analysis (for more details, see Appendix E).

For the Arc perimeter the maximum measurable VF extent was 90º in all four directions (right, up, left, and down), and the maximum modified AMA score possible for the VF measured using the Arc perimeter was 60. The VF extents tested using the HFA were slightly smaller than those measured using the Arc perimeter. The maximum VF extent measurable with the HFA FF246 was 60º to the right, 35º above, 50º to the left, and 55º below. These VF plots are asymmetric because there was no binocular

FF246 protocol available in the HFA, thus the recordings were done on a visual field plot for the right eye for all participants. No assumptions were made about whether the untested points in the VFs measured using HFA were seen or unseen and these points were treated as missing data. The total modified AMA score possible for VF measured using HFA FF246 was still 60 and consisted of the 52 measurable data points plus 8 non-measurable, missing data points. An equivalent VF re-scoring was done for the Arc perimeter VF extents to understand the effect of these HFA-unmeasurable points on the agreement between the two instruments. In the equivalent VF-analysis, only the same 52 points that were measurable on the HFA FF246 were included in the re-scored Arc Perimeter data. The 8 additional data points measured on the Arc perimeter were ignored and treated as missing data since they were considered as missing data points in the HFA FF246 plot. The additional 8 points present on the Arc perimeter were treated as missing data in this analysis in order to ensure the AMA 6E protocol was followed. The analysis was not done for a maximum score of 52 on both fields because if AMA 6E scoring grid is chosen for classification in future, the maximum score available would also be 60. Therefore, all three of the VFs examined in this analysis were scored out of 60 and converted into percentages; all the results presented below are in percentages.

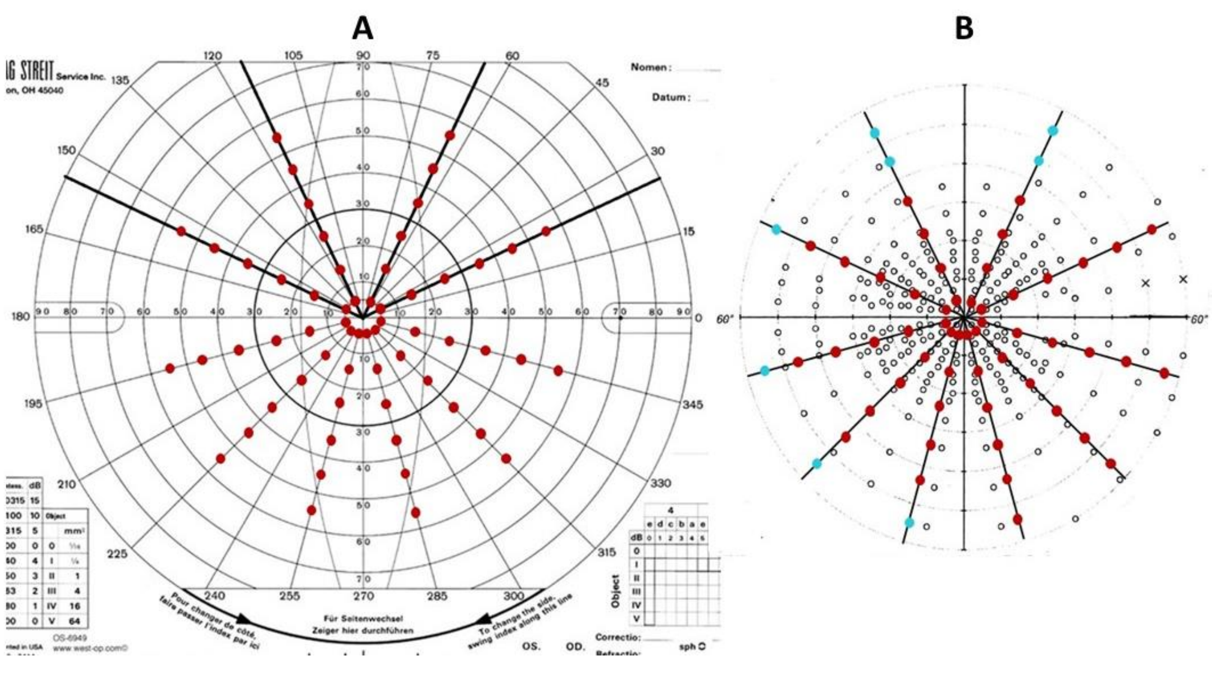

Figure 6-1: The overlay grid used on the Goldmann VF recoring sheets (A) and HFA FF246 output printout (B) for functionally scoring VF extents using the modified AMA scoring method. The cyan coloured points in the AMA grid for HFA FF246 (B) represent the non-measurable VF area using HFA.

6.3.5 Data analysis

Data analysis was conducted using SPSS for Windows (version 25.0, SPSS, Inc.). The modified AMA scoring of VFs measured using the Arc perimeter on the 60 point (full field) and 52 point grids (equivalent field) were compared against those measured using the HFA (52 points). All three of the VFs examined in this analysis were scored out of 60; in the fields with 52 points the additional 8 points were treated as missing data as stated above. The modified AMA scores were not normally distributed and non-parametric tests were used for this comparison between two measurements. The scores were initially compared using Wilcoxon Signed rank tests. Kendall τ correlations (with Bonferroni-Holm correction) and linear regression analyses were used to assess the relationship between the modified AMA scores measured using the Arc perimeter (both full field and equivalent field) and the HFA.[105] Although the correlation analyses are sufficient to identify the strength of the association, they are not capable of measuring the agreement between the two measurement methods.

Bland-Altman plot is a simple method to demonstrate and interpret the agreement between two measurement methods by plotting the mean of the two values (x-axis) against the differences of the values (y-axis) obtained using the two measurement methods. In the Bland-Altman plots, the mean of the differences between the two measurements provides an estimate of the average agreement (bias) between them, and the limits of agreement (LOA) provide the estimates of this bias reported in 95% confidence intervals (mean difference±1.96*SD of the differences, $\alpha = 0.05$).[130] To summarize, the bias from the Bland-Altman plot is a measure of the differences of the Arc perimeter measurements from the HFA measurements, and the range of LOA can be used to identify if these differences are clinically significant. Bland and Altman recommended that the two methods assessed could be considered to have poor agreement between them if 95% of the data points do not lie within ±1.96 SD of the mean difference (LOA) in a plot.

Therefore, Bland-Altman plots were used to compare the bias (mean and 95% confidence interval of the mean) and LOA between 1) Arc perimeter modified AMA scores and HFA modified AMA scores and 2) equivalent Arc perimeter modified AMA scores and HFA modified AMA scores.[131] Once the Bland-Altman plots were generated, 1) the number of data points within LOA, 2) the bias between the two measurement methods, 3) the range of the 95% CI (LOA), and 4) the presence of any possible relationship between the difference of measurements and the mean values were observed for both the full field and equivalent field methods.

6.4 Results

The study participants had a wide range of VF defects (Table 6-1). The average binocular VA of the participants was 0.26 ± 0.52 logMAR (-0.14 to 1.34 logMAR). The average Arc perimeter modified AMA and HFA modified AMA scores were 81.2 ± 28.3% (16.7 to 100.0%) and 67.2 ± 29.9% (3.3 to 86.7%), respectively. The average equivalent field Arc perimeter modified AMA score was 72.3 ± 23.4% (16.7 to 86.7%).

Table 6-1: Summary of the types of VF defects among Para nordic and Para alpine participants.

Type of visual field defect	Number of participants
Peripheral VF defect without central scotoma	9
Peripheral VF defect with scattered peripheral scotomata	Nil
Peripheral VF defect with central scotomata	Nil
Peripheral VF defect with ring scotomata	Nil
Tunnel vision (<10^0 radius)	1
Peripheral island of vision	Nil
Central scotoma without peripheral VF defect	Nil
Full field with absolute scotoma in the central (30°) VF	1
Quadrantanopia (partial/complete) without central scotoma	2
Partial hemianopia without central scotoma	1
Asymmetric central VF with scattered scotomata	1

6.4.1 Relationships of Arc perimeter scores with HFA scores

6.4.1.1 Correlation and regression analyses

There were strong significant correlations between both the full-field (b = 0.80, p<0.001) and equivalent field (b = 0.87, p<0.001) Arc perimeter modified AMA and HFA modified AMA scores. The VFs measured using Arc perimeter were larger than the ones measured using the HFA (mean difference = 14.0 %, p < 0.001) and the difference was smaller when the equivalent field method was used (mean difference = 5.1 %, p = 0.02). The average time taken to complete the binocular VF assessments using the Arc perimeter (3.49 ± 0.91 minutes) was less than the average time taken with the HFA (11.76 ± 7.01 minutes).

Simple linear regressions were calculated to predict the HFA modified AMA scores based on either full-field or equivalent field Arc perimetry modified AMA scores. A significant regression equation was found (F(1,13)=663.37, p<0.001), with an R^2 of 0.98 for the full-field Arc perimeter modified AMA scores. Participants' predicted HFA modified AMA score was equal to -17.78 + 1.05

(Arc perimeter full-field AMA). Similarly, a significant equation was found (F(1,13)=545.28, p<0.001), with an R^2 of 0.98 for the equivalent field Arc perimeter modified AMA scores. Participants' predicted HFA modified AMA scores was equal to -23.25+1.26 (Arc perimeter equivalent field modified AMA scores).

6.4.1.2 Agreement between the measurements

The Bland-Altman plots are presented in Figure 6-2 and Figure 6-3, and the results are provided in Table 6-2. The limits of agreement are indicated by the outer lines, which were determined by calculating the two standard deviations on either side of the mean difference. The difference in the VF scores for all but one participant (93% of participants total) were within the limits of agreement on the Bland-Altman plots for both the full-field and equivalent field comparisons, as would be expected from this analysis. Most of the differences for both analyses were above 0 line, indicating that the Arc perimetry measurements were larger than HFA measurements in most participants.

The average discrepancy, or bias, between the methods was lower in the equivalent field method (5.1%) compared to full-field method (14.0%). The LOA for the plot between Arc perimeter modified AMA scores and HFA modified AMA scores was 5.5 to 22.5, indicating that the measurements using an Arc perimeter could be higher than HFA measurements by 5.5% to 22.5% when the full-field method is used. The LOA for the plot between equivalent field Arc perimeter modified AMA scores and HFA modified AMA scores was -10.0 to 20.2, indicating that the measurements using Arc perimeter could be lower than HFA measurements by 10.0% or higher by 20.2% when the equivalent field method is used. Interestingly, the LOA of the Bland-Altman plot using equivalent field Arc perimetry scores was larger (28%) compared to the full field Arc perimetry scores (18%).

In the comparison of the full field Arc perimeter with the HFA (Figure 6-2), no systematic variation was observed among the differences between the two measurement methods. However, an observable trend was present in the data when comparing the equivalent Arc perimeter score with the HFA (Figure 6-3). In this second comparison, the average difference between the two measurement methods seemed to be greater, or more variable, in participants with VFs smaller than 30% (17.2±8.2%) compared to participants with VFs larger than 30% (2.1±3.6%) in Figure 6-3.

Considering the bias and LOAs from these plots, the equivalent field Arc perimetry method seems to have less bias (close to HFA scores) but more variability (less reliable), especially while testing participants with VFs smaller than 30%, compared to the full-field Arc perimetry method.

Table 6-2: Summary statistics of the agreement between the Arc perimeter and HFA VF measurements.

	Mean difference (%)	LOA of mean difference	SD of differences	Min/max of difference
Arc perimeter - HFA	14.0	22.5 to 5.5	4.4	8.3/26.7
Equivalent Arc perimeter - HFA	5.1	20.2 to -10.0	7.7	-1.7/26.7

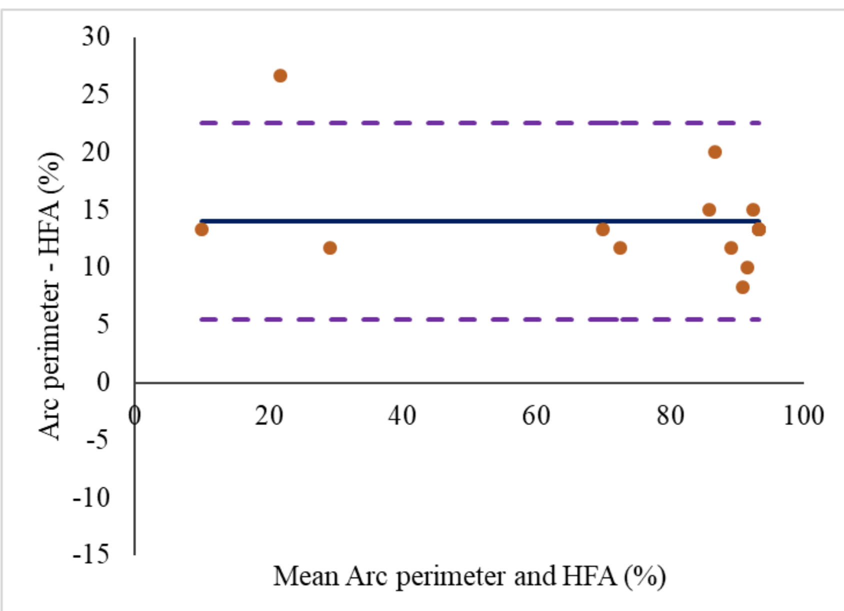

Figure 6-2: Scatter plot of the difference between the Arc perimeter and HFA modified AMA scores plotted against the mean of the Arc perimeter and HFA modified AMA scores. The solid purple line indicates the average of the differences between the AMA scores using Arc perimeter and HFA. The dashed purple lines represent the upper and lower limits of agreement.

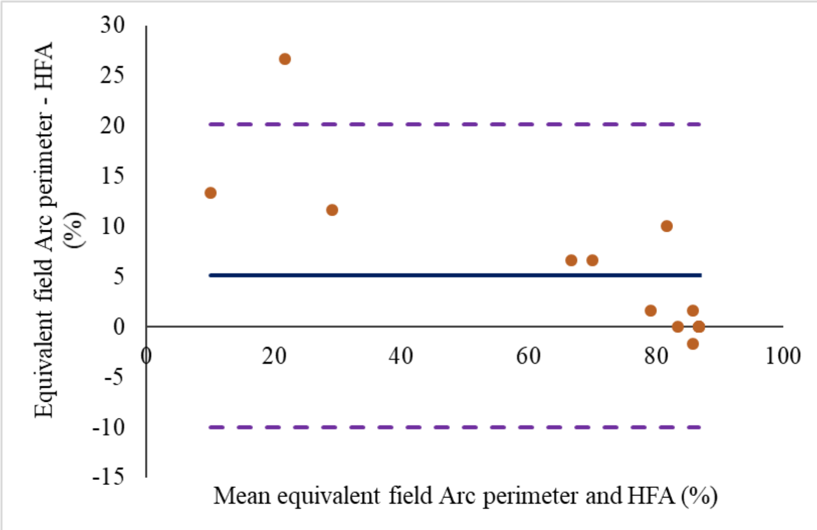

Figure 6-3: Scatter plot of the difference between the equivalent Arc perimeter and HFA modified AMA scores plotted against the mean of the equivalent Arc perimeter and HFA modified AMA scores. The solid purple line indicates the average of the differences between the AMA scores using equivalent field Arc perimeter and HFA. The dashed purple lines represent the upper and lower limits of agreement.

It is noteworthy that, the participant who had the corresponding data point outside the LOA in Figure 6-2 and Figure 6-3 was the only study participant with a highly asymmetric VF (Table 6-1). This participant had two absolute scotomata in Arc perimeter recording; on the HFA plot this participant had multiple absolute and relative scotomata points. Without this participant in the data, the bias would have been smaller, and the LOA would have been narrower in both the plots. However, the linear trend that was observed in the second comparison would have remained, indicating that the differences between Arc perimetry and HFA measurements were higher for all participants with VFs smaller than 30%, irrespective of the type of VF defect.

6.5 Discussion

The Arc perimeter is a manual kinetic perimetry method, while the HFA is a static automated perimetry method, assessing only predetermined points in the VF. The Para nordic and Para alpine studies used an Arc perimeter for VF data collection for research purposes, because the Arc perimeter is readily portable and relatively quick to complete. The purpose of the study presented here was to assess the validity of the measurements taken using the Arc perimeter by comparing the functional VF scores obtained using an Arc perimeter and an HFA in adult participants. The study participants had a range of VF defects like the VF defects observed in the Para skiers' populations. Even though the VF scores obtained using the Arc perimeter were higher compared to those obtained using the HFA, in general, there was good agreement between the two measurement techniques for both the full field and equivalent field scores. The Arc perimeter measurements were also quicker compared to the measurements using HFA.

The Bland-Altman plots suggested that there was a small, but consistent bias of the Arc perimeter measurements (both full field and equivalent field) compared to the HFA measurements. The VF scores using the HFA FF246 method were different from the equivalent field Arc perimetry scores by an average of only 5%; however, this difference was higher (14.0%) when compared with the full-field Arc perimetry scores. On the other hand, the LOA was wider for the equivalent field Arc perimetry scores compared to the full-field scores. The plot on the equivalent field Arc perimetry scores also suggested that there was a trend for the differences to be bigger when the VF area was restricted to the central VF (<30%).

Multiple reasons might contribute to the observed bias and LOA between the measurements. First, the maximum measurable extents of VFs were smaller (<60° radius) with the HFA compared to the measurable VFs with the Arc perimeter (90° radius), contributing to the increased difference between the full-field Arc perimetry scores and the HFA scores. However, the Arc perimetry scores were still slightly higher (by 5%) than the HFA scores even when the equivalent field method was used.

The differences in target and testing conditions between the Arc perimetry and HFA methods might be another reason for the differences between the two measurement methods. The Arc perimetry target size was larger (4.51 mm diameter), compared to the HFA target (2.26 mm diameter), which might have helped the participants detect the target at an earlier point. In addition, the contrast between the background and the target, which might affect the visibility and identification of target, were not measured or compared between the two methods, but also was not equal. The Arc perimeter has much higher contrast between the target and the background than the HFA, because the Arc perimeter uses a white target against a black background (the Arc) while the HFA uses a bright light (white target) against an off-white background. The higher contrast between the target and the background may also have helped the participants detect the target earlier and contributed to the higher VF scores in the Arc perimetry method compared to the HFA.

The Arc perimeter, being a kinetic measurement method, provides the flexibility to test along every point on each meridian, which might help to identify the seen / non-seen boundaries in a VF more accurately, compared to testing the predetermined points in static methods such as in HFA. Previous studies comparing the VFs assessed using kinetic (Goldmann or Octopus) and static (HFA 30-2 or FF120 or Esterman) perimetry methods suggested that static perimetry results are slightly worse (plots show more severe defects) and are less reliable than the kinetic methods to detect VF defects.[132–134] The results from current study also suggest that the VFs measured using HFA were worse (smaller VFs) compared to the VFs measured using Arc perimeter. The HFA FF246 method tests predetermined points, which are approximately 2.5° apart in the central 20° of the VF and 10° apart in the peripheral VF, making reliable continuous VF boundary assessments challenging. Measurements using static automated perimetry methods are also vulnerable to fixation losses, which could occur due to participant's poor central VA or poor comprehension. Therefore, the higher variability observed in this study for participants with smaller than 30% VF might be due to possible fixation losses and lack of flexibility in testing boundaries in the HFA method.

One of the disadvantages of using a manual perimeter such as Arc perimeter in routine VF examinations is that the measurements could be affected by the inter-observer variability, mainly due to varying target velocities. In the research conducted in this thesis, including the study described above and the classification research studies, all of the VF extents were measured by the same examiner, reducing this source of variability. However, it is important to note that the high risk of inter-observer variability with the Arc perimeter means that this instrument should only be used for research purposes (by a trained, and consistent examiner), not for classification or clinical management purposes.

Test-retest repeatability is another important factor to be considered when comparing two measurement methods. If one method has poor test-retest repeatability the agreement between the two methods is bound to be poor too. However, due to time constraints, assessments of the test-retest repeatability (intra-observer or inter-observer) of both the Arc perimetry and the HFA were not done during this study. Therefore, future studies including more participants with VFs in the lower (<30º) range and assessing the repeatability and inter-observer variations are needed before using Arc perimeter for purposes other than research. It is possible that manual kinetic measurement methods such as Goldmann or Arc perimetry might provide a truer reflection of the VF boundaries of participants with VFs smaller than 30%, if conducted by a trained examiner. However, the current study had only three participants with less than 30% VF, and future studies with more participants with less than 30% VF are required to confirm these assumptions.

In conclusion, the Arc perimeter measurements, when collected by a single, trained researcher, seem to be valid compared to the HFA measurements, and the differences are smaller, although more variable, when equivalent field scores (out of 52 points) are used for both test methods. Although the Arc perimeter is a manual kinetic method, it can be used as a simple and efficient alternative to the HFA for measuring functional VF extents in situations demanding quick, easy to use, reasonably accurate, portable equipment for research purposes only.

6.6 Thesis progress V

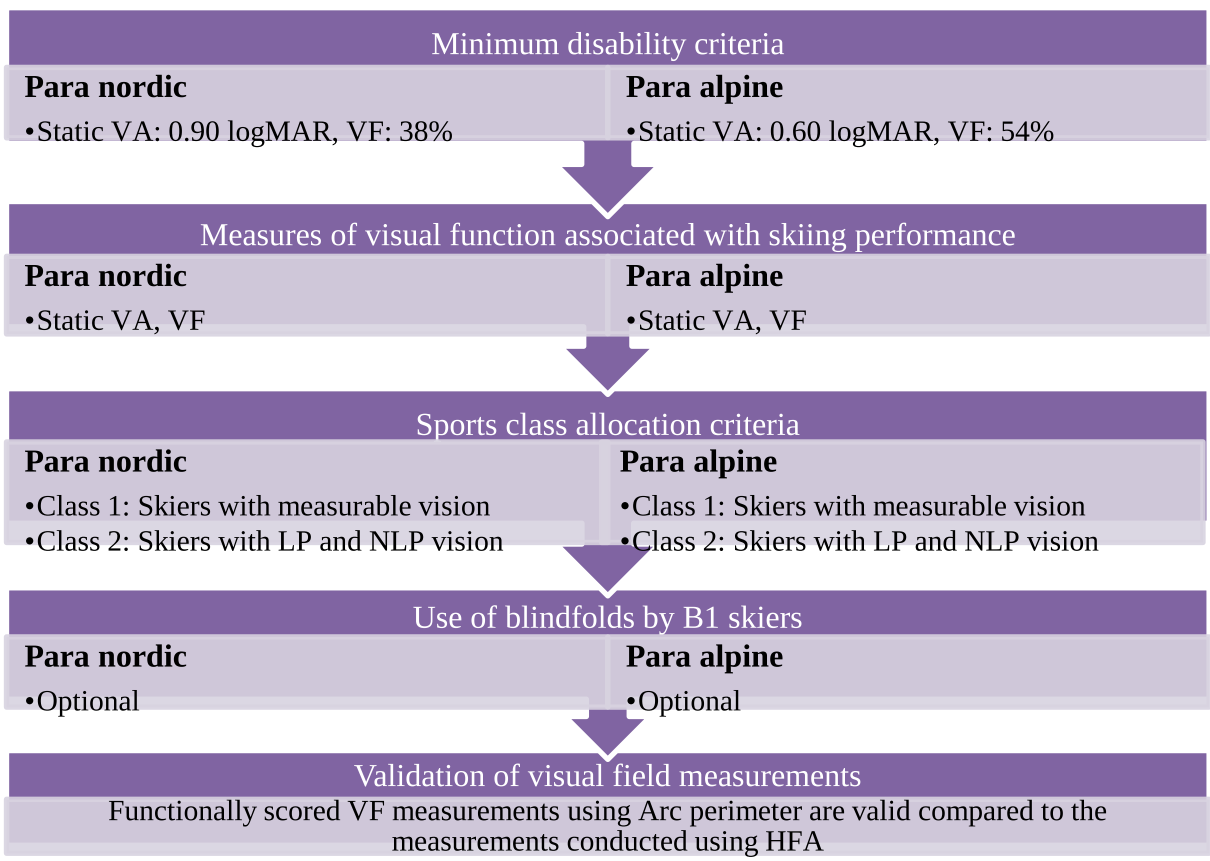

Figure 6-4: Thesis progress V outlining the main objectives and conclusions of Chapter 2 - 5.
The findings from the Chapter 5 suggest that the VF measurements conducted during the Para nordic and Para alpine studies using Arc perimeter are valid compared to the VF measurements using HFA.

Chapter 7
Discussion

7.1 Introduction

The Paralympics consist of 28 different sports across the Summer and Winter Games, and are a parallel sport platform to the Olympics.[135] Elite athletes with a wide range of physical, visual or intellectual impairments participate in the Paralympics, inspiring and motivating individuals with disabilities to dream big and achieve their goals. The popularity of the Paralympics also has helped in changing the attitudes related to inclusiveness and accessibility in societies.[3,136] In order to maintain the popularity of the Paralympics and to continue promoting equality for all, it is essential to assure Paralympic athletes that their impairments are not limitations to winning in Paralympic competitions. In an effort to make competition fair for athletes, the International Paralympic Committee (IPC) has implemented classification systems and sport rules regarding adaptations for the Paralympic sports. The purpose of Paralympic classification is to reduce the impact of impairments on the outcome of competitions by allocating athletes into groups such that athletes in one group have similar limitations in sports performance due to their disabilities.[137] The purpose of the unique sport rules regarding adaptations is to facilitate playing the sport efficiently and safely by accounting for the capabilities of each athlete.

Currently, athletes with visual impairments (VI) are eligible to participate in Paralympic competitions if their best-corrected visual acuity (VA) is worse than or equal to 1.0 logMAR or their visual field (VF) radius is less than or equal to 20 degrees in the better eye. Eligible athletes are classified into the following three classes: athletes with quantifiable static VAs worse than 2.6 logMAR as well as athletes with and without light perception vision (B1), athletes with static VAs ranging from 1.5 logMAR to 2.6 logMAR or a VF radius of less than or equal to 5 degrees (B2), and athletes with static VAs ranging from 1.0 logMAR to 1.4 logMAR or a VF radius of less than or equal to 20 degrees (B3).[8] This classification system was designed based on medical definitions of low vision, and did not consider the uniqueness of each sport.[32] The impact of the wide range and severity of visual function impairments affecting athletes' performances might differ between different sports depending on the visual demands involved in them. The lack of research evidence supporting the current classification system has directly lead to the research presented in this thesis as well as additional research in VI sports such as Para swimming, Para judo, and Para athletics.[34–36]

In addition to the classification criteria, the IPC has also implemented rules regarding specific unique adaptations such as the use of blindfolds and the appointment of guides for the VI category in Paralympics.[6] Guides assist the athletes by safely directing them through the competition. The use of guides is mandatory in some sports and classes, while optional in others. The rules regarding the use of blindfolds vary between sports and were implemented in an effort to equalize the impact of VI on the performances of athletes. There is currently no literature on the impact of guides or blindfolds on the sports performances by athletes with VI.[32] However, it is unlikely the sports would exist without guides, even though it is possible competition could take place without blindfolds.

This thesis consisted of studies conducted to design evidence-based classification systems specific to Para nordic and Para alpine skiing. Similar to the current classification systems, new classification systems should have a minimum disability criteria (MDC; also known as minimum impairment criteria) and sports class allocation criteria.[7] The guidelines detailed by the joint position stand to conduct classification research recommended that the sports performance environments must also be taken into account while designing new classification systems to address the certain limitations in the current systems.[32] For example, the current classification system is based on the levels of visual function in the better eye of athletes, but athletes use information from both their eyes while performing in most sports, therefore the classification criteria also should be based on binocular assessments.

Chapter 2 of this thesis described studies conducted to determine the MDC, while the studies described in Chapter 3 and Chapter 4 were aimed at determining the sports class allocation criteria. Separate studies were conducted for Para nordic and Para alpine skiers. The thesis also included studies conducted to assess the impact of blindfolds on skiing performances of skiers in the B1 class. Chapter 6 described a final study that was conducted to determine the validity of the VF measurements obtained using the Arc perimeter, which was the instrument used in every project described in the thesis to assess the participants' VFs. All visual functions described in the thesis were assessed binocularly for all study participants.

7.2 Factors affecting nordic and alpine skiing

Nordic and alpine skiing are highly dynamic winter sports. Nordic courses are on flatter terrains with uphill, downhill, and curved segments while alpine courses run downhill. Nordic skiers navigate through tracks that are often narrow and grooved and are sometimes in the tree-laden areas. Alpine skiers race down the hill passing through a certain number of gates (depending on the discipline) and the courses are shorter, wider, and involve sharp turns compared to nordic courses. The four individual alpine skiing disciplines differ in terms of the length and width of the courses, the number of gates, and the techniques used. The downhill (DH) and super-G (SG) alpine disciplines are considered to be speed disciplines, where skiers reach speeds of up to ∼130 km/h. The slalom (SL) and giant slalom (GS) disciplines are considered to be more technical events, where skiers reach speeds ranging from 20 to 60 km/h.[24,25,63,138]

Performance in nordic and alpine skiing likely depends on a wide range of physical, training, cognitive, and psychological factors of the skiers. Some of the physical characteristics reported to be associated with better nordic and alpine skiing performance are strong leg muscles and better cardiorespiratory function.[138–141] While it is possible for Paralympic skiers with VI to improve their fitness and muscular strength to the expected levels through the necessary training, their skiing performances are still affected by their impairments in vision and, thus, the classification systems should minimize the impact of these impairments.

7.3 Visual functions associated with Para nordic and Para alpine skiing

Nordic and alpine skiing require the integration of information from multiple sensory and motor systems, and one of the most important sensory systems could be the visual system due to the unique nature of the sport environments, the risks, the speed, and the technical skill involved in these sports. The visual information required for safe skiing involves identifying boundaries and following the course while avoiding obstacles. Skiers also need to quickly process information regarding gates, obstacles, trees, or fellow skiers to make quick decisions and vary their skiing techniques based on visual feedback.[49,52,53] In addition, skiers need to process information regarding subtle contrast changes to understand course characteristics such as changes in slope, bumps, or iciness, which often gets affected by factors related to weather, light, and snow conditions.

Several visual functions such as static and dynamic VA, contrast sensitivity (CS), motion perception, light sensitivity (LS), glare sensitivity (GLS), colour vision, depth perception, and VF could be related to nordic and alpine skiing performances. The area of the VF used by the skier and the demands on each visual function might vary depending on the direction and speed of skiing. Previous research suggested that GLS of the better eye and static VA could be associated with Para nordic skiing performance and that static VA was a significant predictor of Para alpine skiing performance, while colour vision was not associated with either Para nordic or Para alpine skiing performance.[33,60,61]

Skiing performance could also be affected by other factors such as the skier's age, age of onset of VI, age of onset of skiing, total lifetime hours of skiing, and the number of races that the skier competed in the performance points calculation period. Hence, the two studies described in Chapter 3 of this thesis to identify the visual functions predictive of skiing performance examined the effect of factors related to age and training in addition to the effect of impairments in visual function on Para nordic and Para alpine skiing performances. The visual functions examined in these studies were static VA, dynamic VA, CS, LS, GLS, GLR, TMP, RMP, and VF.

These studies concluded that static VA had the potential to be predictive of Para nordic skiing performance and was predictive of performance in technical disciplines of Para alpine skiing. Visual field was also found to be strongly associated with nordic and slalom skiing performances. In addition, the performance plots created to represent the relationships between areas of VF loss and skiing performance schematically also suggested strong and moderate associations of VF with nordic and alpine skiing performances, respectively (Appendix E). Contrast sensitivity also appeared to be associated with, though not predictive of, Para alpine skiing performance.

Static VA is one of the most common assessments of spatial vision and is extremely useful to detect deficits in the visual system. Although the static VA does not seem to directly provide information about the perception of low contrast images or objects in motion, previous research had reported significant strong correlations between the static VA and measures of CS and dynamic VA.[142,143,144] Consistent with previous literature, the studies described in Chapter 3 found that static VA was significantly associated with dynamic VA and CS in both the Para nordic and Para alpine data. Static VA and VF were the visual functions that best explained changes in skiing performance and adding additional tests was not necessary. The magnitudes of correlations between static VA and CS were higher in the Para nordic ($\rho=-0.60$, $p<0.001$) and Para alpine ($\rho=-0.80$, $p<0.001$) populations compared to the reported associations in individuals without low vision ($\rho=-0.21$, $p=0.003$).[145] However, the correlations from the studies in this thesis were similar to those reported in low vision populations, especially when CS was measured using the qCSF method.[142,146] The high correlations between SVA and CS could have masked the relationships between CS and skiing performance, as once static VA and VF were taken into account, CS was not a significant predictor of performance in either sport. Thus, the studies concluded that static VA and VF are the only visual functions that should be included in Para nordic and Para alpine classification even though visual functions such as contrast sensitivity, glare sensitivity, and dynamic VA were expected to be predictive of skiing performance based on the high visual demands involved in these sports.

7.4 Minimum disability criteria in Para nordic and Para alpine skiing

The minimum levels of impairments in visual functions affecting sports performance could vary between sports due to differences in aspects of visual information such as viewing distances, target sizes, lighting conditions and visual space involved in them. Certain sports such as table tennis or judo require athletes focus on targets at closer distances, while sports such as skiing, or cycling require distance vision. Some sports, such as shooting, require athletes to focus on their central vision, while other sports such as football, might need information from the periphery in addition to the central field.[53] The studies described in Chapter 2 of the thesis investigated the minimum disability criteria (MDC) in Para nordic and Para alpine skiing by simulating static VA, CS, and VF impairments in able-sighted skiers as recommended by the joint position stand.[32] The studies on Para nordic and Para alpine MDC identified that the skiing performances were affected with moderate levels of VA and VF impairments.

The minimum impairment levels in static VA affecting the skiing performances in Para nordic and Para alpine skiing were similar to the previously reported minimum impairment levels of static VA in other visually complex sports such as cricket (0.5 to 0.8 logMAR) and shooting (0.53 logMAR).[38,91,92] Both VA and VF impairments were found to affect alpine skiing performances at a less severe stage of impairment compared to the nordic skiing performances. Although nordic and alpine skiing have high visual demands, nordic skiing is comparatively slower, and the skiers need to focus more on sustained performance for longer durations compared to alpine. Alpine skiing is completed in much shorter times compared to nordic skiing, and the skiers are more focused on maintaining their speed and balance while racing downhill at high speeds. The higher speeds of alpine also increase the need to gather and process information quickly to minimize the risk of injuries.[49,109] Thus, the lower levels of VA and VF impairments affecting alpine skiing could be due to the higher competition speed and higher visual demands in Para alpine skiing compared to Para nordic skiing.

One of the limitations of the MDC studies was that only peripheral VF constrictions were feasible to be simulated binocularly. Even though peripheral VF constriction is the most common type of VF impairment found among skiers with VI (Chapter 3), other types of impairments such as central scotoma or peripheral islands of vision were also observed among these participants. Thus, caution should be taken while classifying participants with other types of VF defects. However, the performance plots generated with the AMA VF scores (without any bias to central VF) of the Para nordic and Para alpine participants (Appendix E) suggested that all types of visual field loss negatively impacted skiing performance with a slight bias to central and lower VF. In addition, the reported VA of individuals with absolute central scotoma (8 to 20 degree in diameter) are very low (range: 1.10 logMAR to 1.70 logMAR),[147] which would make them qualified to compete based on the VA cut-off criterion for both Para nordic and Para alpine sports. Therefore, the VF cut-off criteria generated using simulated VF impairments are valid while applying on skiers with peripheral VF constrictions.

The optimum VA and VF cut-off values in the MDC studies were obtained from the Youden's J calculations based on the ROC plots generated. Most of the Youden's J curves calculated using the nordic and alpine data did not have sharp peaks, which is another possible limitation of these studies. However, the final recommendations on the VA and VF cut-off values were made only after considering the static VA and VF values corresponding to the first and second best Youden's Js as well as the results from the decision tree analyses. The cut-off levels based on the ROC and decision tree analyses that equally maximized sensitivity and specificity and decision tree analysis were a static VA of 0.90 logMAR and a VF of 38% in nordic and a static VA of 0.60 logMAR and a VF of 54% in alpine skiing.

The sim-specs used in the MDC studies simulated static VA impairments ranging from -0.02 to 1.37 logMAR and -0.02 to 1.50 logMAR in nordic and alpine skiers, respectively. All the Para nordic participants in the second and third experiments had Static VAs worse than 1.18 logMAR (range: 1.18 to 2.68 logMAR, LP and NLP), and most (82%) of the Para alpine participants had Static VAs worse than 1.00 logMAR (range: 0.04 to 1.64 logMAR, LP and NLP). The levels of simulated impairments (starting from the level 6 (nordic) and level 5 (alpine) sim-specs simulators) in the MDC study overlapped with the levels of static VA in the actual Para nordic and Para alpine skiers, ensuring that effect of a broad range of VA impairments, starting from levels of VA, at which skiers are not currently eligible, to levels of VA that some of the currently eligible skiers have, were looked at in the MDC studies. Similarly, the bespoke goggles used in the MDC studies simulated VF impairments ranging from 83.1% to 22.0% and 85.7% to 19.9% in nordic and alpine skiers, respectively. The Para nordic and Para alpine participants in the second and third experiments had their VF ranging from 100.0% to 0.0% and 89.2% to 0.0% in nordic and alpine skiers, respectively, and the range of VF simulated in the MDC studies overlapped with the VF extents of the Para nordic and Para alpine participants, ensuring that the simulation studies made assessing the effect of a broad range of VF impairments, from levels at which the skiers are not currently eligible to levels some of the currently eligible skiers have, possible. Both the static VA and VF impairments simulated in the MDC studies overlapped with the lower (better vision) end of the range of VI in the actual Para nordic and Para alpine populations in the studies, facilitating the inclusion of participants with VI levels ranging from no impairment to profound VI and LP or NLP vision in all of the studies conducted in this thesis.

The MDC studies facilitated the assessment of changes in performance of skiers at multiple levels of VI. Simulation studies are considered as the most appropriate way to assess the minimum VI affecting performance in non-adapted forms of sports as the researchers have control over the types and levels of impairments simulated as well as on the adaptation levels of participants.[32] In spite of the limitations mentioned above, the studies were carefully designed and had consistent conclusions from multiple data analyses methods, indicating that the results obtained from these studies are likely as close to the actual values as is possible to measure. The VA and VF cut-off values equally maximizing the sensitivity and specificity for determining above and below expected-performance levels were chosen as the recommended values from these studies. Ultimately, it is up to the governing body of the sport to make the final decision on the VA and VF cut-off values, which prioritize either improved sensitivity or improved specificity of the classification method. Increasing the sensitivity levels could reduce the specificity and result in the inclusion of athletes who do not have a VI that impacts skiing performance, while increasing the specificity could result in the exclusion of some skiers whose performances are impacted by their VI.

7.5 Sports classes in Para nordic and Para alpine skiing

Once the skiers' eligibility is determined based on the MDC, skiers need to be allocated into classes based on the sports class allocation criteria. The current sports class allocation criteria in Para nordic and Para alpine skiing divides athletes into B1, B2, and B3 classes. Para sports such as swimming and athletics also follow the same criteria to allocate athletes into classes, while Para sports such as triathlon and shooting let all athletes compete as one class.[20,21,26,27] The earlier studies described in Chapter 3 of the thesis concluded that information regarding static VA and VF were sufficient to explain the changes in Para nordic and Para alpine skiers' performance points once age and training factors were taken into account.

Hierarchical clustering analyses were used to identify the presence of clusters within the current Para nordic and Para alpine populations. These analyses were described in Chapter 4 of the thesis, which concluded that when currently eligible skiers were grouped based on the similarities in their skiing performances, static VA and VF were the only visual functions significantly different among the groups. The groups with a higher proportion of skiers with LP and NLP vision in both nordic and alpine skiing data had significantly worse skiing performance points compared to the group of skiers with a higher proportion of measurable static VAs. Thus, the studies concluded that there could be two different sports classes for the current populations of Para nordic and Para alpine skiers, one for skiers with quantifiable vision and the other for skiers with LP or NLP.

The final decision on the sports classes can only be made after taking both the MDC from Chapter 2 and sports class criteria from Chapter 4 into consideration. The current MDC determined the eligibility of skiers based on the static VA level of 1.00 logMAR and an Esterman VF of 21.7% for both the Para nordic and Para alpine skiing sports. The MDC study on able-sighted nordic skiers concluded that a static VA cut-off of 0.90 logMAR and a VF cut-off of 38% could be used as the eligibility criteria for classification of Para nordic skiers. However, skiers with static VAs ranging from 0.90 logMAR to 0.99 logMAR and Esterman VFs ranging from 38% to 21.7% are currently not eligible to participate in the Paralympics, and it would not be fair to combine this group of skiers with the group of currently eligible Para nordic athletes with measurable vision as the performance levels of Para nordic skiers with their static VA or VF in these ranges have not been compared with the currently classified Para skiers with VI. Similarly, the Para alpine MDC study concluded that a static VA of 0.60 logMAR and an Esterman VF of 54% could be used as the eligibility criteria for classification of Para alpine skiers. However, skiers with static VAs ranging from 0.60 logMAR to 0.99 logMAR and Esterman VF ranging from 54% to 21.7% are not currently eligible. These skiers who would become eligible based on the new MDC cannot be combined with the currently eligible skiers with measurable vision as the performance levels of Para alpine skiers with their static VA or VF in these ranges have not been compared with the currently classified Para skiers with VI.

Therefore, in consideration of both the MDC and sports class studies, the experiments described in Chapters 2 to 4 conclude that the new classification systems for Para nordic skiers could have three sports classes: 1) static VA ranging from 0.90 to 0.99 logMAR or VF ranging from 38% to 21.7%, 2) static VA ranging from 1.00 to 2.60 logMAR, VF below 21.7%, and 3) LP and NLP vision. Similarly, Para alpine skiing classification should also have three classes: 1) static VA ranging from 0.59 to 0.99 logMAR or VF ranging from 54% to 21.7%, 2) static VA ranging from 1.00 to 2.60 logMAR, VF below 21.7%, and 3) LP and NLP vision. Similar to the proposed cut-off criteria, these proposed ranges of VA and VF for the sports classes are only suggestions based purely based on the data collected, and a few practical challenges mentioned in the next section should also be considered before making the final recommendations on the sports classes.

7.6 Limitations and practical implications of classification criteria studies

The sample sizes of some of these studies might seem to be small and the data analyses might appear to be limited. However, considering the populations of currently eligible elite skiers as well as the number of skiers who competed during the events at which the studies were conducted, these samples were fairly representative of the Para nordic and Para alpine populations and included over 60% of the population of elite VI Para nordic and Para alpine skiers who competed at each event (Table 3-4). In addition, choosing only the elite skiers who are eligible to compete in WCH competitions as participants ensured that the training or experience related factors, which might affect skiing performance were as similar among the participants as possible. In addition, the researchers have taken care to make sure that the measurement environments and conditions for the vision assessments were as consistent as possible between the studies, and that the skiing performance metrics were robust across environments to ensure that the variabilities due to the measurement conditions were minimised. Furthermore, there was a consistency observed in many of the study results even though the studies were conducted separately for Para nordic and Para alpine sports at varying time points. For example, the average VA and VF at each level of simulated impairment were reasonably comparable between nordic and alpine participants in the MDC studies, and only VA and VF were found to be associated with both Para nordic and Para alpine skiing. These observed consistencies between skiing sports suggest that the study samples were representative of actual populations and the results of the studies are as close to the true results of the populations as possible.

Another possible limitation of the studies described in Chapters 2, 3, and 4 is that initially, Esterman binocular VF grid was used for functionally scoring VFs of participants, which gives relatively higher importance to the central and lower areas of VF, which are assumed to have more functional relevance. Though this method was helpful in obtaining a summary score for the VFs of all our participants and analysing the data, it is possible that the bias due to the assumed importance of certain VF areas could affect the study results. In addition, it is likely that two different types of VFs with different sizes may have the same VF percentage value due to the nature of this scoring method. For example, an individual with full visual field with a central scotoma of 15° radius and another individual with 25° radius of peripheral VF constriction will have the same VF value of 85.0% when scored using Esterman grid and converted to percentages. To assess the influence of the bias in the Esterman scoring method on the MDC as well as the sports class criteria developed, the results of the experiments described in Chapters 2, 3 and 4 were re-examined using two unbiased AMA scoring methods (Appendix E), and none of the study conclusions (corresponding VF radius in degrees) changed, even though the exact numbers of the VF cut-off changed. Thus, if the sport governing body decides to proceed with one of the unbiased AMA scoring methods, the VF cut-off levels from the re-examined results could be used to keep the classification research results comparable across sports.

In addition, there are a few challenges associated with the practicality of implementing a new classification system for determining the eligibility or sports class allocation. There is a certain degree of variability associated with any test method, which can occur due to the repeatability or intra/inter observer variabilities. For example, two successive VA measurements of an individual with low vision could differ by 0.20 to 0.30 logMAR when an ETDRS chart is used for measurements.[148] The optimum VA cut-off that was obtained for the nordic data was 0.90 logMAR, which differs by only 0.10 logMAR units from the current cut-off criterion. Although reducing the current cut-off VA level would allow a new group of skiers with VAs between 0.90 logMAR and 1.00 logMAR in the Para nordic sport, it is likely that the effect of these skiers' impairments in VA on their performances are similar to that of the currently eligible skiers. Thus, it might not be practical or fair to allocate these newly eligible Para nordic skiers to a separate class. However, the new VA cut-off for the Para alpine sport is 0.60 logMAR, which is different by 0.40 logMAR from the current cut-off criteria, and it seems fair to allocate these newly eligible skiers to a different class.

Finally, it is also challenging to decide what happens to the individuals with VA or VF slightly better than the cut-off levels. For example, a nordic skier with static VA of 0.86 logMAR will not be eligible to participate if the cut-off VA is exactly 0.90 logMAR and if the measurements are conducted with 0.02 logMAR units of precision. However, it could be argued that the difference of the measured VA from the cut-off VA is only 0.04 logMAR and this difference is within the range of the repeatability of ETDRS charts. Therefore, the fairness in rejecting the eligibility for that skier is questionable. Similar challenges exist for the VF cut-off for eligibility. One option to overcome these challenges is to make sure that the measured value is as close as possible to the actual value by taking multiple measurements and taking an average value as the final measurement. However, this might not be practical in case of HFA measurements due to the long test durations and related logistics issues. Another option is to round the VA values measured to the nearest multiple of 0.10. For example, if a participant's VA is 0.86 or 0.92, it could be considered as equivalent to 0.90 and could be considered as eligible. Similarly, the VFs measured could also be rounded in some way. Unfortunately, there is no reports available on the variability of VFs across different instruments and scoring methods. However, since the AMA scoring methods have points that are 10 degrees apart, and since most of the points in the peripheral field of Esterman's grid are 10 degrees apart, the VF radii (in degrees) measured as part of classification process could be rounded to the nearest multiple of 10 to account for variability within the measurement methods and in the scoring method. Finally, since the measurements conducted during the classification process are crucial in determining skiers' eligibility as well as sports class, the sport governing body should also make sure that the classifiers follow consistent measurement procedures and conditions, and that there are options for appeals and repeated assessments.

7.7 Final class recommendations

Considering the results from the studies described in Chapters 2 to 4 and all the practical issues mentioned above, the final recommendations regarding Para nordic and Para alpine classification are as follows: For the Para nordic sport, skiers are eligible to compete in the VI category if their static VA is ≥0.90 logMAR. Nordic skiers with VA better than 0.90 logMAR are eligible to compete in VI category if their VF is ≤38.0% Esterman score. Once the eligibility is determined, Para nordic skiers could be allocated to one of the two classes based on their static VA: 1) skiers with static VA ranging from 0.90 to 2.60 logMAR (all quantifiable VA) and 2) skiers with LP and NLP vision. For the Para alpine sport, skiers are eligible to compete in the VI category if their static VA is ≥ 0.60 logMAR.

Nordic skiers with VA better than 0.60 logMAR are eligible to compete in VI category if their VF is ≤54.0% Esterman score. Once the eligibility is determined, Para nordic skiers could be allocated to one of the three classes based on their static VA: 1) skiers with static VA ranging from 0.60 to 0.99 logMAR or with VF ranging from 54.0% to 21.7% Esterman score, 2) skiers with static VA ranging from 1.00 to 2.60 logMAR or with VF ≤21.7% and 3) skiers with LP and NLP vision.

It should be noted that the research data can only be used to provide initial recommendations based purely on the data that was collected and available to the researchers. The ultimate decision on cut-off criteria or class allocation should be made considering all the factors related to the practicality issues, including the sport technical rules, that would be involved in the implementation of classification systems in Paralympic sports. It should also be noted that rigorous follow up studies must be conducted to evaluate the performance of any new classification systems that are implemented, to determine if they are working as anticipated and to modify them if necessary, if these recommendations are taken into consideration by the governing body of the sports and new rules for classification are developed for the sports.

7.8 Blindfold rules

Currently, athletes in the B1 class are required to wear blindfolds in sports such as skiing and swimming. In some other sports such as goalball and football-5-a side, all VI athletes are required to wear blindfolds. The majority (96%) of the panellists in a Delphi study conducted to identify preferences in classification research have agreed that while it is not appropriate to mandate the use of blindfolds for all the B1 athletes, this rule might be required in some sports to make competition fair for all athletes.[149] The Para nordic and Para alpine studies investigating the effect of blindfolds on the skiing performances of B1 skiers suggested that there was no significant impact of the blindfold condition on performance. Interestingly, the blindfold condition preferences varied among skiers, but skiers' preferences were also not significantly associated with their skiing performances.

Previous research has reported that psychological factors such as self-confidence and fear could affect the skiing performances in both nordic and alpine skiers.[150–152] Self-confidence had a positive impact, enhancing performances in skiers, while fear had a negative impact on reducing the performance levels. The mandatory use of blindfolds might affect the skiers' performances by altering the levels of self-confidence and fear. For example, a skier with LP vision who was used to training without the blindfold might feel less confident and scared if forced to ski with the blindfold during a competition. These factors, in addition to the stress levels related to Paralympic competition, could have a negative impact on skiing performances in such situations. Thus, the Para nordic and Para alpine studies concluded that the use of blindfolds should be optional for skiers during the competitions. Similar research is needed in other sports such as Para swimming, Para athletics and Para triathlon to assess the effect of rules regarding the mandatory use of blindfolds on the sports performances of athletes.

7.9 Validation of visual field measurements conducted using Arc perimeter

Since the Para nordic and Para alpine studies used Arc perimetry as it is a relatively easy, quick and portable perimetry method to assess the VFs of skiers, the final study described in the thesis was aimed at validating the VFs measured using the Arc perimeter in comparison with the Humphrey Field Analyser (HFA). There was reasonable agreement between the VFs scores obtained using the Arc perimeter and the HFA. Therefore, the Arc perimeter could be used as a valid screening tool to measure the binocular VF extents of participants in similar classification research studies, which demand a perimetry method that is reasonably accurate, easy and quick to test and portable. Due to the limitations of being a manual perimeter, the Arc perimeter measurements should always be conducted by a well-trained researcher, and only measurements taken under consistent conditions with a consistent examiner should be compared. As a consistent examiner for classification is not possible, the Arc perimeter should only be used for research purposes. Automated perimetry methods such as HFA or Octopus will be more reliable for classification purposes when the measurements are conducted by different examiners.

7.10 Future directions

The Para nordic and Para alpine studies conducted to identify the visual functions predictive of skiing performances and to determine the sports classes for competition had currently eligible Para skiers as participants. The studies had limited participation of skiers with VA ranging from 2.30 to 2.90, especially in Para alpine, where we had no participants with VAs in this range. In addition, the proposed MDC based on the studies would allow new groups of Para nordic and Para alpine skiers to participate in future competitions, if taken into consideration. Thus, continuous follow up is required to assess the performance of the new classification criteria in both Para nordic and Para alpine skiing. Follow up studies on the performance of classification should focus on both analyses of trends in performance based on the classes as well as expert feedback. Feedback could be obtained from both the Para nordic and Para alpine sports experts such as the coaches, guides, skiers and the officials through methods such as Delphi studies.

Goggles are an essential part of ski gear, protecting skiers from the external elements. Para nordic and Para alpine skiers use a wide range of ski goggles, with varying tints or filters. Currently, there are no rules regulating the use of such goggles. As the use of tints and filters could affect various aspects of vision such as glare or contrast, future studies could also explore the effect of using different tints or filters in the skiing sports.

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Appendix A
Ocular Health and Skiing Experience Questionnaire

Participant ID:_______________ M/F/Other Date:_______________________________

Age:________________ Team/Position (eg:Guide/Coach):________

1- Do you wear any type of vision correction (i.e. glasses, contact lenses)? if yes please specify.
2- Do you wear any type of vision correction while skiing (i.e. glasses, contact lenses)? if yes please specify.
3- Have you been diagnosed with any eye problem? (If your answer is NO please go to question 6)
4- Could you specify what the problem was and whether it is still present?
5- Could you specify medications/treatment that you are taking/took for the problem?
6- Do you have a family history of eye problem? If yes please specify.
7- Do you regularly take any supplements or medication? If yes please specify.
8- How many years of experience do you have in skiing? Please specify the year you started skiing.
9- On an average, how many hours of training do you get in skiing and in strength and conditioning in a week? Please specify if it varies with seasons.
10- How many years of experience do you have in the current position? Please specify the year.

Appendix B
Detailed information on the simulated visual impairments and the visual function assessments at each level of impairment

B.1 Cambridge simulation spectacles

The Cambridge simulation spectacles (sim-specs) simulate general visual acuity and contrast sensitivity loss. Varying levels of vision impairments can be simulated by combining multiple pairs sim-specs on top of each other.[64] We used eight levels of sim-specs (i.e. up to eight pairs) to simulate simultaneous VA and CS impairments for these studies (Figure B-1). Simulations starting from the from the minimum possible impairment level (level 1) were used as no assumptions were made about the minimum VA and CS that could affect skiing performance. The estimated simulated VA using level 6 sim-specs for a participant with 0.00 logMAR baseline VA is 1.34 logMAR.[80] Since the current MDC for VA is 1.00 logMAR, impairment levels up to level 8 were to ensure skier's performances were negatively impacted by some of the simulated impairments.[78]

Figure B-1: One of the Cambridge simulation spectacles (level 5) used in the studies.

All participants wore their habitual optical correction (no correction or contact lenses, no participants habitually skied in glasses) during the vision assessments. Participants' VA and CS were first assessed using the level 8 (most severe) simulated impairment. VA and CS were then reassessed for each of the other 7 levels of simulated impairments in order of decreasing impairment severity. Finally, VA and CS were assessed without any simulated impairments. The measurements made without any simulated impairments were used as participants' baseline VA and CS. VA (Table B-1 & Figure B-2) and CS (Table B-2 & Figure B-3) of both the nordic and alpine study participants reduced systematically with an increase in the level of VA and CS impairments.

Table B-1: Mean and standard deviation of VA at each level of impairment (logMAR).

Sport		Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8
	Mean	-0.02	0.14	0.37	0.64	0.85	1.05	1.22	1.37
Nordic	SD	0.21	0.19	0.17	0.14	0.1	0.12	0.10	0.11
	Median	-0.08	0.09	0.37	0.59	0.85	1.04	1.18	1.36
	Mean	-0.03	0.18	0.56	0.81	1.20	1.40	1.46	1.50
Alpine	SD	0.17	0.15	0.13	0.13	0.07	0.08	0.07	0.06
	Median	-0.08	0.12	0.57	0.84	1.21	1.42	1.49	1.50

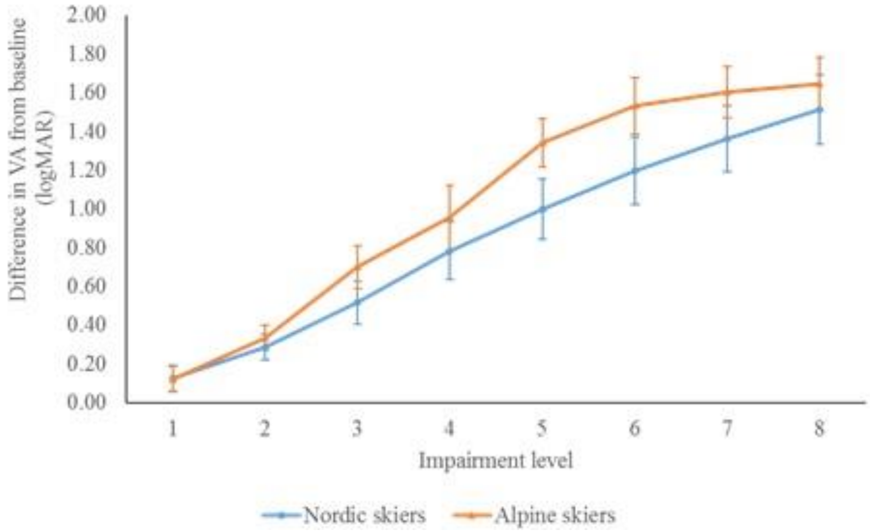

Figure B-2: Mean and standard deviation of the differences in VA from the habitual VA at each level of simulated impairment (logMAR).

Table B-2: Mean and standard deviation of CS at each level of impairment (logCS).

Sport		Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8
	Mean	1.77	1.70	1.46	1.26	0.95	0.77	0.53	0.34
Nordic	SD	0.03	0.05	0.12	0.14	0.11	0.12	0.11	0.12
	Median	1.76	1.72	1.44	1.26	0.96	0.78	0.52	0.36
	Mean	1.76	1.62	1.23	0.93	0.60	0.39	0.28	0.22
Alpine	SD	0.03	0.11	0.15	0.15	0.11	0.09	0.08	0.09
	Median	1.76	1.64	1.24	0.94	0.62	0.38	0.30	0.20

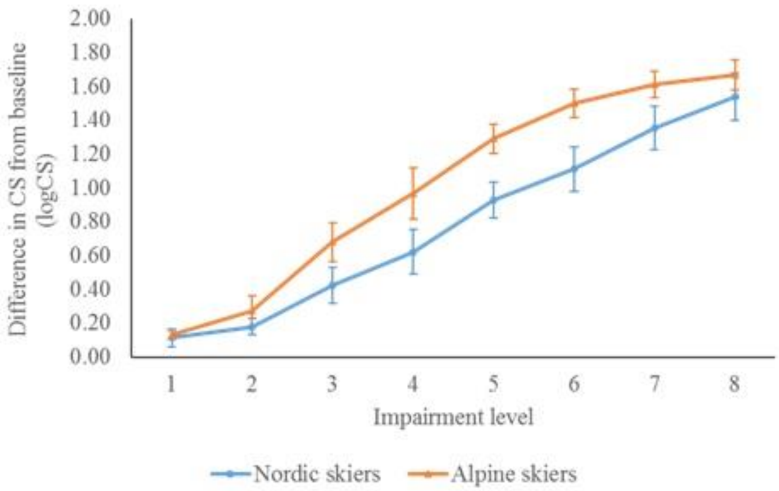

Figure B-3: Mean and standard deviation of the differences in CS at from the habitual CS at each level of simulated impairment (logCS).

B.2 Bespoke VF impairment goggles

Binocular peripheral VF impairments were simulated by manually painting clear swim goggles (levels 3-6) and safety goggles (Figure B-4). Six levels of simulated VF impairment goggles were used, which constricted the binocular VFs of participants systematically. Only peripheral VF constrictions were simulated in these studies as there were no feasible options to simulate reliable central VF impairments or any other type of VF impairments binocularly.

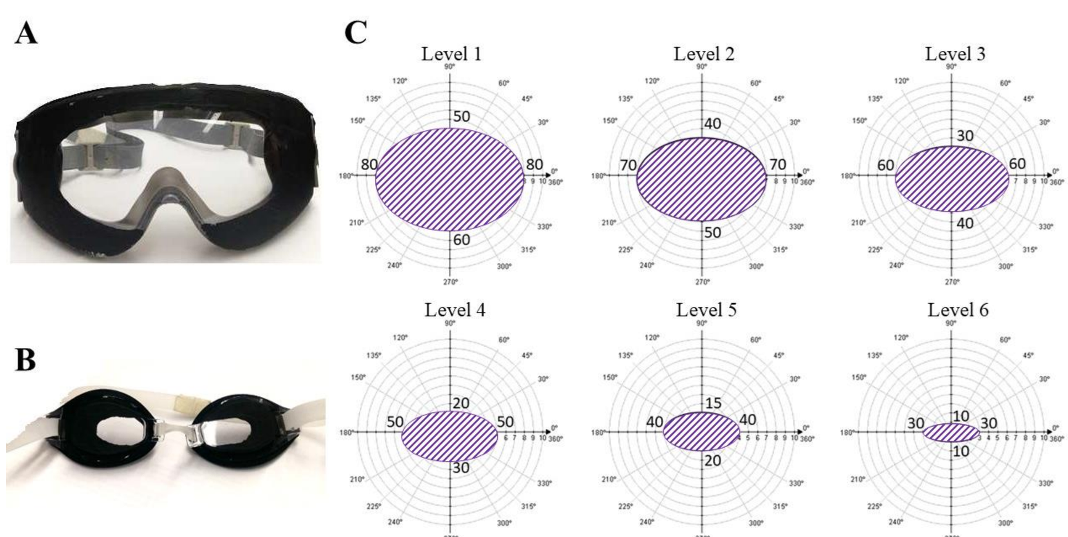

Figure B-4: Examples of VF impairments simulations (A) safety goggles and (B) swim goggles used in the studies and (C) illustrations of the 6 levels of peripheral VF constrictions simulated. The estimated visual field seen at each level of simulation are represented as diagonal patterned ovals; anything outside the ovals was unseen (C). The horizontal and vertical extent of the fields (in degrees) are provided on each grid.

Similar to the VA and CS assessments, all participants wore their habitual optical correction under the bespoke goggles during the VF assessments. Participants' VF was first assessed using the clear safety goggles (no impairment) followed by the level 1 impairment goggle. VF measurements were repeated for all the other 5 levels of VF impairments in increasing order of severity of simulated impairment. The measurement with the clear safety goggle was used as participants' baseline VF. Peripheral VFs (Table B-3 & Figure B-5) of both the nordic and alpine study participants reduced systematically with increasing levels of VF impairments.

Table B-3: Mean and standard deviation of participants' visual fields with an increase in the level of simulated impairment (% of Esterman scores).

Sport		Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
	Mean	83.1	71.7	63.1	50.3	33.4	22.0
Nordic	SD	2.1	10.5	4.3	6.4	4.9	4.4
	Median	82.9	75.0	62.9	50.0	32.9	22.1
	Mean	85.6	76.4	59.8	47.8	30.8	19.9
Alpine	SD	3.7	2.1	3.4	3.3	3.7	4.0
	Median	84.2	75.8	60.4	47.5	30.0	20.0

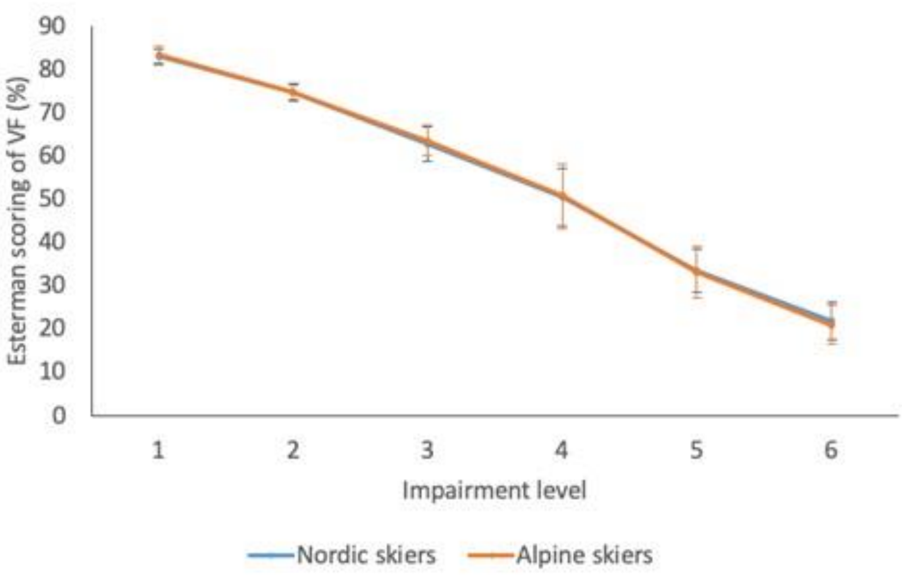

Figure B-5: Mean and standard deviation of the Esterman scoring of VF at each level of simulated impairment (%).

Appendix C
Detailed information on the fatigue and order effects in nordic and alpine participants

C.1 Fatigue effect

The fatigue effect was calculated by comparing the habitual vision (clear goggle) race times of each participant for each course. Non-parametric Friedman tests of differences among the clear goggle trials were conducted, and the p-values were insignificant for the nordic study (p=0.94) as well as for both the courses of alpine study (course one p=0.72 and course two p=0.52) (Figures C-1 to C-3).

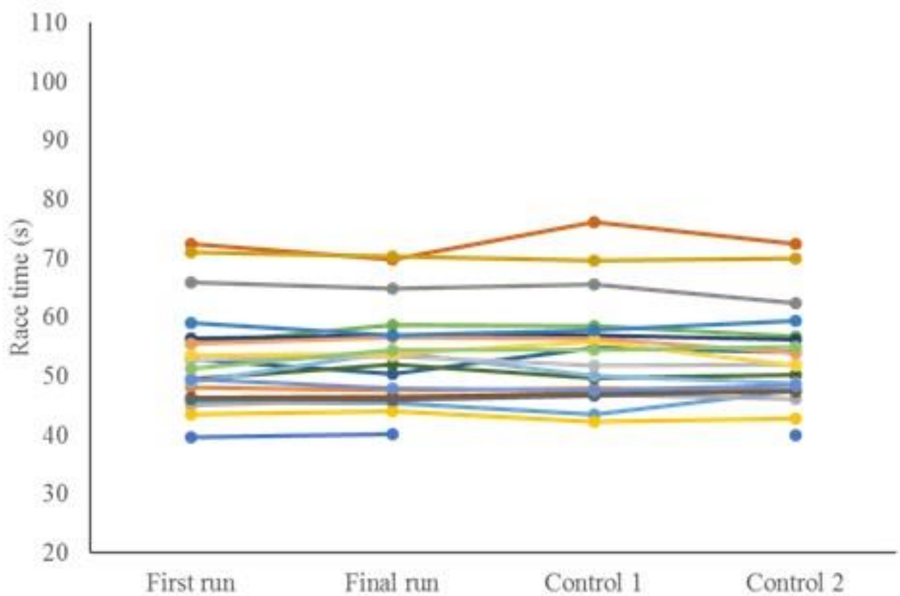

Figure C-1: Comparison of race times with clear goggle conditions for the nordic course. Each line on the graph represents one subject.

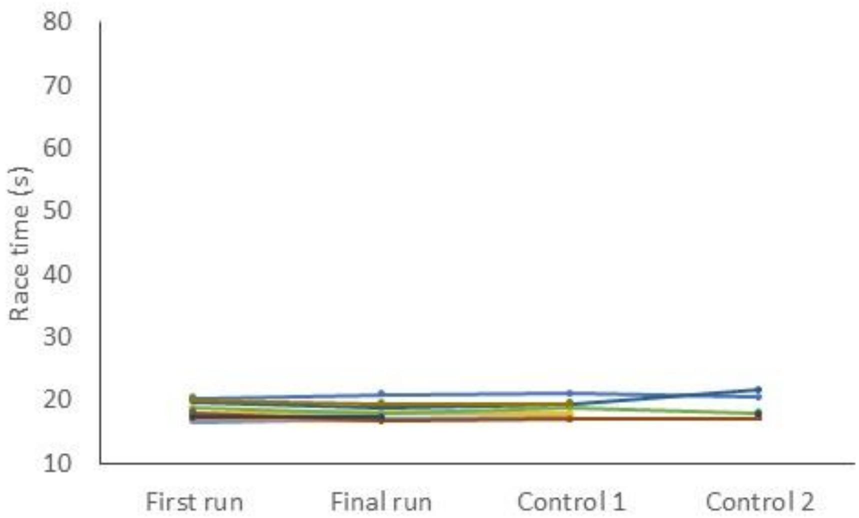

Figure C-2: Comparison of race times with clear goggle conditions for alpine course 1. Each line on the graph represents one subject.

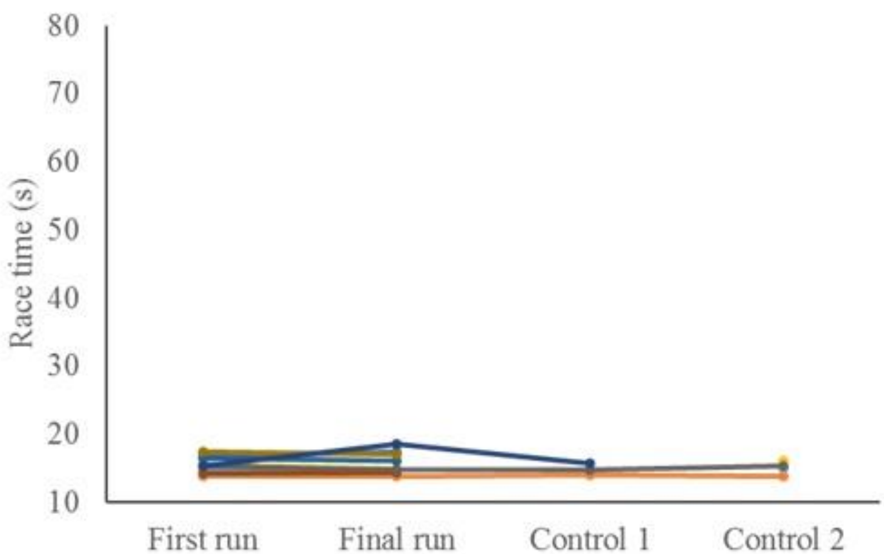

Figure C-3: Comparison of race times with clear goggle conditions for alpine course 2. Each line on the graph represents one subject.

C.2 Order effect

Race times of all participants for all runs were plotted in the order of skiing trial to investigate whether or not there was a systematic increase or decrease in runtime due to learning the course or fatigue as the testing progressed. There was no significant order effect (p=0.20) for the ski trials conducted for any of the nordic participants (Figure C-4).

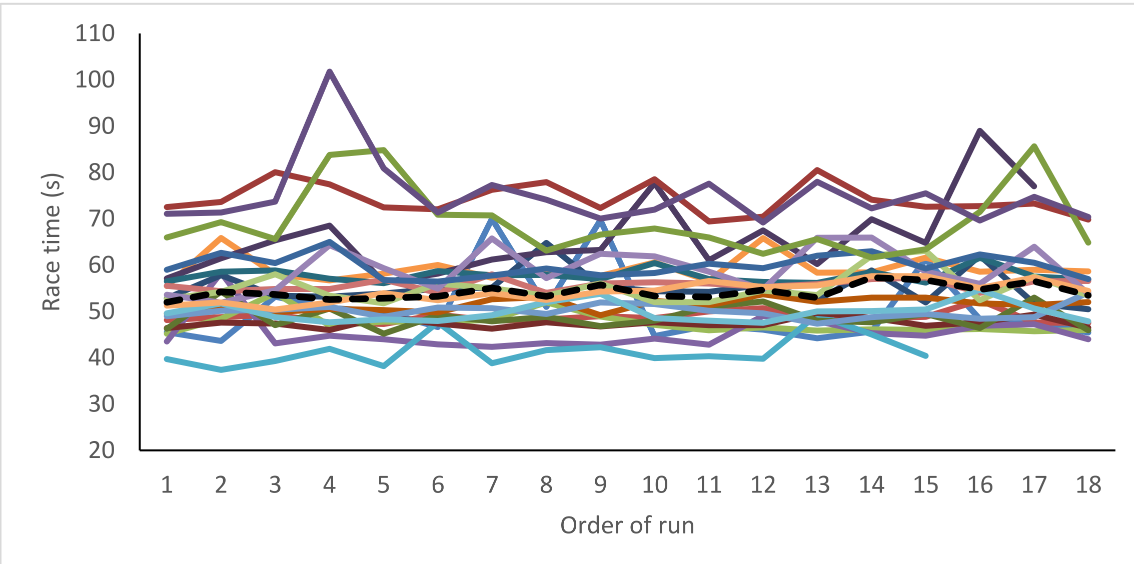

Figure C-4: The race times in the order of skiing trials for all nordic participants. Each line on the graph represents one subject. The black dashed line represents the overall median value of all participants at each trial.

There was no significant order effect (p=0.10) across the trials for the alpine participants on course 1 (Figure C-5). However, the race times were significantly higher (p=0.001) in the 5th and 9th ski trials on course 2 (Figure C-6). Upon further investigation, it was found that a higher proportion of severe vision impairment simulators were used during 5th and 9th ski trials compared to the rest of the trials, even though the order of simulators were randomized across all of the ski trials. Out of the 11 participants, seven (63.60%) wore a severe impairment simulator (VA and CS level 5 and higher, and VF level higher than 4) while skiing the 5th and 9th ski trials. On each of the other six ski trials, five or fewer participants ($\leq$ 45.5%) wore a severe impairment simulator while skiing. Thus, it was concluded that the order effect observed in course 2 was due to an increased number of higher impairment simulators even after randomizing.

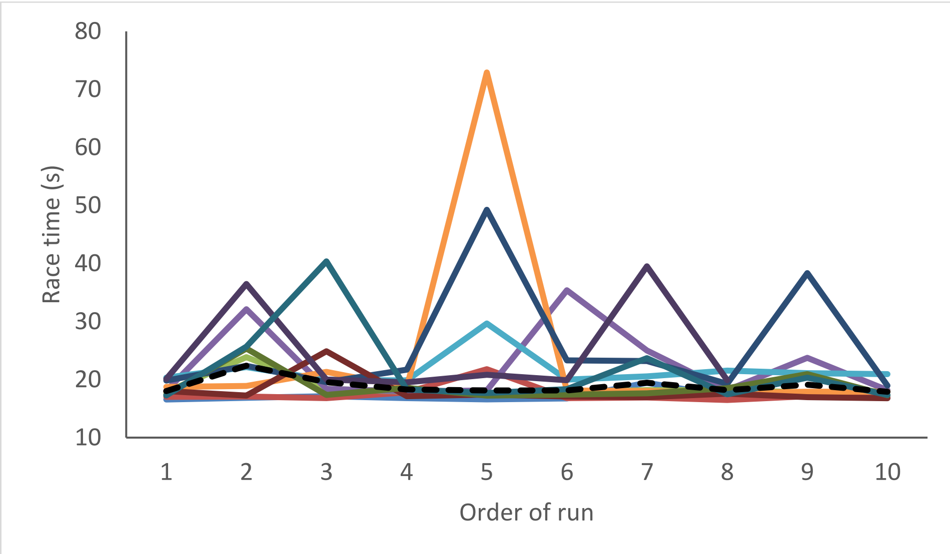

Figure C-5: The race times in the order of skiing trials on course 1 for all alpine participants. Each line on the graph represents one subject. The black dashed line represents the overall median value of all participants at each trial.

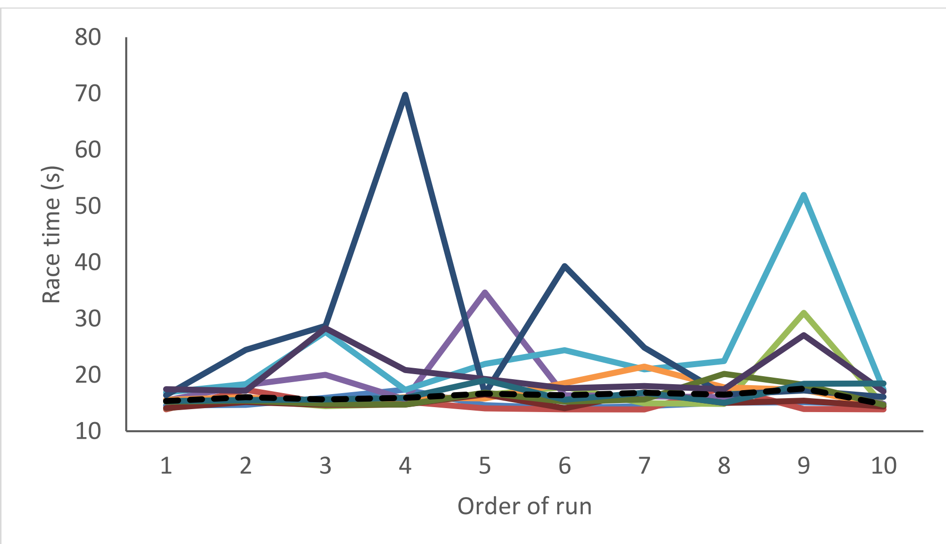

Figure C-6: The race times in the order of skiing trials on course 2 for all alpine participants. Each line on the graph represents one subject. The black dashed line represents the overall median value of all participants at each trial.

Appendix D
Developmental History Questionnaire

GENERAL PARTICIPANT INFORMATION

Participant ID #: ____

Age: _____________________________________

Gender: ____

Sport: ____

Competition events: ____

Your vision impairment

At what age were you first diagnosed? ____________________________

How did your impairment develop?

- ☐ Fully blind from birth
- ☐ Vision impaired from birth and stable since
- ☐ Vision impaired from birth, which progressively got worse over time:
  Times of major progression were at ages ______ and ______ and ______
- ☐ Vision impairment acquired at age _______ and stable since
- ☐ Vision impairment acquired at age _______ , which progressively got worse over time:
  Times of major progression were at ages ______ and ______ and ______

Do you have any other impairments (e.g. a hearing impairment)?

- ☐ No
- ☐ Yes, namely ____

YOUR VISION CORRECTION

Do you wear glasses? ____

Do you wear glasses while training? _____________________________

Do you wear glasses while competing? ____________________________

Are you wearing your glasses right now? __________________________

Do you wear contacts lenses? ______________________________________

Do you wear contacts while training? ____________________________

Do you wear contacts while competing? ___________________________

Are you wearing your contacts right now? _________________________

YOUR SKIING CAREER

In this section we wish to know more about your involvement in skiing.

Is skiing your main sport? ______________________________

Did you compete in other sports? If yes, at what ages? ______________________________

Do you still compete in those sports? ______________________________

Please use this first table to highlight (by colouring in the appropriate boxes in the table) the following:

- The ages at which you were practicing in different training environments (e.g. local club, regional training centre, state training centre, national training centre). There can of course be overlap in these. If you never trained in a certain environment, please just leave that blank.
- At what ages you competed in non-Paralympic competitions and when you competed in Paralympic competition.
- When you competed in the different VI sport classes (B3, B2, and B1).
- When your vision impairment was stable and when it was progressively getting worse.

	AGE																														
	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Training environment																															
Local club																															
Regional training centre																															
State training centre																															
National training centre																															
Competition																															
Regular competition																															
VI (Paralympic) competition																															
Sport class																															
B3																															
B2																															
B1																															
Vision impairment																															
Stable																															
Progressing																															

With this next table we want to get some more detail about your training activities over the years. We are interested in how many hours you trained in an **average week** each year of your skiing career. Please split up your activities for each of your training environments and start from your current age and work backwards in time.

		AGE																													
		5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Local club	Hours per week Skiing																															
	Hours per week Strength & cond.																															
	Months per year																															
Regional training centre	Hours per week Skiing																															
	Hours per week Strength & cond.																															
	Months per year																															
State training centre	Hours per week Skiing																															
	Hours per week Strength & cond.																															
	Months per year																															
National training centre	Hours per week Skiing																															
	Hours per week Strength & cond.																															
	Months per year																															

Appendix E
Updated Para nordic and Para alpine sports class analyses with rescored visual fields and visual field vs. performance plots

E.1 Introduction

Visual field (VF) functional scoring systems are simple and efficient ways to express the extent of the VF as a percentage or fraction. While having limited value in the diagnosis of an ocular condition, these functional scores could explain individuals' impairments in functional vision better than the clinical methods.[153,154] Most of the functional scoring methods assign proportionally higher values to certain parts of the VF, which are considered more valuable for a visual task. These methods were designed under the following assumptions: 1) the centre and lower VF were more important than the peripheral and upper VF, and 2) the horizontal meridian was more valuable than any other meridian,[153,154] because we use the central vision for most of our daily activities (e.g., driving, writing), and the majority of our daily visual tasks are below eye level (e.g., walking, cooking).[155,156] Functional scoring of VF data are generally done by overlaying grids on perimetry recording sheets, and then counting the number of grid points that fall within the VF boundary. Though these systems were designed to provide scores of the functional impact of field loss on activities of daily living, they could also be useful in relating VF loss to sports performance.

The most commonly used functional scoring systems are the Esterman score and the American Medical Association (AMA) Visual Field Score.[153,157,158] Initially, the Esterman functional scores were used as the summary statistic of our participants' VF in both the Para nordic and Para alpine studies. Esterman introduced this method in 1967, which divides the binocular field into 120 unequal units (Figure E-1). These units are smaller and denser in the central and lower areas, and around the horizontal meridian, resulting in more significant reductions in the score for a central or lower field loss compared to a peripheral or upper field loss of the same size.[69,153]

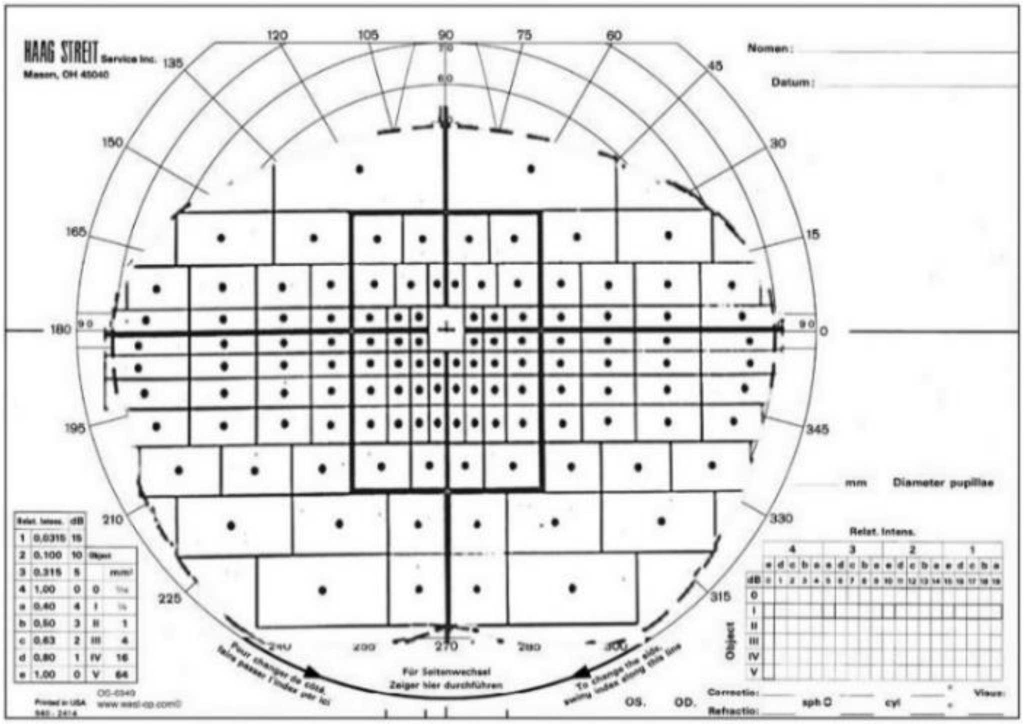

Figure E-1: The Esterman grid used to overlay on the VF recording sheets for functionally scoring the VF of Para nordic and Para alpine participants. Reprinted from Ophthalmology, 82/11, Esterman, B, Functional scoring of the binocular field, 1226-34, Copyright (1982), with permission from Elsevier.

The AMA scoring method was introduced in 1958, which uses a grid with ten meridians (25, 65, 115, 155, 195, 225, 255, 285, 315, 345 degrees), and ten eccentricities on each meridian (five in the central 10 degrees: 1, 3, 5, 7, 9 degrees, and five outside that: 15, 25, 35, 45, 55 degrees), giving a total score out of 100 (Figure E-2).[71,158] VF are scored according to whether the target was seen or not seen at each position on the scoring grids. A total of 50% of the possible AMA visual field score is allocated to the central visual field (10 degrees radius), with the remaining 50% distributed over the remaining field (typically 10-60 degrees eccentricity). To reflect the greater importance of the inferior (lower) VF (e.g., for walking, reading), 60% of the total possible VF is allocated to the inferior half of the grid.[129]

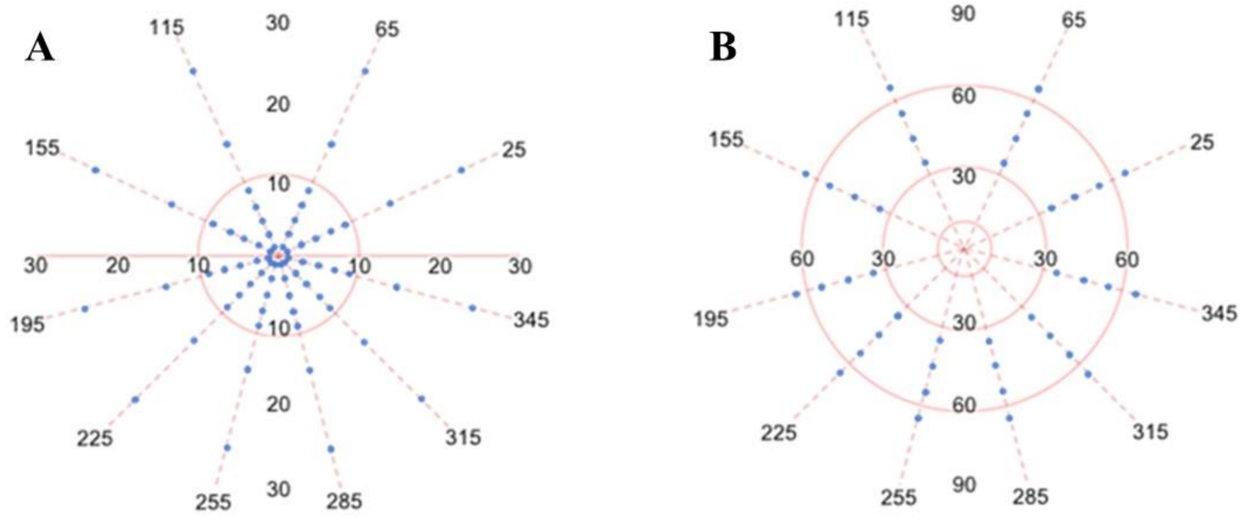

Figure E-2: AMA overlay grid used for the central 30 degrees of the visual field (A) and outside of the central 30-degree radius (B). Reproduced with permission from the unpublished report of Mann DL and Ravensbergen RHJC. Protocol for AMA-Style Analysis of Visual Field, 2019, which was adapted from the original paper Colenbrander A. Aspects of vision loss – visual functions and functional vision. Vis Impair Res. 2003;5(3):115-136. doi:10.1080/1388235039048919.

The Esterman and the AMA scoring methods have proven to be highly effective in assessing the functional impact of VF loss on activities of daily living.[159] However, the functionally important VF areas in each sport might be different depending on the visual tasks involved. For example, the central VF might be more critical for shooting, while central and peripheral vision might be equally important in football. Thus, an unbiased approach, based on a modified AMA scoring system, was recommended for classification research.[71] The VF data of our Para nordic and Para alpine participants in the study described in Chapter 3 were rescored using two unbiased modified AMA scoring methods designed by Mann and Ravensbergen.[71] This appendix describes the methods used for rescoring the data and the results of the repeated analyses using the rescored data. Additionally, this appendix examines how the modified AMA scores compared to the Esterman scores and assesses which aspects of the VF are most relevant to Para nordic and Para alpine skiing performance.

E.2 Materials and Methods

A modified unbiased AMA grid containing all the 10 meridians from the original AMA grid was used for re-scoring the VF data from studies described in Chapter 2 and Chapter 4. We rescored the data using two different versions of the grid: 1) AMA 7E with ten meridians (25, 65, 115, 155, 195, 225, 255, 285, 315, 345 degrees) and 7 eccentricities on each meridian (5, 15, 25, 35, 45, 55, 65 degrees) (Figure E-3) and 2) AMA 6E with ten meridians (25, 65, 115, 155, 195, 225, 255, 285, 315, 345 degrees), and six eccentricities on each meridian (5, 15, 25, 35, 45, 55 degrees). Thus, the increased importance given to the central VF in the original AMA grid was removed, although the inferior VF was still given more weightage in the unbiased AMA scoring systems. The maximum scores for the AMA 7E and AMA 6E were 70 and 60, respectively.

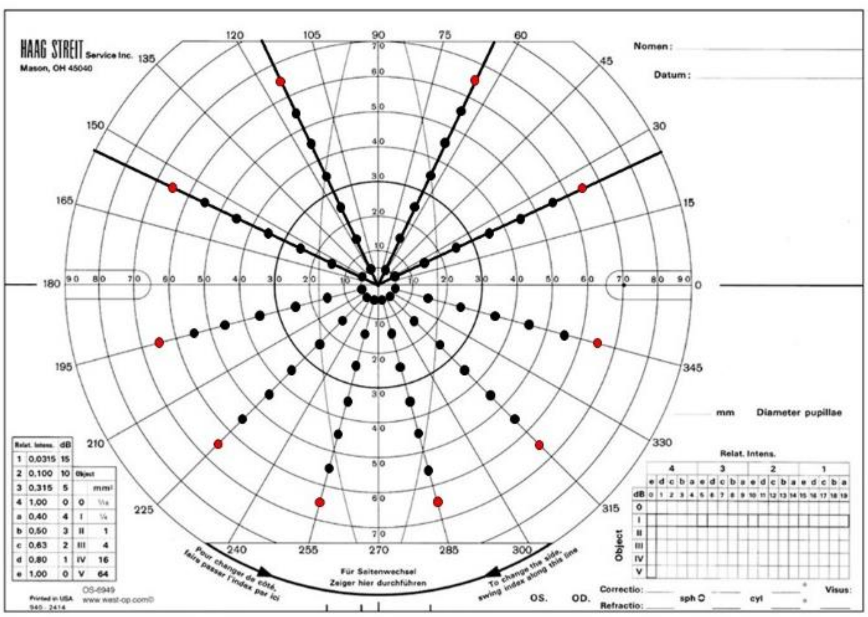

Figure E-3: The overlay grid used for the AMA scoring of VF. The AMA 7E grid included all the 7 points in each meridian, including the red points at the 65° eccentricity. The AMA 6E grid included only the black points in the grid. This figure was adapted from the unpublished report of Mann DL and Ravensbergen RHJC. Protocol for AMA-Style Analysis of Visual Field, 2019.

E.2.1 Data analysis

All the simulation VF data were rescored using the AMA 7E and AMA 6E scoring methods, and the ROC and decision tree analyses were repeated for both Para Alpine and Para Nordic studies. The correlation and regression analyses that were used to identify the relationship between VF and skiing performances, as well as the hierarchical cluster analysis that was used to identify the groups of participants with similar skiing performances were also repeated using the AMA 7E and AMA 6E rescored VF scores separately. Finally, the relationship between sports performance and location of the VF impairments was established by comparing sports performances of skiers who could and could not see at each given point examined in the VF.

E.3 Results

E.3.1 Re-examination of the minimum disability criteria using the re-scored VF

The AMA 7E and AMA 6E scores were comparable to the Esterman scores in both nordic and alpine participants (Table E-1 and Table E-2).

Table E-1: Summary of the three VF scores in the nordic study using simulated VF impairments.

Simulation level	Esterman (%)	AMA 7E (%)	AMA 6E (%)
1	83.1±2.1	86.2±3.0	95.9± 2.0
2	71.7±10.5	73.3±3.0	85.5± 3.4
3	63.1±4.3	61.5±5.7	71.7± 6.6
4	50.3±6.4	47.7±5.0	55.7± 5.9
5	33.4±4.9	34.7±3.7	40.5± 4.3
6	22.0±4.4	28.0±3.7	32.7± 4.3

Table E-2: Summary of the three VF scores in the alpine study using simulated VF impairments.

Simulation level	Esterman (%)	AMA 7E (%)	AMA 6E (%)
1	85.6±3.7	87.3±1.9	96.5±0.9
2	76.4±2.1	73.7±2.5	86.0±2.9
3	59.8±3.4	57.7±5.0	67.4±5.8
4	47.8±3.3	45.2±2.9	52.8±3.4
5	30.8±3.7	33.3±3.4	38.9±3.9
6	19.9±4.0	25.0±4.0	29.2±4.7

E.3.1.1 Para nordic skiing minimum disability VF criteria

Chapter 2 included the results of the ROC and decision tree analysis based on the Esterman scores of the nordic and alpine participants' VFs. For reference, the first maximum Youden's J (0.50) for nordic participants found with the Esterman scoring grid was at 37.9% with a sensitivity of 0.71 and specificity of 0.79 and the second maximum Youden's J (0.48) was at 38.8% with a sensitivity of 0.78 and specificity of 0.71.

E.3.1.1.1 Re-analysis with AMA 7E scoring grid

The ROC curve for the rescored AMA 7E VFs in the nordic data indicated good discrimination between nordic participants with expected and below expected levels of performance (AUC = 0.80 ± 0.05; $p < 0.001$, 95% confidence interval = 0.71–0.89). The cut-off level of AMA 7E VF that would achieve maximum Youden's J (0.53) was at 35.7% with a sensitivity of 0.71 and specificity of 0.82. The second maximum Youden's J (0.51) found was at 46.4% with a sensitivity of 0.83 and specificity of 0.68. An average VF cut-off (average of first and second best Youden's J) of 41.1% corresponds to an equivalent VF of approximately 30° radius (Table E-3).

The current cut-off criteria specified in the sports rules, which corresponds to an AMA 7E VF of 30.0%, has a Youden's J value of 0.33, indicating that this cut-off correctly classifies only 33% of nordic participants, with a sensitivity of 0.42 and specificity of 0.91.

When a decision tree was built with VA, CS, and rescored AMA 7E VF in the model, the first binary split was made using a cut-off for a VA of 0.97 logMAR. This cut-off maximized the differentiation of the expected and below-expected performance scores, respectively, below and above the cut-off value. When VA was ≤ 0.97 logMAR, the next best predictor of poor performance was VF ≤ 35.7%.

E.3.1.1.2 Re-analysis with AMA 6E scoring grid

The ROC curve for the rescored AMA 6E VFs in the nordic data also indicated good discrimination between nordic participants with expected and below expected levels of performance (AUC = 0.80 ± 0.05; $p < 0.001$, 95% confidence interval = 0.71–0.89). The cut-off level of AMA 6E VF that would achieve maximum Youden's J (0.53) was at 41.7% with a sensitivity of 0.71 and specificity of 0.82. The second maximum Youden's J (0.51) found was at 54.2% with a sensitivity of 0.83 and specificity of 0.68. An average VF cut-off (average of first and second best Youden's J) of 48.0% corresponds to an equivalent VF of approximately 30° radius (Table E-3).

The current cut-off criteria specified in the sport rules corresponds to an AMA 6E VF of 33.3% and has a Youden's J value of 0.22, indicating that this cut-off correctly classifies only 22% of nordic participants, with a sensitivity of 0.29 and specificity of 0.93.

When a decision tree was built with VA, CS, and rescored AMA 6E VF in the model, the first binary split was made using a cut-off for a VA of 0.97 logMAR. This cut-off maximized the differentiation of the expected and below-expected performance scores, respectively, below and above the cut-off value. When VA was ≤ 0.97 logMAR, the next best predictor of poor performance was VF ≤ 41.7%.

E.3.1.2 Para alpine skiing minimum disability VF criteria

For reference, the first maximum Youden's J (0.59) for alpine participants found with the Esterman scoring grid was at 54.0% of VF with a sensitivity of 0.88 and specificity of 0.71 and the second maximum Youden's J (0.58) was at 57.5% with a sensitivity of 0.92 and specificity of 0.67.

E.3.1.2.1 Re-analysis with AMA 7E scoring grid

The ROC curve for VF in the alpine data with the rescored VFs using the AMA 7E indicated good discrimination between alpine participants with expected and below expected levels of performance (AUC = 0.84 ± 0.05; $p < 0.001$, 95% confidence interval = 0.74–0.93). The cut-off level of AMA 7E VF that would achieve maximum Youden's J (0.61) was at 55.0% with a sensitivity of 0.92 and specificity of 0.69. The second maximum Youden's J (0.60) found was at 46.4% with a sensitivity of 0.83 and specificity of 0.76. An average VF cut-off (average of first and second best Youden's J) of 50.7% is close to the average of the AMA 7E scores corresponding to equivalent VFs 30° and 40° (Table E-3).

The current cut-off criteria specified in the sport rules, which corresponds to an AMA 7E VF of 30.0%, the Youden's J value was 0.16, indicating that this cut-off correctly classifies only 16% of alpine participants, with a sensitivity of 0.29 and specificity of 0.88.

When a decision tree was built with VA, CS, and VF in the model, the first binary split was made using a cut-off for VF of 55.0%. This cut-off maximized the differentiation of the expected and below-expected performance scores above and below the cut-off value. When the visual field extent was ≤55.0%, the next best predictor of poor performance was static visual acuity ≤ 0.59 logMAR.

E.3.1.2.2 Re-analysis with AMA 6E scoring grid

The ROC curve for VF in the alpine data with the rescored VFs using the AMA 6E also indicated good discrimination between alpine participants with expected and below expected levels of performance (AUC = 0.84 ± 0.05; $p < 0.001$, 95% confidence interval = 0.74–0.93). The cut-off level of AMA 6E VF that would achieve maximum Youden's J (0.61) was at 64.2% with a sensitivity of 0.92 and specificity of 0.69. The second maximum Youden's J (0.60) found was at 54.2% with a sensitivity of 0.83 and specificity of 0.76. An average VF cut-off (average of first and second best Youden's J) of 59.2% is close to the average of the AMA 7E scores corresponding to equivalent VFs 30° and 40° (Table E-3).

At the current cut-off criteria specified in the sport rules, which corresponds to an AMA 6E VF of 33.3%, the Youden's J value was 0.16, indicating that this cut-off correctly classifies only 22% of alpine participants, with a sensitivity of 0.25 and specificity of 0.91.

When a decision tree was built with VA, CS, and VF in the model, the first binary split was made using a cut-off for VF of 64.0%. This cut-off maximized the differentiation of the expected and below-expected performance scores above and below the cut-off value. When the visual field extent was ≤55.0%, the next best predictor of poor performance was static visual acuity ≤ 0.59 logMAR.

E.3.1.2 Conversion of scores to radius in degrees

The current classification systems in Para nordic and Para alpine skiing define the criteria to determine eligibility and to allocate skiers into classes based on the degrees of VF radius. Thus, the current VF assessments and recordings conducted as part of the classification process also are done in terms of degrees of VF radius. Table E-3 includes the equivalent Esterman, AMA 7E, and AMA 6E scores of various levels of central VF in 10-degree radius intervals. However, it should be noted that the points along each meridian of AMA 7E and AMA 6E grids are 10 degrees apart, and there are no points exactly at 10, 20, 30, 40, 50, or 60 degrees because the first points are at 5 degrees. Therefore, it is possible that two participants with different VF radii could have the same AMA score. For example, a participant with a 6-degree radius VF would have the same AMA 7E score (14.3%) as a participant with a 14 degree radius VF.

This issue also applies for the Esterman's scores presented in the table; however, due to the higher density of points in the center 30-degree radius of Esterman grid, the range of VFs with the same Esterman score is narrower for VFs with a radius less than 30 degrees, especially when these fields were not symmetrically distributed around the center of the grid.

Table E-3: Comparison of the three VF scores at various levels of peripheral, symmetrical, circular VF constrictions.

VF radius (degrees)	Esterman (%)	AMA 7E (%)	AMA 6E (%)
10	5.8	14.3	16.7
20	21.7	28.6	33.3
30	40.0	42.9	50.0
40	54.2	57.1	66.7
50	69.2	71.4	83.3
60	85.0	85.7	100.0
70	88.3	100.0	NA
80	100.0	NA	NA

E.3.2 Re-examination of the sports class allocation criteria using the rescored VF

The average AMA 7E and AMA 6E scores for the Para nordic and Para alpine skiers are provided in Table E-4. The original Esterman scores are also provided for comparison. The correlation, regression, hierarchical clustering, and decision tree (nordic) analyses were repeated using the AMA 7E and AMA 6E scores instead of the Esterman's scores, which did not result in any changes in the conclusions regarding the sports classes in either Para nordic or Para alpine skiing.

Table E-4: Summary of the three VF scores in Para nordic and Para alpine skiers used to determine sports classes.

Sports	Statistic	Esterman (%)	AMA 7E (%)	AMA 6E (%)
Para nordic	Mean± Standard deviation	41.3 ± 33.6	41.7 ± 33.0	46.7 ± 36.8
	Min / Max	0.0 / 100.0	0.0 / 100.0	0.0 / 100.0
Para alpine	Mean ± Standard deviation	40.7 ± 34.9	42.5 ± 31.2	46.3 ± 32.4
	Min / Max	0.0 / 89.2	0.0 / 97.1	0.0 / 100.0

E.3.2.1 Para nordic skiing sport classes

In the Para nordic data, consistent with the correlations from the Esterman scoring, the AMA 7E and AMA 6E scores were also significantly correlated with Para nordic skiing performance (AMA 7E: τ_b = -0.40, p=0.006 and AMA 6E: τ_b = -0.37, p=0.011).

The results of the hierarchical cluster analysis of the Para nordic data did not differ significantly when the AMA 7E or AMA 6E scores were substituted for the Esterman scores. The Para nordic decision tree results also did not change with the AMA 7E or AMA 6E scores. The summary statistics of all the three VF scores in Para nordic skiing are provided in Table E-5.

Table E-5: Comparison of the three VF summary statistics in the Para nordic clusters.

Score	Cluster 1 (N=10)	Cluster 2 (N=7)	Cluster 3 (N=9)
Esterman score (%)	58.3±24.1	55.2±33.9	11.6±22.0
AMA 7E (%)	59.3±20.8	54.5±33.4	12.2±24.2
AMA 6E (%)	66.3±24.3	60.7±35.2	13.9±27.8

E.3.2.2 Para alpine skiing sport classes

Similarly, in the Para alpine data, slalom (SL) performance points were significantly correlated with AMA 7E (τ_b = -0.47, p= 0.017) and AMA 6E (τ_b = -0.49, p= 0.013). None of the other Para alpine discipline performance points were significantly associated with any of the revised VF scores.

The results of the hierarchical cluster analysis in each of the Para alpine disciplines data did not differ significantly when the AMA 7E or AMA 6E scores were substituted for the Esterman scores either. The summary statistics of all the three VF scores in Para alpine skiing are provided below in Tables E-6 to E-9.

Table E-6: Comparison of the three VF summary statistics in the Para alpine DH clusters.

Score	Cluster 1 (N=5)	Cluster 2 (N=4)
Esterman score (%)	50.2±25.2	42.5±45.3
AMA 7E (%)	53.4±26.6	45.4±36.1
AMA 6E (%)	57.7±25.4	50.4±39.1

Table E-7: Comparison of the three VF summary statistics in the Para alpine GS clusters.

Score	Cluster 1 (N=8)	Cluster 2 (N=5)	Cluster 3 (N=2)
Esterman score (%)	47.1±30.0	46.7±41.6	0.0
AMA 7E (%)	46.6±22.6	52.9±38.0	0.0
AMA 6E (%)	52.1±22.8	55.7±39.0	0.0

Table E-8: Comparison of the three VF summary statistics in the Para alpine SG clusters.

Score	Cluster 1 (N=10)	Cluster 2 (N=1)	Cluster 3&4 (N=1&1)
Esterman score (%)	42.3±34.4	32.5	0.0
AMA 7E (%)	46.3±29.9	34.3	0.0
AMA 6E (%)	50.7±30.8	40.0	0.0

Table E-9: Comparison of the three VF summary statistics in the Para alpine SL clusters.

Score	Cluster 1 (N=13)	Cluster 2 (N=2)
Esterman score (%)	46.9±33.2	0.0
AMA 7E (%)	49.0±28.1	0.0
AMA 6E (%)	53.5±28.5	0.0

E.3.3 Visual field loss and skiing performance

The performance plots generated with the AMA 6E scores were used to determine which locations of visual field loss negatively impacted skiing performance using templates provided by Mann and Ravensbergen.[71] The AMA 6E scoring system was chosen because it has been used in similar classification research in other sports, and works for all perimeters used during Paralympic classification such as the Humphrey Field Analyzer and Octopus are not capable of measuring VF beyond a 60° radius.

The results for the Para nordic and the Para alpine disciplines are provided in Figure E-4 and Figure E-5. The red colour in the plot indicates that performance got worse with VF loss in this area and darker shades of red indicate progressively worse sports performance. White indicates that there was no difference in performance with VF loss in this area and green areas indicate there was a relative improvement in performance despite VF loss in these areas.

Overall, the Para nordic VF summary plot shows that impairments anywhere in the visual field have negative impacts on performance. Visual field losses in the central field (0°-40°) and around the horizontal meridian appear to be more strongly associated with decreased Para nordic performance. The lower VF also seems to be slightly more important for performance compared to the upper VF.

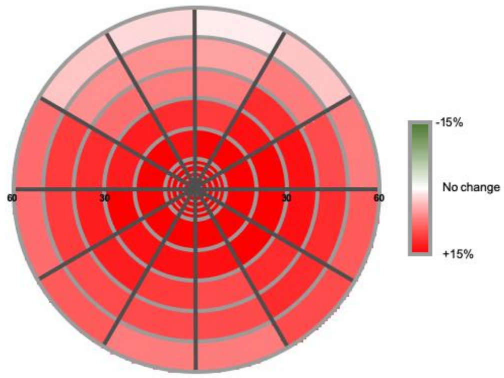

Figure E-4: Schematic demonstration of the difference in performance between the Para nordic skiers who could and could not see in each area of the VF.

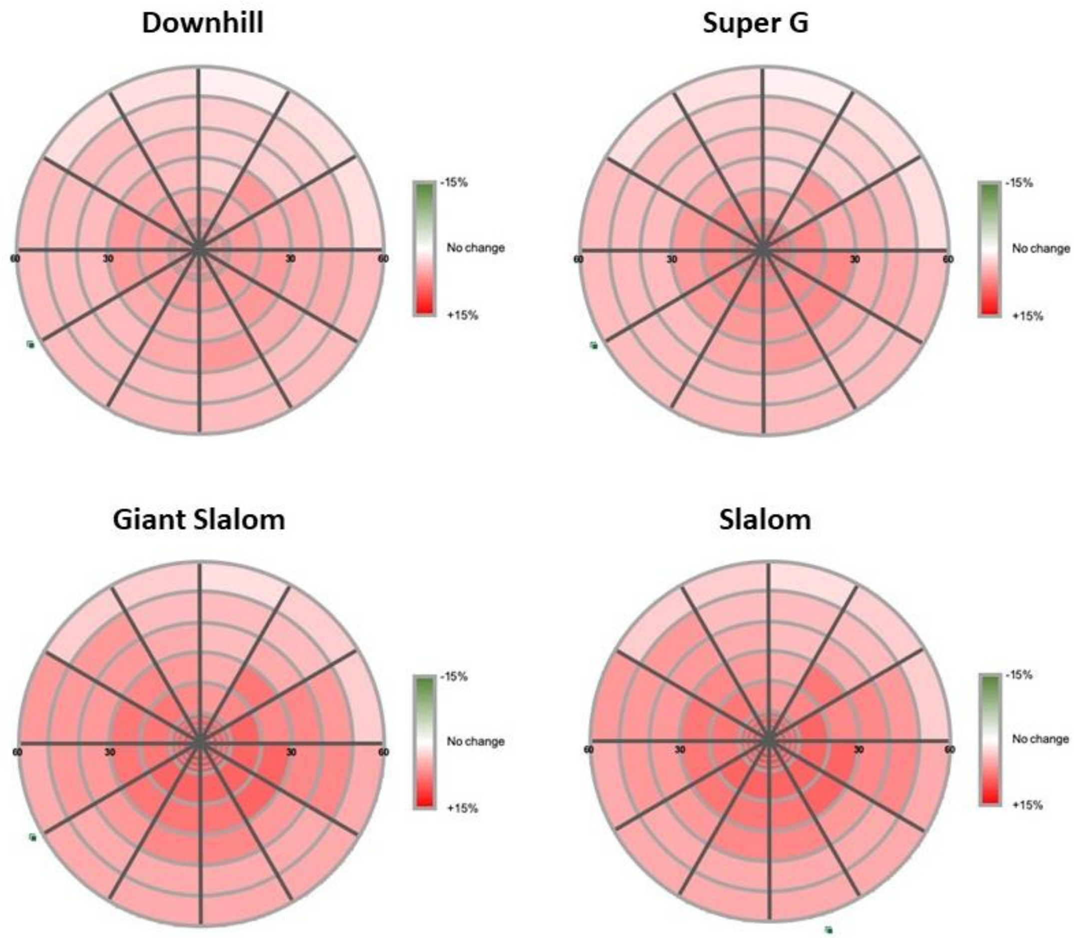

Figure E-5: Schematic demonstration of the difference in performance between the Para alpine skiers in the four disciplines, who could and could not see in each area of the VF.

Overall, the Para alpine VF summary plots also show that impairments anywhere in the visual field have negative impacts on skiing performance. Visual field losses in the central field (0°-30°) and around the horizontal meridian have a slightly stronger association with decreased performance, especially in more technical disciplines like SL and GS.

To summarize, both Para nordic and Para alpine skiing performances appear to be reduced by VF impairments anywhere in the VF. However, the effects of VF impairments are stronger in the Para nordic data, compared to any of the Para alpine disciplines. The central VF extent important for Para nordic performance also seems to be larger compared to any of the Para alpine disciplines.

E.4 Discussion

E.4.1 Re-examination of the visual field criteria for minimum disability and sport classes

The analyses with the rescored VF values suggest that none of the study conclusions in the MDC or sports class studies for either sport would have changed if the AMA 7E or AMA 6E scoring methods were used instead of Esterman scoring. Hence, the results from these studies are valid despite the type of VF scoring method used.

The variability between scoring methods is likely due to differences in the total scores of each method (120 for Esterman, 70 for AMA 7E, and 60 for AMA 6E) and variability between the location of each of individual points scored.

In the MDC data, although the exact VF score values for the MDC changed, the VF radius corresponding to the optimum cut-off values remained similar with the rescored VFs in both nordic and alpine data. However, the difference between 1st and 2nd Youden's J were greater for AMA 6E compared to AMA 7E or Esterman. The points on the AMA grids are 10° radius apart from each other, unlike the Esterman grid, which has a higher density of points in the central VF, which could have attributed to this increased difference between the first and second Youden's Js in the ROC analyses of AMA scores. The smaller denominator (60) in the AMA 6E scorings percentage conversions, compared to AMA 7E scoring percentage conversions (70) could also have contributed to these increased differences observed in AMA 6E values compared to AMA 7E values. In addition, the lack of a sharp peak in all the VF ROC curves could also have contributed to these differences, especially in the second maximum Youden's J because of the increased possibility for having similar Youden's J values at different VF cut-offs due to the flat curves.

Interestingly, the average of the VF cut-off values corresponding to the first and second Youden's Js for the nordic data obtained through the analysis of Esterman's scores, AMA 7E, and AMA 6E corresponded to an equivalent VF of 30° and appear to be reasonably comparable between scoring methods. The average of the VF cut-off values corresponding to the first and second Youden's Js for the alpine data obtained through the analysis of Esterman's scores, AMA 7E, and AMA 6E corresponded to an equivalent VF of 40°, 35°, and 35°, respectively, and are also comparable between scoring methods.

The current classification systems in Para nordic and Para alpine skiing define classification criteria in terms of degrees of VF rather than percentage of VF, as demonstrated in Table D-3. Although the functional scoring systems provide a method to obtain VF scores for individuals with VF defects, which are different in aspects such as type, size, and location, the most common and simplest clinical method to measure and record VFs are in degrees. The current studies suggested that even though the exact scores of AMA 7E, AMA 6E, and Esterman scores are different from each other, the equivalent VF in degrees appear to be comparable across the three scoring methods. Converting scores across different measurement instruments using scoring grids might not be accurate because the number and location of points that fall on the scoring grids differ between the instruments. Therefore, the most appropriate way to define the VF criteria for classification will be to use the degree equivalents of VFs, measurements in degrees will be more repeatable across instruments, and scores calculated using any scoring method for research purposes could be converted back to equivalent degrees of VF for classification.

E.4.2 Visual field loss and skiing performance

Unlike the original AMA and Esterman's scoring methods, the AMA 7E and 6E methods are not heavily biased towards the central visual field, thereby allowing functional scoring of VFs and assessment of the relative importance of each VF area for sports performance without making prior assumptions on the importance of certain VF parts compared to others. In addition, conducting initial studies using the unbiased scoring methods also make it possible to develop sport-specific VF scoring systems if necessary. For example, if the central 40° field was found to be the only area of the VF strongly associated with performance in a Para sport, a VF scoring grid could be developed that weighted central VF losses higher or only looked at the central VF. Similarly, if the peripheral field was found to be essential for performance in a sport, a sports-specific scoring grid could be developed that weighted peripheral vision losses more heavily than central vision losses.

The performance plots are a useful way to investigate and schematically represent the relationships of VF impairments to skiing performance in addition to the correlation and regression analyses. Consistent with the analyses described in Chapter 3 and Chapter 4, VF seems to be strongly associated with both Para nordic and Para alpine skiing performance, especially in the more technical disciplines. The association appears stronger in Para nordic participants compared to the Para alpine participants. This could be due to the wider visual space, which the Para nordic skiers need to observe while skiing through the curved, uphill, and downhill sections in nordic courses. In addition, the Para nordic skiers in B2 and B3 classes often ski without the help of a guide and might be relying more on their vision from both centre and peripheral VF compared to the Para alpine skiers, who are obliged to ski with a guide. Thus, the Para alpine skiers might be relying more on the central visual field and may be prioritising watching their guide over attending to the entire course. In the highest speed disciplines that require the skiers to gather information and respond quickly such as DH or SG, it is possible that the skiers may also rely more heavily on the auditory instructions from their guides and less on their own visual feedback, thereby decreasing the impact of visual field loss on performance. However, care must be taken when drawing these types of conclusions, especially in DH, due to the lack of participation of skiers with most severe impairments (B1 class) in the DH discipline as the lack of participation of B1 skiers in the DH discipline may also be an indication that the central visual field is crucial for DH performance.

E.5 Conclusion

The AMA 6E and 7E methods appear to be comparable to the Esterman method for functionally scoring VFs, particularly when using degree equivalents rather than % VF extent across VF testing methods. Unlike the Esterman method, the AMA 6E and 7E methods are not biased toward the central VF and could be used to explore the effects of impairments in each VF area on the sports performance.

Although the International Paralympic Committee governing board has not yet decided how binocular VFs should be scored for classification purposes, the AMA 6E scoring method is more likely to be used because of the limitations of the Humphrey Visual Field Analyzer. The Humphrey Visual Field Analyzer, which is the most common VF measurement instrument used during classification, is not currently capable of measuring binocular VF beyond 60º, and in some meridians cannot even measure out to 60º VF extent. Using scoring grids that have points beyond 60º may result in increased variability between VF scores when two different instruments or VF assessment methods are used. For example, the AMA 7E score of a participant's Goldmann plot will be different from that of the same participant's HFA plot because the Goldmann VF tests much further out into the periphery than the HFA. One way around this dilemma would be to use degrees VF instead of a % functional score, as degrees VF should be more comparable between instruments.

As the results of all three VF scoring systems appear to be reasonably comparable, as demonstrated here, we recommend using values calculated based on the AMA 6E scoring method for future classification research and then converting this score to degrees when proposing possible rule changes based on existing classification research. Using a functional scoring method for research allows for VF loss across the entire VF to be weighted in a somewhat equitable way, regardless of the location of the loss and will also allow for comparison of research results across sports, which may provide additional insight into the impact of visual field loss on performance. In turn, converting values back to degrees for the rules allows equitable comparison between VF instruments. One of the remaining challenges that needs to be addressed with future research, is whether or not visual field loss in the periphery is actually comparable or equitable to visual field loss centrally. The performance plots presented here, would suggest, that, at least for skiing, any visual field loss has a relatively equal impact on performance, regardless of its location, however this may not be true for other sports or activities.

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