Ice Hockey Helmet Fit Using 3D Modeling

David James Greencorn

Department of Kinesiology and Physical Education, Faculty of Education,

McGill University

Montreal, Quebec, Canada

February 2017

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Science Kinesiology and Physical Education

Abstract:

Ice hockey helmets must pass rigorous standardized impact tests to become certified for sale. However, these tests are performed with the helmet attached to a headform with the exact same shape from which they are designed. Human head shapes are not uniform, and very few standards exist for helmet fitting for the common user. The goal of this study was to create a 3D acquisition protocol to assess the geometric fit of ice hockey helmets with the proper head-helmet interface and orientation. The following study recruited 30 participants who wore 5 ice hockey helmet models in an attempt to quantify ice hockey helmet fit using 3D modeling, and analyzing fit parameters in two ways. First, by comparing geometric fit measures (dimensional differences or DD) in a cross-sectional plane of the head to the perception of fit scores. Second, by using principal component analysis (PCA) to determine the largest components of fit. Significant differences were noted between helmet models for both perception of fit scores as well as the DD (i.e. overlaps or gaps between the head surface and the helmet liner). However, in most cases the helmets that were perceived to be significantly tighter than another showed no significant difference in DD. The principal components of fit that were calculated included the overall uniformity of helmet-head contours emphasizing the differential between the DD of the front and back regions of the head, the lateral DD magnitudes, the front-back DD magnitudes, and the uniformity of the DD for the absolute back of the head and the rear lateral boss. PCA shows promise as a future method to investigate fit for a variety of purposes and fields.

Résumé:
Les casques de hockey sur glace doivent passer des tests d'impacts rigoureux and respectant des standards pour devenir certifié pour la vente magasin. Par contre, ces tests sont performés avec le casque attaché à une tête de mannequin qui est de la même forme que celle qui a été utilisé pour la fabrication. La forme de la tête des humains ne sont pas uniformes et très peu de standards existent pour la convenance du casque pour le consommateur régulier. Le but de cette étude est de créer un protocole d'acquisition 3D pour évaluer la convenance des casques de hockey et l'évaluation réelle de l'orientation. Cette étude a recruté 30 participants qui ont porté 5 différent model de casques de hockey dans le but de quantifier la convenance utilisant un modélisation 3D et analyser les paramètres de convenance de deux façons. Premièrement, en comparant la convenance des mesures géométriques (différences dimensionnels ou DD) dans un plan cross-sectionnelle de la tête aux scores sur la perception de convenance. Deuxièmement, en utilisant les principales composantes d'analyses (PCA) pour déterminer la composante de convenance la plus important. Signifiantes différences a été noté entre les modèles de casques pour la perception de convenance et aussi la DD (chevauchements ou un espace entre la surface de la tête et le liner du casque). Par contre, dans la plupart des cas les casques qui étaient perçus comme plus serré que les autres démontraient aucune différence signifiante dans la DD. Les principales composantes de convenance qui ont été retenus sont l'uniformité du contour tête-casque en général ce qui emphase la différence entre la DD des régions du devant et du derrière de la tête, en plus des magnitudes des DD latérales, avant-arrières et de l'uniformité de la DD du derrière de la tête et des bosses arrière latérales. PCA démontre un potentiel pour être une méthode dans le futur pour rechercher sur la convenance dans une variété de buts and champs d'expertises.

Contents

List of Figures

List of Tables

Acknowledgements

I would like to begin by thanking my thesis supervisor, Dr. David Pearsall. This project would not have been possible without your vision, feedback, and expertise. I am very thankful for the opportunity to work in the Ice Hockey Research Group under your supervision, so thank you for your valuable advice over the course of this project. I am grateful for everything I learned. To my thesis advisory committee, including Dr. Shane Sweet, and Dr. J. Scott Delaney, thank you for your guidance and feedback on this thesis.

To Dan Aponte, saying thank you is not nearly enough. You helped evolve my protocol, from helping to find better 3D acquisition methods, to teaching me all there is to know about cameras. I learned so much about teamwork and goal setting from working alongside you. Our countless hours taking photos, making jokes, and getting the job done will be engrained in my memory forever. I wish you the best of luck as you continue the H.E.A.D. Project and eventually become Dr. Dan. Sincerely thank you, this project would have been impossible without you!

To Dr. Shawn Robbins, thank you for your help and expertise with running principal component analysis. Thank you especially for on how short notice you made this project a priority. This analysis added a full dimension to my study and led to some interesting findings.

To the lab members of the Ice Hockey Research Group, past and present, thank you for making the lab a place where I wanted to be. The atmosphere you all created made it a joy to walk up the four flights of industrial sized stairs just to see what shenanigans were underway. Specifically, to Phil Renaud, Jaymee Shell, and Adrien Gerbé, thank you guys for taking me under your wing when I was a new student. You made me feel welcome from day one. To Aleks Budarick and Dan Boucher, thank you for being my lab-mates from the beginning. We got through many ups and downs together and I am excited to have made such great friends with the people I was around 24/7.

To the rookies: Aiden Hallihan, Brian McPhee, and Kristie Liu, your head scans, positive attitudes, and encouragement made this year a lot more enjoyable. A special thank you to Brian for being the poster-boy of this thesis.

Finally, I would like to thank my family and my "practically family" (Brent Campbell, Mitch George, and Michael Thomson) for encouraging me through every step of this Master's degree. I would not be where I am today without your constant love and support, so thank you for always being there for me and helping me achieve my goals.

Contribution of Authors

David Greencorn, MSc candidate, McGill University, was responsible for the research design and protocol, recruitment, and data collection for this study. He was also responsible for the data processing, analysis, and writing of this thesis. David J. Pearsall, PhD, Associate Professor, Department of Kinesiology and Physical Education, McGill University, contributed to the research design, protocol, and planned analysis as the candidate's supervisor.

The thesis advisory committee consisting of, Dr. Shane Sweet, PhD, Assistant Professor Department of Kinesiology and Physical Education, McGill University, and Dr. J. Scott Delaney, MD, Associate Professor and Research Director, Department of Emergency Medicine, McGill University Health Centre and McGill Sport Medicine Clinic contributed to the research design and protocol. Dr. Shawn Robbins, Assistant Professor, School of Physical and Occupational Therapy, McGill University executed the principal component analysis for the data of this thesis.

Daniel Aponte, PhD Student, McGill University, was responsible, in part, for the research design and protocol, recruitment, and data collection for this study.

1. Introduction

In Canada, ice hockey is one of the most commonly played sports; sadly, it also is one of the nation's leading causes of sport related concussion [1]. In a study done on Canadian university varsity athletes, approximately 8% of male hockey players had sustained a concussion over a three-year period with some athletes experiencing multiple concussions [2]. Ice hockey helmets have been a requirement for competitive play since the 1980's in an attempt to reduce the number of head injuries, in particular skull fractures and concussions. To become commercially available, helmets must pass a series of standardized tests.

The primary measurement criteria used to determine the head impact protection afforded by a helmet is its ability to attenuate peak linear accelerations based on controlled, standardized impact testing of surrogate headforms with the helmet [3-5]. While high impact-induced linear accelerations are known risk factors for concussive injury, researchers within the past decade have also suggested that impact-induced head angular accelerations are an equal if not greater risk factor for concussion [6,7]. However, most certification organizations have not yet included the latter criteria as a measure for helmet certification given the complexity of standardizing and setting clinically relevant impact criteria thresholds.

Standardized helmet impact testing involves approximation of many factors to "standardize" the test protocol. The most basic property defines the generic, representative headform in terms of shape and mass, scaled to size range (small, medium and large) with male and female adult anthropometric norms based on Caucasian population samples. An obvious criterion is the assessment of helmet fit, often measured in terms of required areas of coverage over the cranial head region and sufficient helmet-to-head retention (or stability). Yet, scrutiny reveals that helmet fit is more complex; for example, differences in head shape geometric proportions (e.g. width-to-length ratio) will modify both area of coverage and helmet retention properties. For a helmet to be stable on the head there must be compression of the inner foam against the head to offer sufficient grip to maintain proximate orientation. If a person has a head shape towards the 30th or 70th percentiles in width-to-length, for example, the helmet's foams will be regionally pre-compressed differently. Differences in the state of foam pre-compression (or lack thereof) may substantially affect the energy dissipation of particular helmet regions or as a whole. This leads us to believe that fit is an important quality of ice hockey helmet protection.

How can fit be measured? Some researchers have been investigating fit by the comparison of the two geometric shapes: in the case of helmet fit, that would mean comparing the shape of the head to the shape of the interior of the helmet. For example, in this manner Cai et al. presented a novel investigation of dimensional differences between the head and ice hockey helmets [8]; however, this study had limitations. First, the head-to-helmet were not aligned as worn; rather, the head principal plane and helmet were "virtually" aligned post hoc. Second, the inner foams were deemed to be non-compressible, but in order for the helmet to be anchored securely on the user's head there must be pre-compression of the inner foam. Third, the participants of the study never wore the helmets to give feedback on the subjective measure of fit.

Fit is not an easily quantified measure. Generally, when purchasing a helmet, the user will wear multiple helmets and purchase the helmet that feels the best to them, subjectively. In the footwear literature, studies have investigated subjective and geometrical fits, and it was found that the two fit measures were strongly correlated [9]. In the same light, we wanted to investigate whether or not helmet fit be assessed in a similar way, in terms of combined subjective and geometric scores. Thus, the rationale for this study was to address the limitations in Cai et al., to identify how well subjective and geometric scores and helmet fit scores interrelate, and to identify specific helmet-to-head fit configurations. Our first objective was to create a protocol to concurrently assess helmet and head alignment. Second, to quantify fit using both subjective and geometric measures. Third, to identify specific helmet-to-head fit categories. Fourth, to identify specific helmet model fit characteristics.

We hypothesize that, similarly to Witana et al., there will be a correlation between subjective and geometric fit measures, allowing us to classify tightness of fit using units of millimetres (mm), with small amounts of variance in preference. We hypothesize that we will see fit differences in areas of the helmet that are not adjustable, namely in the width dimension and the congruency of curvature along the front and back regions of the head-helmet interface.

2. Literature Review

When purchasing a sport helmet, the user is often asked if the helmet fits well. Proper fit is assumed to be more protective against head injuries, although it is hard to define. Extensive research has been conducted on sport concussions and other head injuries, yet these devastating injuries persist. The scope of this chapter will 1) review head injury types related to blunt impacts, including skull fractures and concussions; 2) discuss ice hockey helmet design properties, including materials, and impact standards; 3) review prior "fit" parameter studies.

2.1 Head Injuries

Head injuries may be classified as injuries to the skull or injuries to the brain [10]. In some cases, both skull and brain injuries occur from one incident. Primary head injuries range in severity from quite mild (e.g. facial laceration) to quite severe (e.g. hematoma or open skull fracture). In some cases, these may precipitate secondary brain injuries resulting from excessive intracranial pressure due to the brain's inflammatory response and swelling. The following section will give a brief description of different forms of common head injuries related to sport.

2.1.1 Skull Fractures

Like all human bones, the bones of the skull may fracture under sufficient force (or pressure) from impacts. Skull fractures fall into two main categories: linear skull fractures and depressed skull fractures [11]. Further, any fracture may be considered 'open' or 'closed', depending on whether the skin is broken or not. Linear skull fractures do not disrupt the orientation of the cranial bones. Depressed skull fractures, on the other hand, break the cranial bones such that they result in the bone being dislodged, generally toward the brain. The latter type of fracture risks having sharp bone edges penetrate the dura mater, which may also cause an open skull injury.

Schmitt, Zürich et al. performed drop tests on cadavers that measured the forces required to cause skull fractures in different areas of the skull. They showed that the occipital area of the skull required the most force to create a fracture [10]. The temporal bone is suggested to be the weakest part of the skull, and it has been found that a depressed skull fracture could occur in that region if localized pressure exceeded 4 MPa [12]. A depressed skull fracture may puncture blood vessels in the brain causing bleeding in the brain. Bleeding and clotting in the brain is known as a hematoma.

2.1.2 Hematoma

Hematomas may be grouped into three categories depending on where the bleeding and clotting transpires: epidural hematoma (bleeding between dura mater and inside of the skull), subdural hematoma (bleeding into the subdural space), and intracerebral hematoma (homogeneous collections of blood within the brain) [10]. Subdural hematomas have a mortality rate above 30% in most studies [13]. These injuries are generally caused by damage to surface blood vessels and blood leaking into the brain tissue [14]. The bleeding and clotting may cause increased intracranial pressure and decrease the proportion of cerebrospinal fluid in the head. Symptoms of hematomas range from altered consciousness, nausea and vomiting, headache, and even to severe seizures and comas. Hematomas fall into the category of localized brain injuries. Another example of localized brain injuries are brain contusions.

2.1.3 Brain Contusion

A brain contusion (bruise) is the most common brain lesion caused by a head impact. Often head impacts result in two separate brain contusions; one bruise will be located at the site of impact (coup) and the other at the opposite side of the brain (contre-coup) with this latter bruise being more severe [15,16]. For a major contusion to occur, Ward et al. suggest that the maximum intracranial pressure must exceed 235 kPa, but that no contusion would occur below

173 kPa during coup and contre-coup events [17]. Brain contusions and hematoma affect localized regions of the brain. On the other hand, diffuse brain injuries occur throughout the brain.

2.1.4 Diffuse Brain Injury and Concussions

Diffuse brain injuries are distributed throughout the brain. Diffuse injuries are believed to result from high linear and rotational accelerations undergone by the brain during a head impact. Furthermore, some research suggests that indirect brain acceleration by whiplash mechanisms may also cause diffuse brain injuries [10,18,19]. The range of diffuse brain injuries extends from mild concussions to diffuse injuries of the white matter. Concussions fall under the category of minor traumatic brain injury (mTBI), and are a mild form of a diffuse axonal injury.

Within this text the general term "concussion" will be used to represent the whole category of mTBI because concussions represent the most common form of mTBI in sport. A concussion may be defined as a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces [20]. It has been shown that when participants' heads undergo linear accelerations of 65 g, 80 g, and 105 g they have a 25%, 50%, and 80% chance of sustaining a concussion respectively [21]. Similarly, rotational accelerations of 4500 rad/s^2, 6000 rad/s^2, and 8000 rad/s^2 represent a 25%, 50%, and 80% probability of sustaining a concussion [21]. Symptoms include headache, nausea or vomiting, impaired balance, dizziness, impaired vision, light and noise sensitivity, fatigue, confusion, impaired concentration, memory problems, and depression [22]. One of the major concerns surrounding concussions is that mild concussions are not a visible injury and can only be diagnosed by the symptoms reported by the patient. While there are some cognition and coordination tests to aid in the diagnosis, many concussions go undiagnosed or unreported [23-27].

Unlike skeletal injuries, brain injury recovery cannot be accurately estimated. This is a major problem, especially for athletes who play contact sports, as they may never leave play or may return to play too quickly after suffering a concussion. Second impact syndrome occurs when someone who has sustained a head injury, often a concussion, sustains a second head impact prior to the resolution of the initial injury [28]. Although the exact mortality rate due to this syndrome are unknown because of undiagnosed or unreported concussions, it has been associated with multiple deaths in young athletes [29]. In an attempt to decrease the occurrence of premature return to play, a six step protocol has been created to aid in having athletes resume athletic participation after a safe amount of time has passed [30].

Having a history of multiple concussions may result in alterations of the brain's white matter microstructure, which can lead to problems later in life [31]. Athletes are sometimes forced into retirement due to multiple medically diagnosed concussions [32]. Concussions may have long-term symptoms that include motor system dysfunctions, decline in memory, poor impulse control, aggressiveness, dementia, depression, and in some cases suicidal behavior [33,34]. For example, Cantu et al. noted in post mortem investigations of multiple professional athletes who had committed suicide that the majority of their brains showed chronic traumatic encephalopathy (CTE), a syndrome that stems from repeated head trauma [35].

Concussions are an emerging public health problem. It is estimated that 1.6 to 3.8 million concussions occur in sport and recreational activities annually in the United States, and that 6.3 million Americans are living with continued concussion-related disabilities [26]. In a study on Canadian varsity athletes, approximately 8% of male hockey players had sustained a concussion over a three-year period with some athletes experiencing multiple concussions [2]. Because of the prevalence of concussions, many rule changes have been instituted in contact sports to lower the risk taken on by athletes. Adding penalties for "checking from behind" and "checking to the head" in ice hockey and the mandatory use of helmets in ice hockey and football are examples of how sports are changing in an attempt to protect athletes' heads from trauma.

2.2 Ice Hockey Helmets

Helmets have been gradually adopted in the game of ice hockey since the 1930's but were generally not worn by the majority of North American players until they became mandatory in the National Hockey League (NHL) in 1979. Helmets have been popularly associated with the prevention of a majority of catastrophic head injuries, yet helmets have not been shown to decrease rates of concussions [36]. While helmets do reduce accelerations sustained by the head, whether they can prevent concussions remains unclear [37]. Unlike single impact helmets that are designed so that padding materials are destroyed on high energy collisions (e.g. bicycle helmets, ski helmets), ice hockey helmets are built to withstand multiple lower energy impacts (similar to lacrosse, and football helmets). Helmets alone cannot prevent concussions, as other factors (e.g. norms permitting excessive violence and risky player behavior as an effect of feeling safer wearing a helmet) counter the efficacy of personal protective equipment worn by players [38]. Nonetheless, in the past three decades, helmet designs and materials have advanced, as have safety standards.

2.2.1 Ice Hockey Helmet Materials

The first hockey helmets worn in the NHL were composed completely of leather [39]. Helmet construction has evolved since the 1950's, adopting synthetic materials that are lighter and have better energy dissipating properties. Current ice hockey helmets are engineered to be for multiple impact use and typically have two parts: the shell and the liner. The shell is the outer robust layer that functions to distribute impact contact area and resist puncture. Shells are made up primarily of low-weight polymers such as polycarbonate, fiber reinforced plastics, acrylonitrile-butadiene-styrene (ABS), and high density polyethylene. The inner liners are generally made of expanded polyethylene (EPE), expanded polypropylene (EPP), vinyl nitrile (VN), or layers of various other proprietary foams. These materials function to absorb mechanical energy during impact, and are required by testing standards to regain their full form and function within 30 seconds [40]. However, it has been demonstrated that after multiple impacts and with age, the materials of these helmets deteriorate and show diminished impact attenuation [41,42]. Helmets should be replaced regularly with use and age [41-44].

While the helmet's foams and plastics are used to protect the head, inner layer low density foams or gel-pads are used to optimize helmet fit, to both improve the stability and comfort of the helmet on the wearer's head. Most studies recommend the obvious, that an athlete should adopt and adjust a helmet to fit well [45]. However, rarely do studies define what fit is too tight or too loose. Fit irregularities may compromise the head-to-helmet alignment presumed for optimal head protection. Unintentional fit irregularities may occur due to the variation in head shapes from the "normal" head defined in helmet standards. Intentional helmet fit irregularities may be introduced by the athlete. For example, they may wear their neck straps too loose, wear their helmet tilted upward, alter the interior padding of the helmet, etc.

2.2.2 Ice Hockey Helmet Impact Testing

To use a hockey helmet in competitive play it must be certified by the governing agency specific to the league and country in which the games are played. Modern ice hockey helmets can influence energy transmission to the head. For example, during a 40 J linear rail impact drop test, helmets can the decrease peak linear accelerations of the head from 380-420 g to 100-130 g [46]. In early certification standards, a helmet model had to pass a series of pass/fail tests, using a 50^{th} percentile headform for the size category of the helmet (small [circumference = 460-560 mm], medium [circumference = 540-590 mm], large [circumference = 580-680 mm]), such that impact accelerations were below risk thresholds for catastrophic head injuries based on skull fracture [40,47]. More recent impact studies have included rotational acceleration thresholds and highlight the need for rotational acceleration attenuation to be added to standards testing [48-50].

2.3 Helmet Fit

One factor often cited in the literature for ineffective helmet function is poor fit, but it is rarely specified or quantified [45]. Linear-rail drop tests of helmets on a standard magnesium headform show that even a helmet on a head that meets the circumferential guidelines may not fit properly. The helmets in one study were sometimes flung from the headform upon impact, despite being properly placed on the headform [46]. This demonstrates that there is an issue with the current helmet fitting guidelines. This is supported by a study by Guo et al. of different head shapes that suggests head shapes should be categorized into nine categories [45]. This runs counter to common practice in certification impact testing methods that use only three headforms for testing [4].

As previously stated, ideal ice hockey helmet fit parameters are unknown and require further investigation. In the case of football helmets, it has been determined that an athlete will begin to report discomfort if the pressure exerted on their head by a helmet exceeds 70 kPa in any area of the head/helmet interface [51]. While this shows that it is not practical to wear a helmet that is too tight, there is a window of fit that allows for helmet stability without causing discomfort for the user. There seems to be no research investigating the static fit of hockey helmets similar to the above study of football helmets [51]. Generally, when purchasing a helmet, only a basic subjective assessment is done to determine the proper helmet for a given individual. The choice is made by “feel” and not by any standardised parameters that could be related to protective capabilities of the helmet for the user. While such parameters would not be evident, the current study hopes to bridge this gap and determine ideal helmet fit.

Proper fit should not be overlooked when discussing helmets. Though the above seems self-evident, to date little effort has been spent on quantifying and defining effective fit parameters. This issue is not as simple to fix as it may seem; the curvature and thickness of the cranial bones can vary substantially from person to person, thus giving very different head shapes [10].

2.3.1 Human Head Anthropometrics

As stated above, head shapes differ between people, and anthropometric studies have been conducted to categorize head dimensional ranges. One such study was conducted on 16 year old Caucasian males and females [52]. This population is relevant to the current project because 16-year-old Caucasians make up a large proportion of hockey players. It was found that between the 5th and 95th percentiles of Caucasian male heads, measurements varied by 20 mm in length (185-205 mm) and 20 mm in width (145-165 mm). The difference between the 5th percentile female head lengths and widths and 95th percentile male head lengths and widths were 40 mm (165-205 mm) and 30 mm (135-165 mm), respectively [52]. Common analyses of head shape use discrete measures (length, width, circumference, etc), but more modern continuous measures (e.g. principal component analysis) of head shape have been used in comparing Caucasian and Chinese head shapes [53]. With such a large variability in human head shapes, it follows that for a given helmet, there is a large range of “fit” possibilities as the helmet is placed on different heads.

2.3.2 Subjective and Qualitative Fit

Fit has been studied intensely for footwear and clothing, as the study of fit to body shape is important for garments, footwear, and apparel, but it has rarely been studied in helmets. Much investigation has been done regarding proper fitting of shoes, both subjectively (qualitative) [54] and objectively (quantitative) [9,55]. Many systems have been patented for shoe fitting and customization [56,57]. Au and Goonetilleke provided a framework for subjective comfort measurements for the foot in general and in specific areas via their questionnaire [54]. Witana et al. hypothesized that comfort scores can be viewed as lack-of-discomfort scores; in other words, one poor scoring region in comfort generally leads to a low overall comfort score [9].

2.3.3 Quantitative Fit of Helmets

When assessing fit, there are four required assessments: dynamic, occupation specific, integration/compatibility, and static assessments [58]. To assess static fit, often 3D modeling is used rather than physical measurements. When comparing 3D scanning methods to physical probing methods in ballistic helmets, it was found that it was not possible to determine which method could more accurately determine dimensional differences (DD) between a headform and a helmet [59]. Subsequently, many studies adapted 3D scanning as a means to gather continuous, rather than discrete, geometrical data [8,45,60,61].

One helmet fit article defined a correct bicycle helmet fit as a small and uniform distance between the helmet liner and the wearer's head shape [60]. This study used 3D scanning to create a helmet fit index for the interior of bicycle crash helmet shells. Perfect fit for a given head shape was defined as having a positive 6 mm DD between the head and the helmet's rigid foam matrix shell at every point, and having full coverage of the desired protection area [60]. Note that in bicycle helmets, an intermediary low density foam is used only to hold this shell off from the head.

In another study using 3D scanning, distances were quantified from human heads to hockey helmets in the mid-sagittal plane and mid-coronal plane, in what looks to be the first study investigating ice hockey helmet fit [8]. Cai, Bolstein et al. used a “principal plane” of the head, defined as one inch above each eye and the inion. This was the plane used to compare head shape to the helmet [8]. These planes were replicated in a study by Ball et al. where the differences between Caucasian head shapes and Chinese head shapes were investigated. The study states that 24-30mm above the Frankfurt plane defines the lowest point that any helmet could be impact tested [62]. While the fitting system created by Cai, Bolstein et al. is a great progression, their definition of ice hockey helmet fit presumes that a head that exceeds the helmet interior does not fit [8]. It can be postulated that due to comfort foams and gels on the interior of ice hockey helmets, the head should actually exceed the boundaries of the helmet interior such that small amounts of compression of these comfort paddings is present.

In the context of ice hockey helmet studies, there is a paucity in the literature comparing quantitative static geometrical fit values to subjective comfort. The current study aims to further knowledge about ice hockey helmet fit and how it differs from head shape to head shape.

2.4 Measurement Technology

There are many ways to acquire 3D models. Often, 3D models of head shapes are created using computerized tomography (CT) [63], magnetic resonance imaging (MRI) [64], laser scanning [8,53,59,62], or photogrammetry [65]. For the purpose of this thesis, CT scans were deemed to have a risk factor that is too great compared to the benefit of the imaging as the amount of radiation absorbed by the participant through CT scanning may lead to increased risk of brain cancer [66]. Pilot MRI data showed that imaging contrast would not allow both the skin of the head and the foam of the helmet to be visible under the same data acquisition settings. It has been shown that there is little difference between photogrammetry and laser scanning as far as accuracy of the system [67]. The low-cost of high quality photogrammetry made it an attractive 3D acquisition for our method.

The review of the literature led to the designing of the protocol for this thesis. The following chapter represents the manuscript created from this research. A depiction of the protocol may be found in figure 3.

3. Manuscript

Ice Hockey Helmet Fit Using 3D Modeling

David J. Greencorn[1], Daniel I. Aponte[1], David J. Pearsall[1]

[1] Department of Kinesiology and Physical Education, McGill University, Montreal, Quebec, Canada

3.1 Abstract

Ice hockey helmets must pass rigorous standardized impact tests to become certified for sale. However, these tests are performed with the helmet attached to a headform with the exact same shape from which they are designed. Human head shapes are not uniform, and very few standards exist for helmet fitting for the common user. The goal of this study was to create a 3D acquisition protocol to assess the geometric fit of ice hockey helmets with the proper head-helmet interface and orientation. The following study recruited 30 participants who wore 5 ice hockey helmet models in an attempt to quantify ice hockey helmet fit using 3D modeling, and analyzing fit parameters in two ways. First, by comparing geometric fit measures (dimensional differences or DD) in a cross-sectional plane of the head to the perception of fit scores. Second, by using principal component analysis (PCA) to determine the largest components of fit. Significant differences were noted between helmet models for both perception of fit scores as well as the DD (i.e. overlaps or gaps between the head surface and the helmet liner). However, in most cases the helmets that were perceived to be significantly tighter than another showed no significant difference in DD. The principal components of fit that were calculated included the overall uniformity of helmet-head contours emphasizing the differential between the DD of the front and back regions of the head, the lateral DD magnitudes, the front-back DD magnitudes, and the uniformity of the DD for the absolute back of the head and the rear lateral boss. PCA shows promise as a future method to investigate fit for a variety of purposes and fields.

3.2 Introduction

In Canada, ice hockey is one of the most commonly played sports; sadly, it also is one of the nation's leading causes of sport related concussion [1]. In a study done on Canadian university varsity athletes, approximately 8% of male hockey players had sustained a concussion over a three-year period with some athletes experiencing multiple concussions [2]. Ice hockey helmets have been a requirement for competitive play since the 1980's in an attempt to reduce the number of head injuries, in particular skull fractures and concussions. To become commercially available, helmets must pass a series of standardized tests.

The primary measurement criteria used to determine the head impact protection afforded by a helmet is its ability to attenuate peak linear accelerations based on controlled, standardized impact testing of surrogate headforms with the helmet [3-5]. While high impact-induced linear accelerations are known risk factors for concussive injury, researchers within the past decade have also suggested that impact-induced head angular accelerations are an equal if not greater risk factor for concussion [6,7]. However, most certification organizations have not yet included the latter criteria as a measure for helmet certification given the complexity of standardizing and setting clinically relevant impact criteria thresholds.

Standardized helmet impact testing involves approximation of many factors to "standardize" the test protocol. The most basic property defines the generic, representative headform in terms of shape and mass, scaled to size range (small, medium and large) with male and female adult anthropometric norms based on Caucasian population samples. An obvious criterion is the assessment of helmet fit, often measured in terms of required areas of coverage over the cranial head region and sufficient helmet-to-head retention (or stability). Yet, scrutiny reveals that helmet fit is more complex; for example, differences in head shape geometric proportions (e.g. width-to-length ratio) will modify both area of coverage and helmet retention properties. For a helmet to be stable on the head there must be compression of the inner foam against the head to offer sufficient grip to maintain proximate orientation. If a person has a head shape towards the 30th or 70th percentiles in width-to-length, for example, the helmet's foams will be regionally pre-compressed differently. Differences in the state of foam pre-compression (or lack thereof) may substantially affect the energy dissipation of particular helmet regions or as a whole. This leads us to believe that fit is an important quality of ice hockey helmet protection.

How can fit be measured? Some researchers have been investigating fit by the comparison of the two geometric shapes: in the case of helmet fit, that would mean comparing the shape of the head to the shape of the interior of the helmet. For example, in this manner Cai et al. presented a novel investigation of dimensional differences between the head and ice hockey helmets [8]; however, this study had limitations. First, the head-to-helmet were not aligned as worn; rather, the head principal plane and helmet were "virtually" aligned post hoc. Second, the inner foams were deemed to be non-compressible, but in order for the helmet to be anchored securely on the user's head there must be pre-compression of the inner foam. Third, the participants of the study never wore the helmets to give feedback on the subjective measure of fit.

Fit is not an easily quantified measure. Generally, when purchasing a helmet, the user will wear multiple helmets and purchase the helmet that feels the best to them, subjectively. In the footwear literature, studies have investigated subjective and geometrical fits, and it was found that the two fit measures were strongly correlated [9]. In the same light, we wanted to investigate whether or not helmet fit be assessed in a similar way, in terms of combined subjective and geometric scores. Thus, the rationale for this study was to address the limitations in Cai et al., to identify how well subjective and geometric scores and helmet fit scores interrelate, and to identify specific helmet-to-head fit configurations. Our first objective was to create a protocol to concurrently assess helmet and head alignment. Second, to quantify fit using both subjective and geometric measures. Third, to identify specific helmet-to-head fit categories. Fourth, to identify specific helmet model fit characteristics.

We hypothesize that, similarly to Witana et al., there will be a correlation between subjective and geometric fit measures, allowing us to classify tightness of fit using units of millimetres (mm), with small amounts of variance in preference. We hypothesize that we will see fit differences in areas of the helmet that are not adjustable, namely in the width dimension and the congruency of curvature along the front and back regions of the head-helmet interface.

3.3 Methods

This section describes the participants recruited for the study, the equipment and software used, the method through which the 3D models were gathered and created, and the analysis performed on the collected data.

3.3.1 Ethics

The McGill Human Research Ethics Board II criteria (certificate # 135-0816) approved the methods involved in this research study.

3.3.2 Participants

The thirty adult male participants recruited to take part in this study had played hockey regularly within three years of participating. Their head widths (maximum breadth above the level of the ears), lengths (apex to inion), and circumference (measured through the landmarks used for length and width) were measured. Their age, years of hockey experience, highest level played, current helmet (brand, model, size, and colour) were also recorded. Participants ranged in highest level played from recreational to American Hockey League.

Table 1 Descriptive statistics of participant sample

Parameter	Mean ± SD	Max	Min
Age (Years)	26 ± 6	46	19
Hockey Experience (Years)	19 ± 7	35	10
Head Circumference (mm)	590 ± 11	614	573
Head Length (mm)	208 ± 6	221	198
Head Width (mm)	161 ± 5	172	152

3.3.3 Helmets

Five helmet models were used in both medium and large sizes. The specific models include Bauer Re-akt 200, Bauer Re-akt 75, Bauer IMS 9.0, CCM Resistance, and Warrior Krown PX3. Hereafter, these helmets are referenced to by a randomized helmet number code. To blind the participant to the make and model of helmets worn, helmet logos were covered.

3.3.4 Equipment

A Canon EOS Rebel T6i/750D with a EF-S 18-55mm f/3.5-5.6 IS STM lens (Canon Canada Inc., Mississauga, Ontario, 2015) was used to capture photos (6000 x 4000 pixel resolution) of the helmets and the participants' heads. The same camera was used to record videos (1920 x 1080 pixel resolution) of participants wearing helmets, and frames were extracted from these videos for rendering the 3D intermediate models using a video to .jpg converter. Videos, rather than photos, were used for the intermediate models to save time in the protocol. Refer to section 3.3.6 for the intermediate model protocol (refer to figure 1 for the studio setup). The programs used to process the data included AutoDesk® ReMake (Autodesk Inc., 2016), MeshLab (open source program), 3D Builder© (Microsoft Corp., Redmund, Washington, USA, 2015), and MATLAB® (MathWorks Inc. Natick, Massachusetts, USA, 2016).

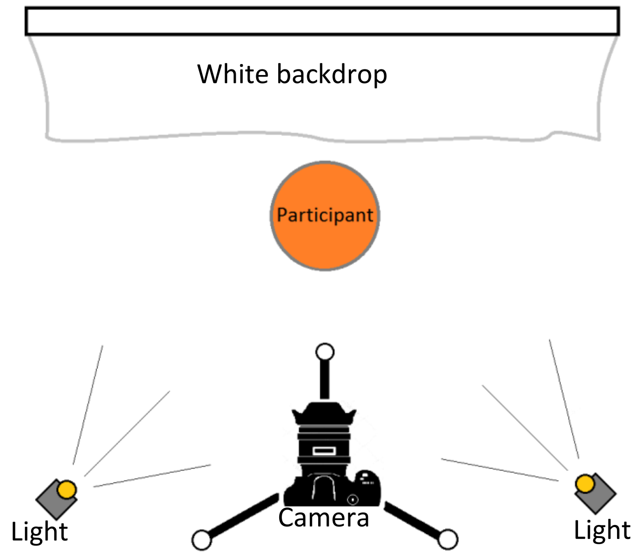


Fig. 1 Photo/video capture setup, top view.

Each participant sat on the pivoting chair that rotated slowly 360 degrees to take 50 pictures about the participant's vertical axis. The distance from each the camera and the lights to the person was 1 m.

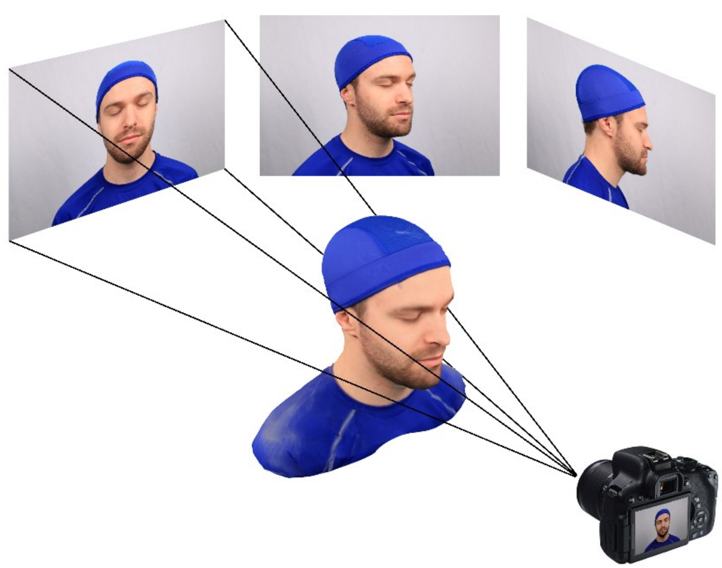


Fig. 2 Camera and participant positions (foreground) and the sample photo views (background) used to make the 3D model (centre of image).

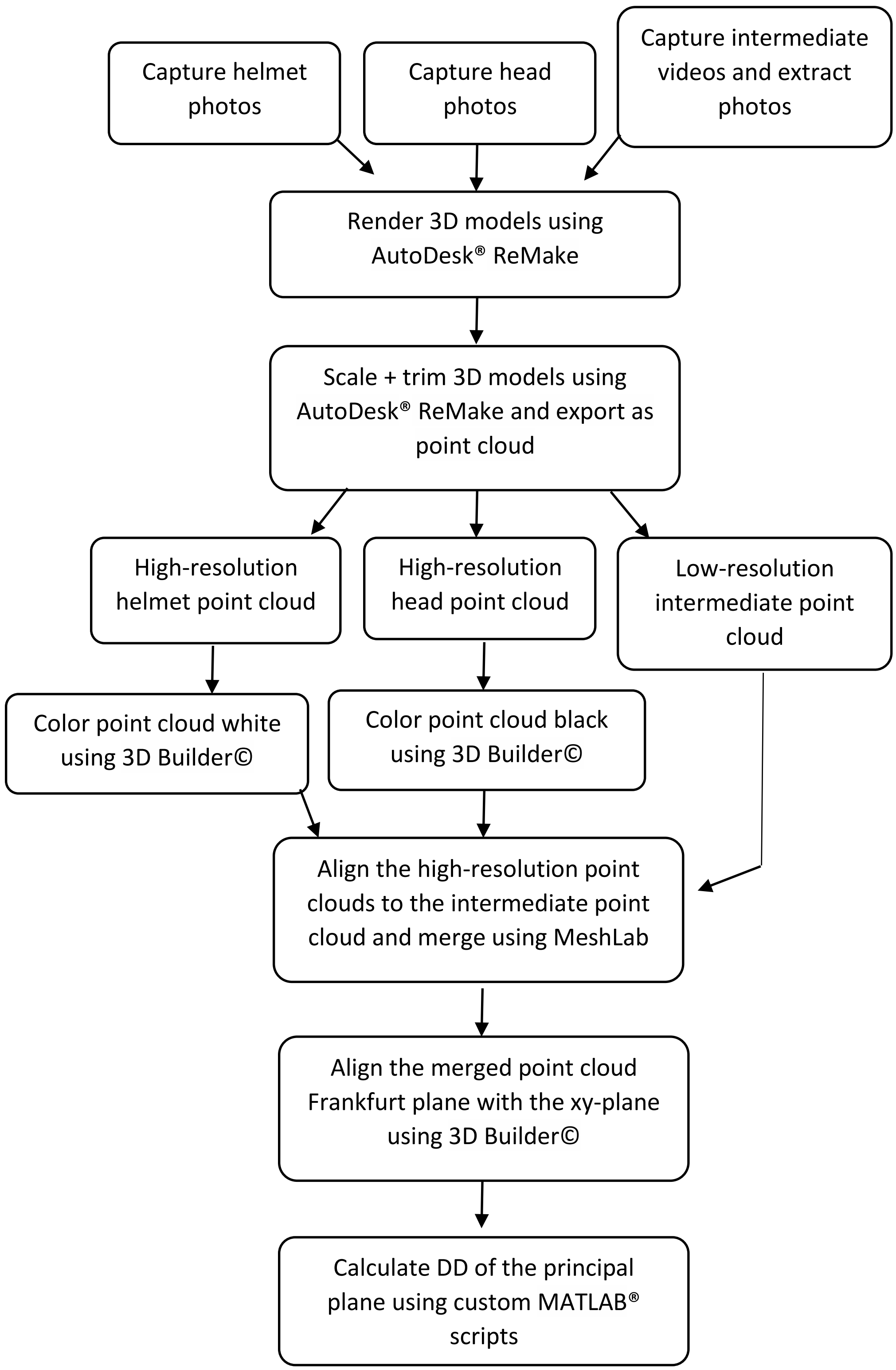


Fig. 3 Data process diagram

3.3.5 Creating the Database of 3D Helmet Models

A library of high-resolution (refer to table 4 for resolutions and face count) helmet models was created. The library included each length adjustment of each helmet model, resulting in a catalogue of 56 helmet model variations. The 3D models were decimated to 1.5 million polygons to reduce computing time for further processing steps. The helmets' exterior shells were spray-painted matte black to reduce the reflections of the helmet exterior, thereby enhancing detection and quality in the subsequent model rendering. This was accomplished by taking approximately 150 well lit (500-watt, tungsten bulb softboxes were used with an illuminance estimated at 1700 lux) photos of the exterior and interior of each helmet's surface with a reference scale present. The photos were taken in accordance to the AutoDesk® Remake Guide specifications [68]. These photos were imported into AutoDesk® ReMake and were rendered into a 3D mesh (*.rcm file). The mesh was then scaled using the "set scale & units" feature and selecting a measured distance of 150 mm on the scale that was included in the 3D model.

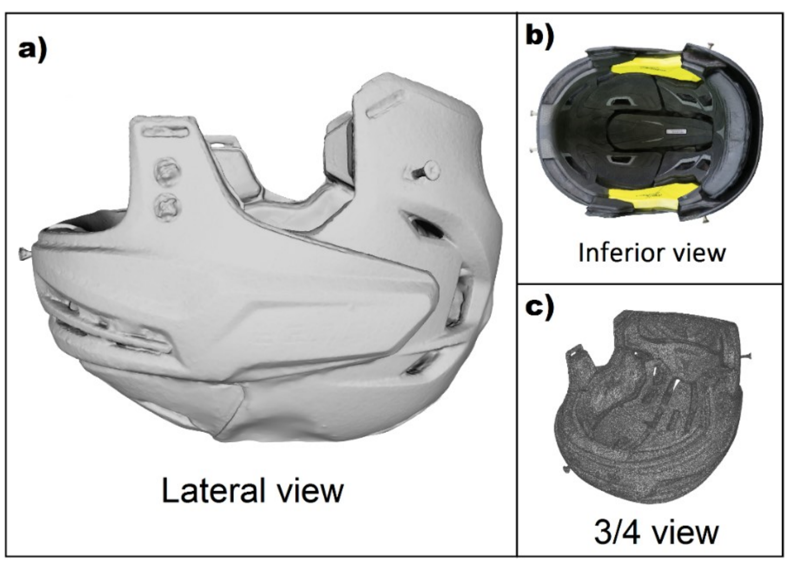


Fig. 4 Example of fully rendered 3D model of a helmet: (a) lateral view (no color texture); (b) inferior view (full color texture); (c) 3/4 view (wireframe)

3.3.6 Participant Testing Protocol

The study's protocol was as follows: creating 3D models of the participant's heads, creating 3D models of the participant wearing each helmet, and administering a fit questionnaire for each helmet.

High-resolution (refer to table 2 for resolutions and face count) head models were created of each participant in a similar method. Participants wore a clean spandex cap to reduce hair artifacts on cranial head shape and a spandex shirt to reduce shirt position discrepancies between photos. Each participant sat on a stable chair (HermanMiller Caper Multipurpose Stool) that permitted transverse rotation in front of a white textile background. Each participant held a static neutral facial expression and neck position, with eyes closed. Participants were instructed to make a small pivot rotation (~8°) of the chair seat (by pressing their feet against the chair's lower foot rest ring support) after each picture was taken. Approximately 50 well lit photos were taken at three camera heights: the first height was slightly below the participant's chin, the second and third heights were approximately 350 mm above each previous level. The camera angle was adjusted to keep the head centred. The photos were taken within 4 to 5 minutes per level. Subsequently, all photos were imported into AutoDesk® ReMake to render a digital 3D mesh of the participant's head shape. The 3D meshes were scaled using the head length measure (measured with Lafayette 01291 calipers with a resolution of 1 mm) as the reference.

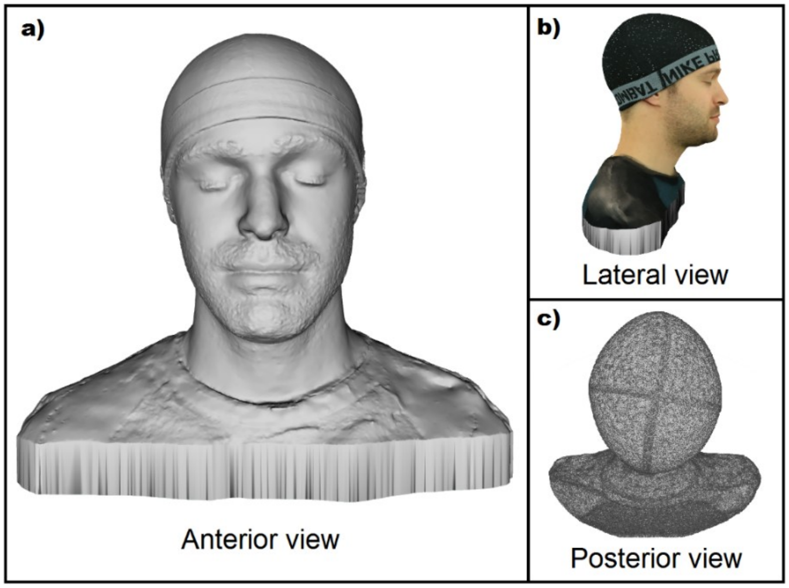


Fig. 5 Fully rendered participant 3D model: a) anterior view (no color texture); b) lateral view (full color texture); c) posterior view (wireframe)

Once the head scans were complete, the participants put surgical caps on their heads and were subsequently given 5 helmets to wear in a random order. The tester aided the participants in sizing the helmet by adjusting the helmet clasps to set the helmet shell's front-back span, as preferred by the participant. The adjustment and size of the helmet for each model were recorded. To determine participant specific helmet-to-head orientation and coverage, lower-resolution intermediate captures of the participant combined with wearing each helmet were collected using high-definition video at 30 frames per second, rather than still photographs. This was done to reduce the collection time window to 2 minutes instead of 15 minutes, which kept the protocol to a more reasonable one-hour time commitment for participants. The videos were collected at the same three camera heights as the high-resolution head photographs.

Approximately 70 still frames from each level were imported into AutoDesk® ReMake for the 3D rendering. In order to scale the intermediate meshes, each helmet was marked with a 60 mm reference scale. The intermediate 3D models were of lower resolution compared to the high-resolution head and the high-resolution helmet 3D models (refer to table 2 for resolutions and face count). The purpose of the intermediate 3D models was for the alignment of the two high-resolution 3D models, not for geometrical analysis.

Fig. 6 Example of fully rendered intermediate 3D model of a participant wearing a helmet

Table 2 3D model and point cloud resolution

3D model/point cloud	Approximate number of vertices	Approximate number of polygons	Point resolution
High-resolution helmet (non-dessimated)	2 500 000	4 000 000	20 vertices/mm^2
High-resolution helmet (dessimated)	900 000	1 500 000	12 vertices/mm^2
High-resolution head	500 000	900 000	10 vertices/mm^2
Low-resolution intermediate	70 000	130 000	4 vertices/mm^2

Following each helmet scan, the participant answered a questionnaire (Appendix D) regarding their perceptions to:

1. Overall helmet FIT as well as region specific helmet fit on a Likert scale of:

   -3 (“too loose”), 0 (“perfect”), and 3 (“too tight”),

2. Overall and region specific COMFORT Likert Scale of:

   1 (lowest comfort) to 7 (highest comfort),

3. Overall and region specific STABILITY of the helmet on the head on a Likert Scale of:

   1 = lowest stability, 7 = highest stability), and

4. Overall SAFETY of the helmet on a Likert Scale of:

   1 (“not safe”) to 7 (“extremely safe”).

Following the protocol, the participant’s preferred helmet was recorded.

3.3.7 Data Analysis

The data analysis included cropping and exporting the 3D models, aligning the 3D models, calculating dimensional differences (DD), estimating the error, and completing statistical analyses (fig. 3).

All 3D meshes were cropped to only contain the objects of interest (head, helmet, or head and helmet) and exported as “*.ply” (Polygon File Format, hereby referred to as a “point cloud”). The high-resolution helmet point clouds were textured white in 3D Builder©, and the high-resolution head point-clouds were textured black to facilitate the separation of the helmet and head point-clouds for analysis. This process was important to enable later calculations to determine relative head-to-helmet shapes’ relative contacts and orientations.

The point clouds were imported into MeshLab for alignment (fig. 7, 8). The alignment tools’ “point based gluing” uses an iterative closest point algorithm to minimize the differences between the point clouds’ corresponding facial landmarks to position the high-resolution head point cloud with the intermediate head point cloud. The corresponding high-resolution helmet point cloud with appropriate size and adjustment was aligned with the helmet portion of the intermediate point cloud. Once the alignment of each scan was completed, the intermediate point cloud was deleted and the two high-resolution point clouds were merged and exported as an aligned point cloud.

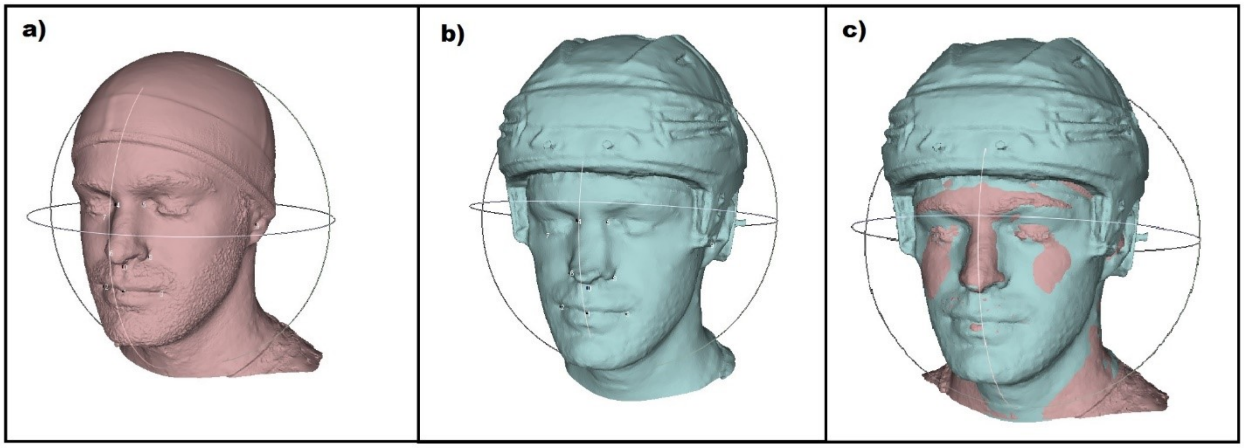


Fig. 7 Head alignment to the intermediate point cloud process using MeshLab: a) high resolution head point cloud; b) intermediate point cloud; c) aligned point clouds

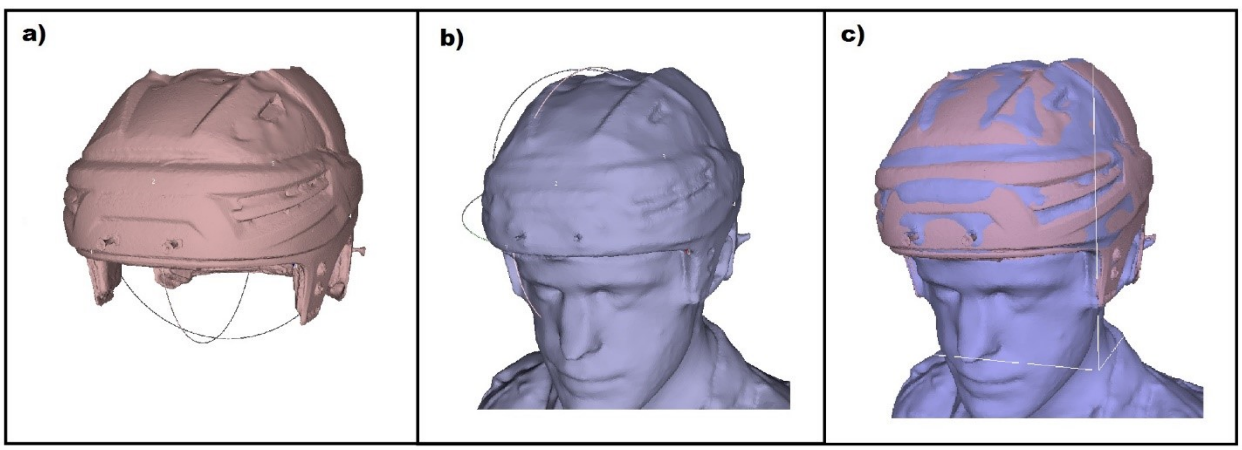


Fig. 8 Helmet alignment to the intermediate point cloud process using MeshLab: a) High resolution helmet point cloud; b) intermediate point cloud; c) aligned point clouds

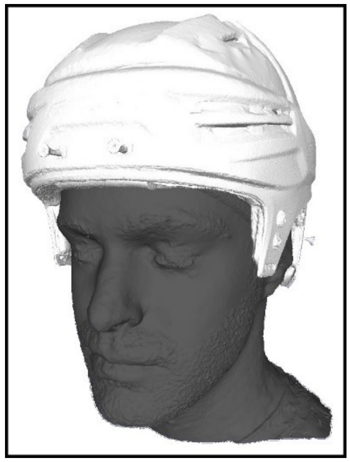


Fig. 9 Fully Aligned High Resolution Model

The aligned point clouds were oriented in 3D Builder© such that the centre of the Frankfurt Plane (plane passing through the inferior borders of the bony orbits and the upper margins of the auditory meatus) was positioned at the origin. This point cloud was saved and was the working file for the geometrical analysis of the head-helmet interface. Using MATLAB® custom scripts, the DD between the head and the helmet (i.e. amount of gap or compression between helmet and head) were measured. These measurements were taken at 65 mm above the Frankfurt Plane using a slice thickness of 1 mm (i.e. all points from 64.5 mm to 65.5 mm above the Frankfurt Plane were "flattened" and used to create the plane of interest). This plane will hereafter be referred to as the principal plane. In many cases, the helmet liner included small ventilation gaps between the interior foam sections, and these gaps were removed from the DD measures (fig. 10).

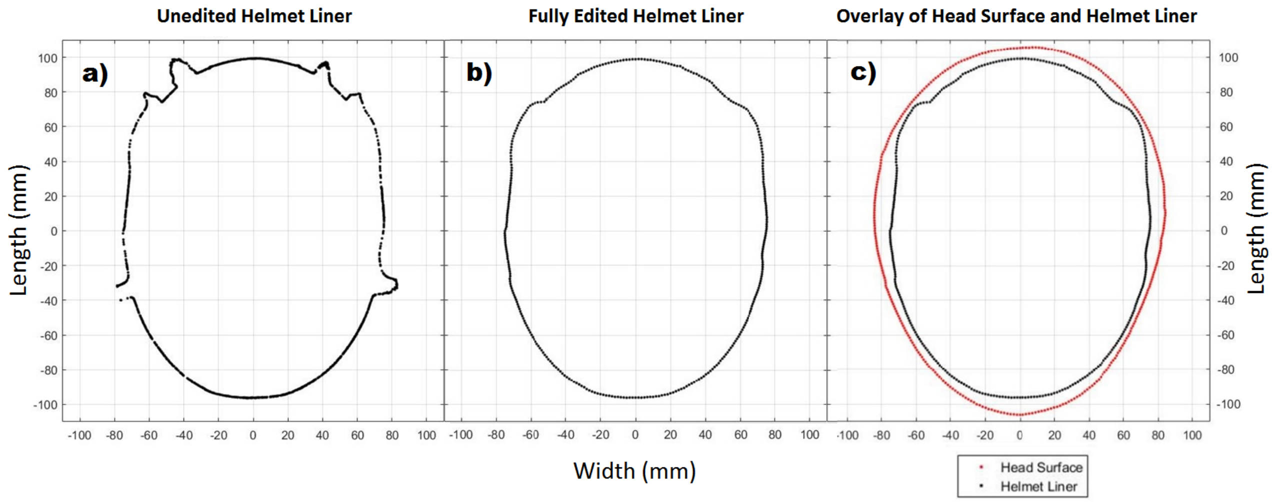


Fig. 10 Steps to remove gaps in the helmet liner: a) initial helmet liner shape; b) interpolated helmet liner shape; c) Cartesian Overlay of the Head Surface and the Helmet Liner. The head surface is noticeably larger than the helmet liner. This is due to the compressibility of the foam and the buckling of the helmet shell, to be addressed in the discussion.

DD is defined as the radial difference between the head and the helmet liner. The data was converted from Cartesian coordinates (fig. 10c) into polar coordinates (fig. 11) for the measurement of the DD, which were measured at each degree for each participant with each helmet. The average, maximum, minimum, and standard deviation of the DD were claculated.

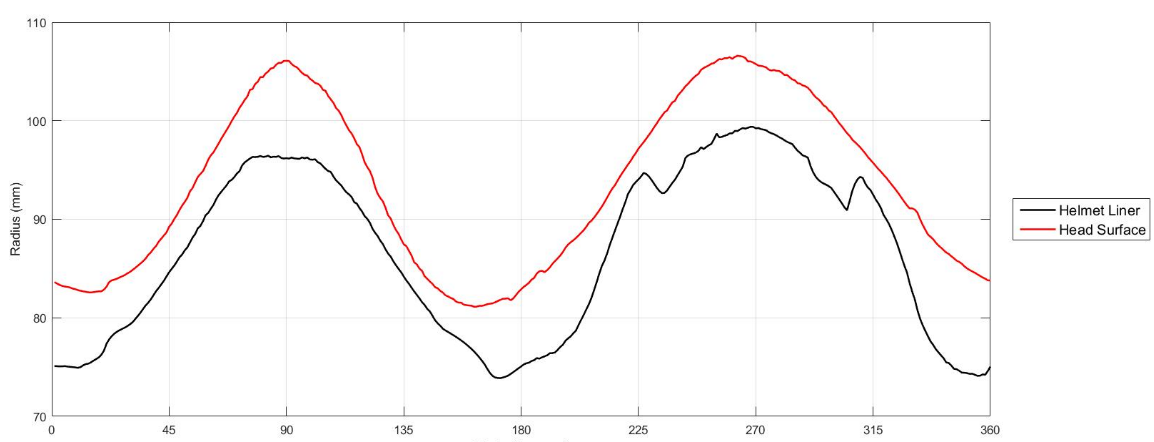


Fig. 11 Polar coordinate overlay of the head surface and the helmet liner

3.3.8 Geometric Helmet to Head Error Measurements

In previous studies, RMSE has been used to determine the measurement error between two systems[69,70]. In theory, this calculation may also be used to determine the error within a measurement system.

The error of the full protocol was estimated using root mean square errors (RMSE). With four participants whom each repeated the scanning protocol, the same processing, alignment and calculation methods were applied to these repeated scans. The RMSE of both the original and repeated scans were calculated for each of the repeated trials (n = 20) and averaged to estimate the protocol error. This identified a RMSE of 2.83 mm (table 3).

To estimate the error in the alignment of the high-resolution models using the low-resolution intermediate model, one high-resolution head model and one high-resolution helmet model were aligned five times using the same intermediate model. The RMSE was calculated, using each degree DD between each alignment and averaged to represent the error due to the alignment of the head and helmet models. Using the same aligned models, the 95% confidence interval error for overall and region-specific DD values (standard deviation, average, maximum, and minimum) were calculated (n = 5). This identified a RMSE 1.14 mm.

To estimate the error in the rendering and scaling of the models, each of the four repeated head scans were aligned with the Frankfurt plane of the original models. The analyzed plane of each scan was centered about the origin to compare the shapes of the models (not their alignments). The RMSE was calculated, using each degree, to determine the dimensional differences between the two models that would ideally be identical. The average RMSE is defined to be the rendering and scaling error (n = 4). The RMSE of the head lengths and widths were also calculated. This identified RMSE estimates from 1.47 to 1.84 mm.

Table 3 Error measurements

Full Protocol RMSE	2.83 mm
Alignment RMSE	1.14 mm
Render/Scale RMSE	1.84 mm
Render/Scale Length RMSE	1.58 mm
Render/Scale Width RMSE	1.47 mm

3.3.9 Statistical Analysis

All statistical analysis was completed using SPSS Statistics software (IBM Corporations, Somers, U.S.A., Version 23.0). The mean, maximum, minimum, and standard deviations of all variables were calculated. Mann-Whitney U tests were run to compare the rank order fit score means (overall, width, and length) between helmet models. A one-way ANOVA was run to compare the DD means (width and length) between the helmet models. Spearman correlations were run between the fit scores and the DD. A one-way ANOVA was used to compare the Z-scores of the principal components extracted from the principal component analysis.

3.4 Results

The following results describe the range of head shapes recorded, their corresponding helmet-to-head perceived fit score, and DD distributions between helmet models. Subsequently, the relationships between perceived fit scores and DD are presented, followed by the principal component analysis (PCA) findings of DD helmet-head fit contours.

3.4.1 Principal Plane Head Shapes

For the adult male participants in this study, their average head dimensions were lengths of 207.8 ± 7.0 mm, widths of 163.9 ± 5.2 mm (fig. 12) and circumferences of 578.5 ± 14.5 mm. These were larger than those found in anthropometric databases (length: 195 ± 8 mm; width: 155 ± 6 mm) [52]. These difference were expected given that our participants were recruited based on wearing medium to large helmets (thus excluding participants with small head sizes). The head length-to-width ratios varied from 1.4 to 1.2 (fig. 13). The relationship between the absolute head length and the length-to-width ratio was ($r = 0.651$, $p < 0.001$). Small left-right asymmetries in head shape about the sagittal plane were observed (fig. 13). A value of asymmetry was calculated for each participant by calculating the RMS difference between the radial distances of the clockwise and counter clockwise corresponding points from the centre of the plane. The asymmetry ranged from 0.7 to 4.9 mm for the participants in our sample.

For the 150 total head-helmet combinations, large helmets represented 24 combinations. There were significant differences between the mean head lengths (medium = 206.6 mm, large = 213.0 mm) ($p < 0.001$) and circumferences (medium = 576.6 mm, large = 586.4 mm) ($p = 0.001$) but no significant difference in head width (med = 163.9 mm, large = 165.0 mm) ($p =.342$) for the participants who wore large versus medium helmets (Note that all ice hockey helmets tested enable shell length extension up to 2 cm. Participants were permitted to change helmet length setting for each helmet model as they preferred).

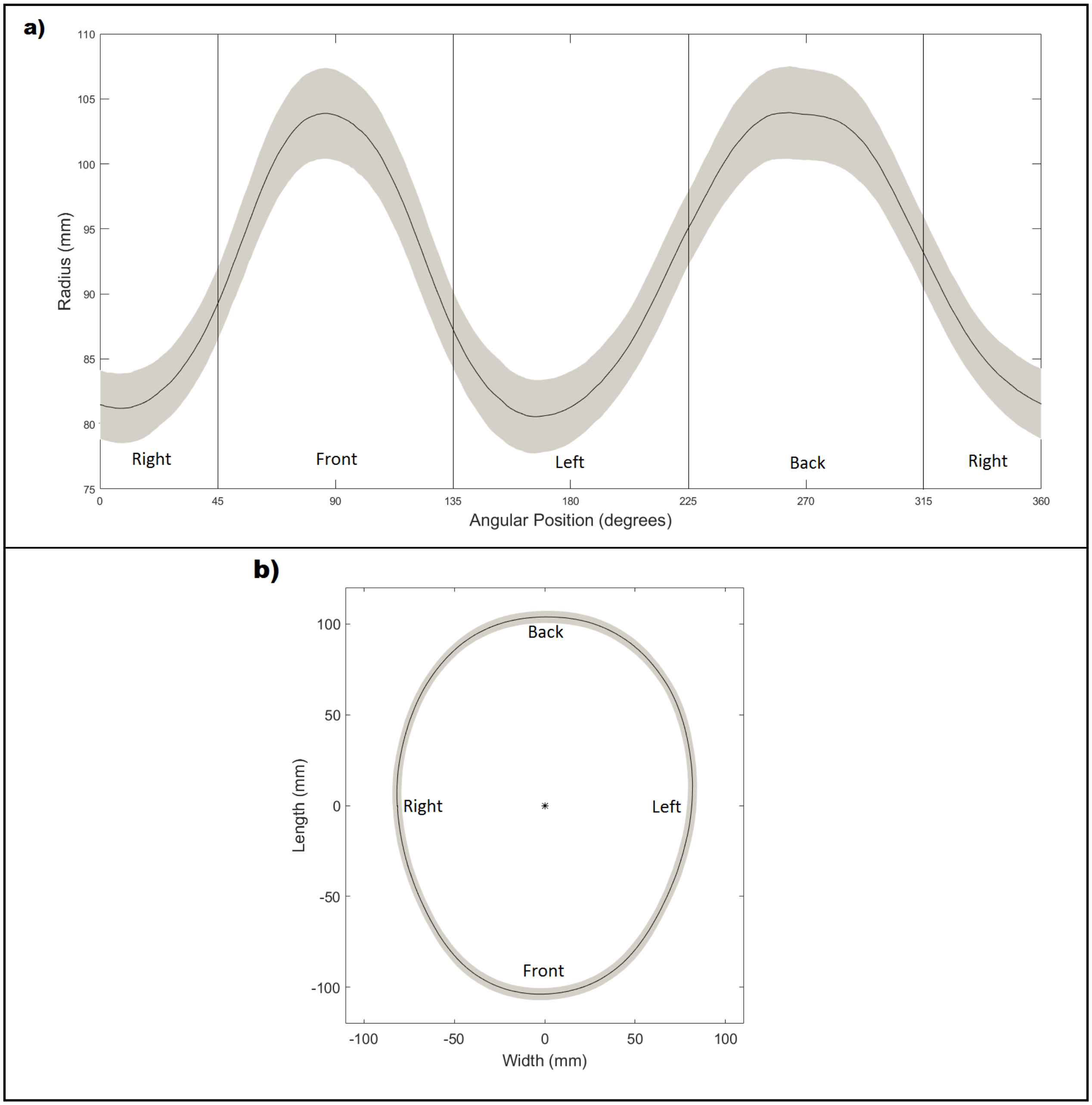


Fig. 12 Mean head shape ± the standard deviation: a) polar coordinates; b) Cartesian coordinates

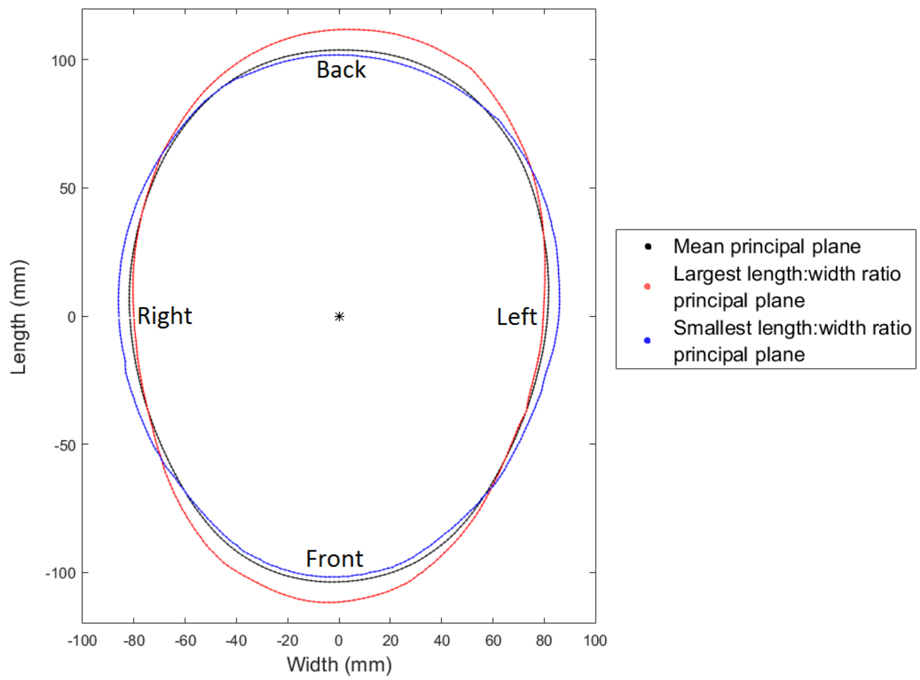


Fig. 13 Overlay of head shapes of the largest and smallest length-to-width ratio.

3.4.2 Subjective Fit Scores by Helmet

Significant differences in fit score parameters were found between helmet models (refer to table 4):

1. Helmet A was scored looser in overall fit compared to helmets B ($U = 212.5$, $p < 0.001$), C ($U= 250.0$, $p = 0.002$), D ($U=269.5$, $p = 0.005$), and E ($U=298.0$, $p = 0.018$).
2. Helmet C was scored tighter in width fit than A ($U = 188.0$, $p < 0.001$), D ($U = 264.5$, $p = 0.004$), and E ($U = 274.5$, $p = 0.007$).
3. Helmet A was scored looser than B ($U = 265.0$, $p = 0.004$) in width scores.
4. Helmet E was scored looser in length fit than B ($U = 282.0$, $p = 0.008$) and C ($U= 320.0$, $p = 0.041$).

Table 4 Distribution of perceived fit scores by helmet model. Perceived fit ranged from -3 to 0 to 3 (too loose, perfect, too tight, respectively) by integer increments (refer to Appendix C for questionnaire). Note, helmet models are identified here were assigned a letter randomly between "A" and "E". Significant differences are denoted by the superscript letter of the helmet from which it differs.

Fit Score	Mean Rank	Median	IQR	Max	Min	Range
Helmet A						
Overall[b,c,d,e]	49.8	-1	1	2	-3	5
Width[b,c]	53.5	0	1	3	-3	6
Length	65.0	0	2	2	-2	4
Helmet B						
Overall[a]	88.4	0	1	3	-1	4
Width[a]	82.7	0	1	3	-1	4
Length[e]	89.17	1	1	3	-1	4
Helmet C						
Overall[a]	87.6	1	2	3	-1	4
Width[a,d,e]	100.4	1	2	3	-1	4
Length[e]	82.8	0	1	3	-1	4
Helmet D						
Overall[a]	77.3	0	1	2	-2	4
Width[c]	69.7	0	2	1	-2	3
Length	79.7	0	1	2	-2	4
Helmet E						
Overall[a]	74.4	0	2	2	-2	4
Width[c]	71.3	0	1	2	-2	4
Length[b,c]	60.8	0	1	2	-2	4

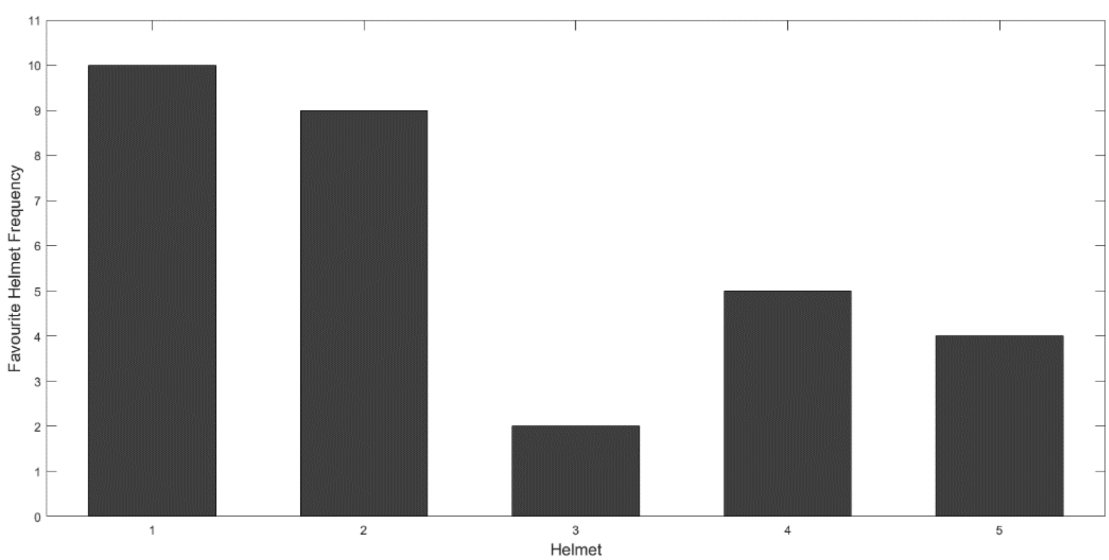


Fig. 14 Favourite helmet distribution.

3.4.3 Dimensional Differences by Helmet

In general, the average DD values were negative (i.e. there is compression occurring at the head-helmet interface). Significant differences in average DD were identified between helmet models. The overall DD average for helmet E was lower (i.e. more head-helmet overlap or compression) than helmets B ($p = 0.006$) and D ($p = 0.003$). Other helmet-by-helmet differences were noted:

1. The average width DD was lower for helmet C compared to helmets A ($p = 0.002$), B ($p = 0.001$), and D ($p < 0.001$).
2. The average width DD was lower for helmet E compared to helmets A ($p = 0.041$), B ($p = 0.021$), and D ($p < 0.001$).
3. The average length DD was higher (less head-helmet overlap or more head-helmet gapping) for helmet C compared to helmets A ($p = 0.001$), D ($p = 0.006$), and E ($p = 0.002$).

Table 5 Distribution of dimensional differences (DD) by helmet model. Significant differences are denoted by superscripts that represent from which other helmet they differ.

DD (mm)	Mean	SD	Max	Min	Range
Helmet A					
Overall	-3.5	2.3	1.9	-6.7	8.6
Width[c,e]	-3.4	3.0	2.7	-9.2	11.9
Length [c]	-3.5	2.1	1.0	-8.3	9.3
Helmet B					
Overall [e]	-3.0	1.3	0.3	-6.0	8.1
Width [c]	-3.3	1.8	1.1	-6.3	7.4
Length	-2.6	1.8	1.1	-7.0	8.1
Helmet C					
Overall	-3.6	1.7	1.1	-8.0	9.1
Width [a,b,d]	-5.9	2.4	-0.5	-10.0	9.5
Length [a,d,e]	-1.3	2.5	3.8	-7.6	10.4
Helmet D					
Overall [e]	-2.7	1.9	1.6	-7.0	8.6
Width [c,e]	-2.2	2.5	3.6	-6.5	10.1
Length [c]	-3.2	1.8	-0.4	-8.8	8.4
Helmet E					
Overall [b,d]	-4.3	1.9	-0.6	-8.4	7.8
Width [a,d]	-5.3	2.7	1.5	-9.9	11.4
Length [c]	-3.4	2.4	0.4	-9.3	9.7

3.4.4 Fit Scores Compared to Dimensional Differences

There was a wide range of DD that corresponded to the fit perception scores. Fig. 15 shows the distribution of the DD within a given fit score. Significant negative Spearman's rank correlations ($p < 0.05$) were found between width DD average and fit width when all helmets were pooled ($\rho = -0.326$) and for within helmets B ($\rho = -0.391$) and C ($\rho = -0.369$). These correlations showed that when the DD decreased (i.e. more overlap / foam compression) the perceived fit score was higher (i.e. tighter). Furthermore, average width DD and perceived width stability scores were significantly correlated for the all helmets ($\rho = -0.183$) and within helmets B ($\rho = -0.396$), and D ($\rho = -0.422$). This revealed that as the DD average decreased, the helmets were perceived to be more stable on the participants' heads. Other significant correlations are listed in table 6. There were no significant differences found for DD distribution between any of the fit scores. The description of the DD distribution for each fit score is noted in Appendix D.

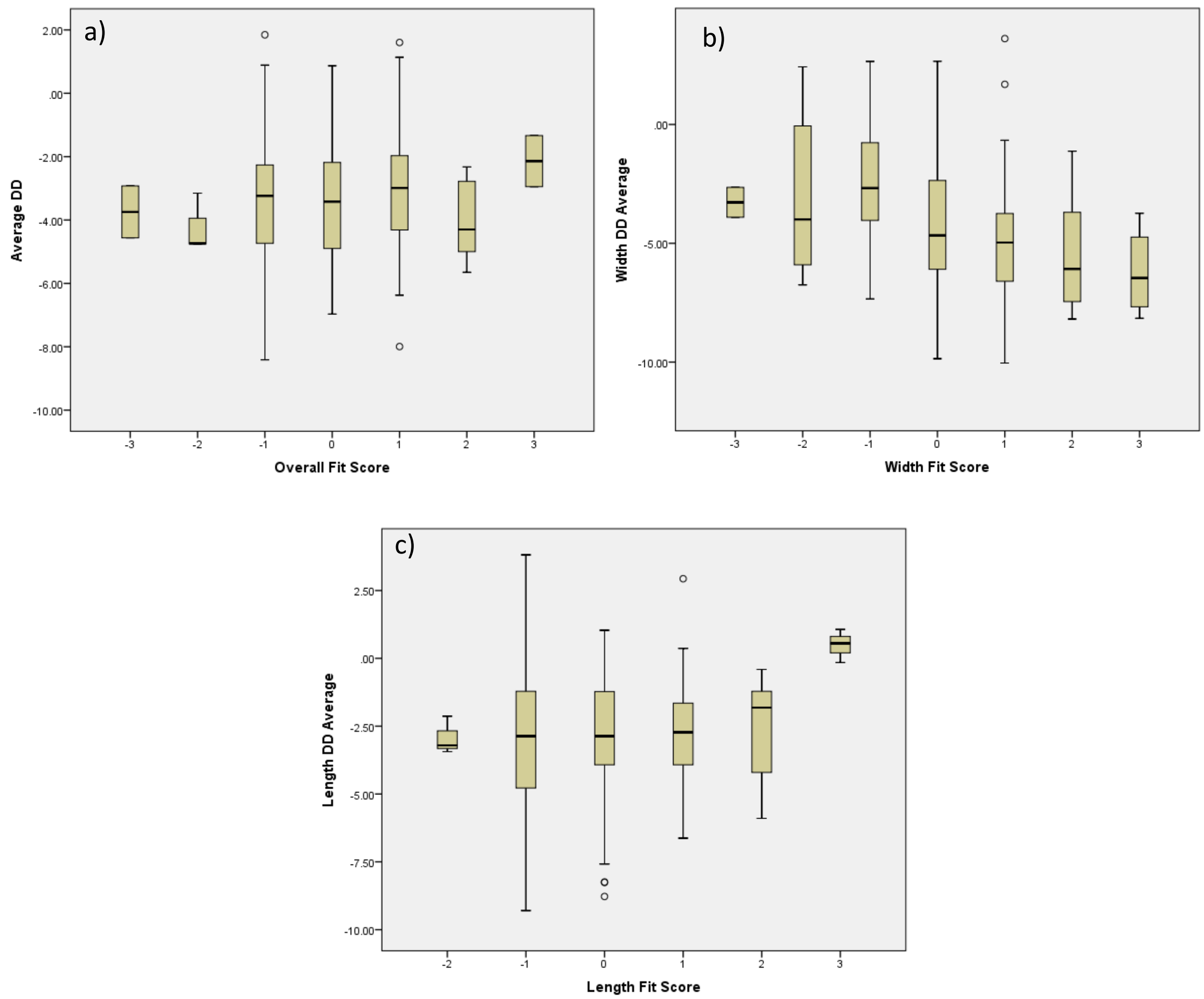


Fig. 15 DD measures compared to (a) Overall Fit Score, (b) Width Fit Score and (c) Length Fit Score (all helmet data combined). The box (75th to 25th quartiles) and whiskers (max and min) around the median DD value for each Fit score category.

Table 6 Significant Spearman's rank correlations ($p < 0.05$) between DD and subjective fit and stability scores

Helmet	All Helmets	A	B	C	D	E
Variables						
Overall DD Average/Width Stability					-0.440	
Overall DD Max/Overall Fit	0.165		0.504			
Overall DD Max/Length Fit	0.232					
Length DD Average/Width Fit	0.246					
Length DD Max/Overall Fit			0.516			
Length DD Max/Width Fit						
Length DD Max/Length Fit	0.232					
Width DD Average/Width Fit	-0.326		-0.391	-0.369		
Width DD Average/Width Stability	-0.183		-0.396		-0.422	
Width DD Minimum/Width Fit	-0.246			-0.426		
Width DD Minimum/Width Stability					-0.506	
Width DD Max/Length Fit	0.208					
Width DD Max/Length Stability				-0.368		

3.4.5 Principal Component Analysis of Dimensional Differences

Principal component analysis (PCA) was used to analyze the DD curves for every helmet and head combination. The figures below depict the eigen vector (i.e. principal component or PC), the position and magnitude of the variabilities in the eigen values (denoted as the grey shaded area in fig. 16-19 (a)), low and high scores for each PC (5 participant averages about each the 5th and 95th percentiles), and the Cartesian representation of the 5th and 95th percentile principal plane and helmet combinations. Four PCs were extracted and cumulatively represent approximately 85% of the variation of the DD waveforms.

PC1 (fig. 16) represents 38.3 % of the variability in the DD waveforms, and corresponds to the difference in DD values between the front and back regions; specifically, increased negative DD in the rear and positive DD in the front of the head-helmet interface. PC1 also represents the uniformity of the DD about head (i.e. high congruency between the head and helmet). Low Z-scores for PC1 show small differences in the DD in the front and back regions of the head and more DD uniformity about the head. High Z-scores for PC1 show large differences in the DD of the front and back regions of the head as well as less overall DD uniformity about the head.

PC2 (fig. 17) represents 24.2% of the variability in the DD waveforms and corresponds to the magnitude of the DD along the lateral aspects of the head. Low Z-scores for PC2 show lower DD values (i.e. more compression) for the lateral regions of the head. High Z-scores for PC2 show greater DD values (i.e. less compression) for the lateral regions of the head.

PC3 (fig. 18) represents 15.3% of the variability in the DD waveforms and corresponds to the magnitude of the DD for the front and back regions of the head. Low Z-scores for PC3 show lower DD values for the front and back regions of the head. High Z-scores for PC3 show greater DD values for the front and back regions of the head.

PC4 (fig. 19) represents 6.9% of the variability in the DD waveforms and corresponds to the uniformity of the DD for the back region of the head, characterizing the relationship of the rear lateral boss and the absolute rear of the helmet. Low Z-scores for PC4 shows high DD uniformity in the back region of the head. High Z-scores for PC4 shows low DD uniformity in the back region of the head.

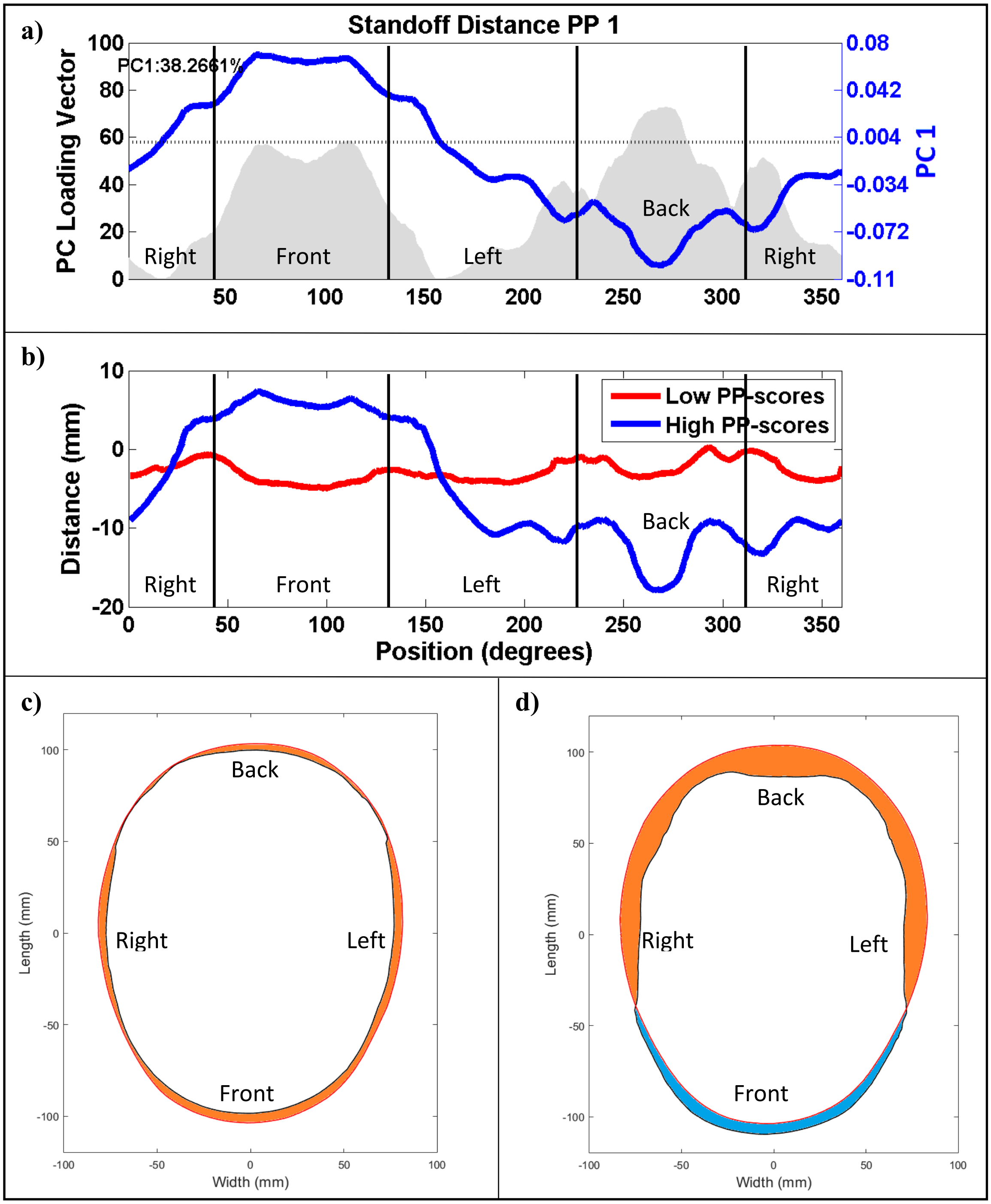


Fig. 16 Principal component 1: a) eigen vector (PC1) represented in blue, variance in the principal component in grey; b) polar coordinate representations of 5th and 95th percentile PC1 Z-scores; c) Cartesian representation of 5th percentile PC1 Z-score, orange marks areas of overlap, blue marks gap regions; d) Cartesian representation of 95th percentile PC1 Z-score, orange marks areas of overlap, blue marks gap regions.

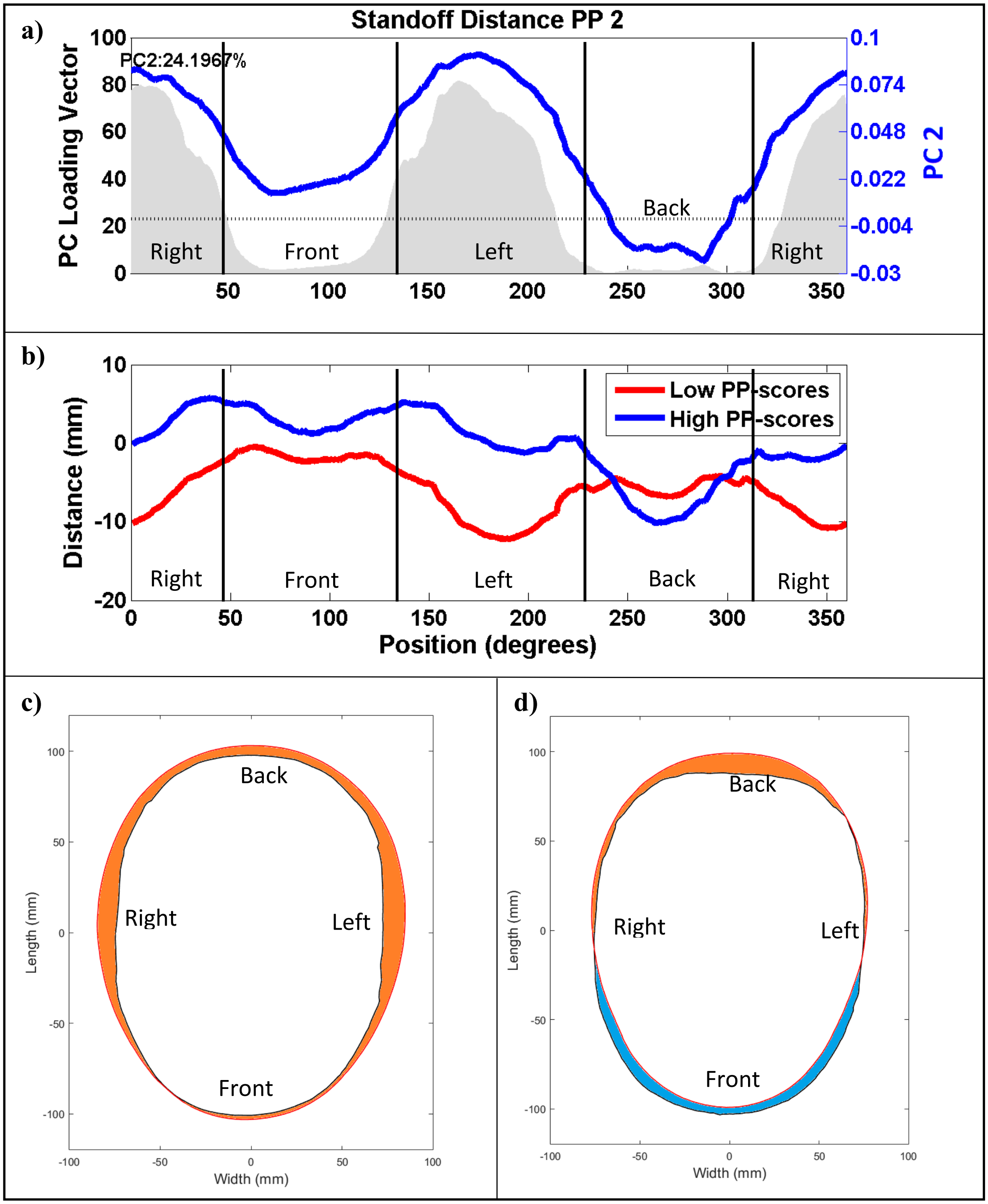


Fig. 17 Principal component 2: a) eigen vector (PC2) represented in blue, variance in the principal component in grey; b) polar coordinate representations of 5th and 95th percentile PC2 Z-scores; c) Cartesian representation of 5th percentile PC2 Z-score, orange marks areas of overlap, blue marks gap regions; d) Cartesian representation of 95th percentile PC2 Z-score, orange marks areas of overlap, blue marks gap regions.

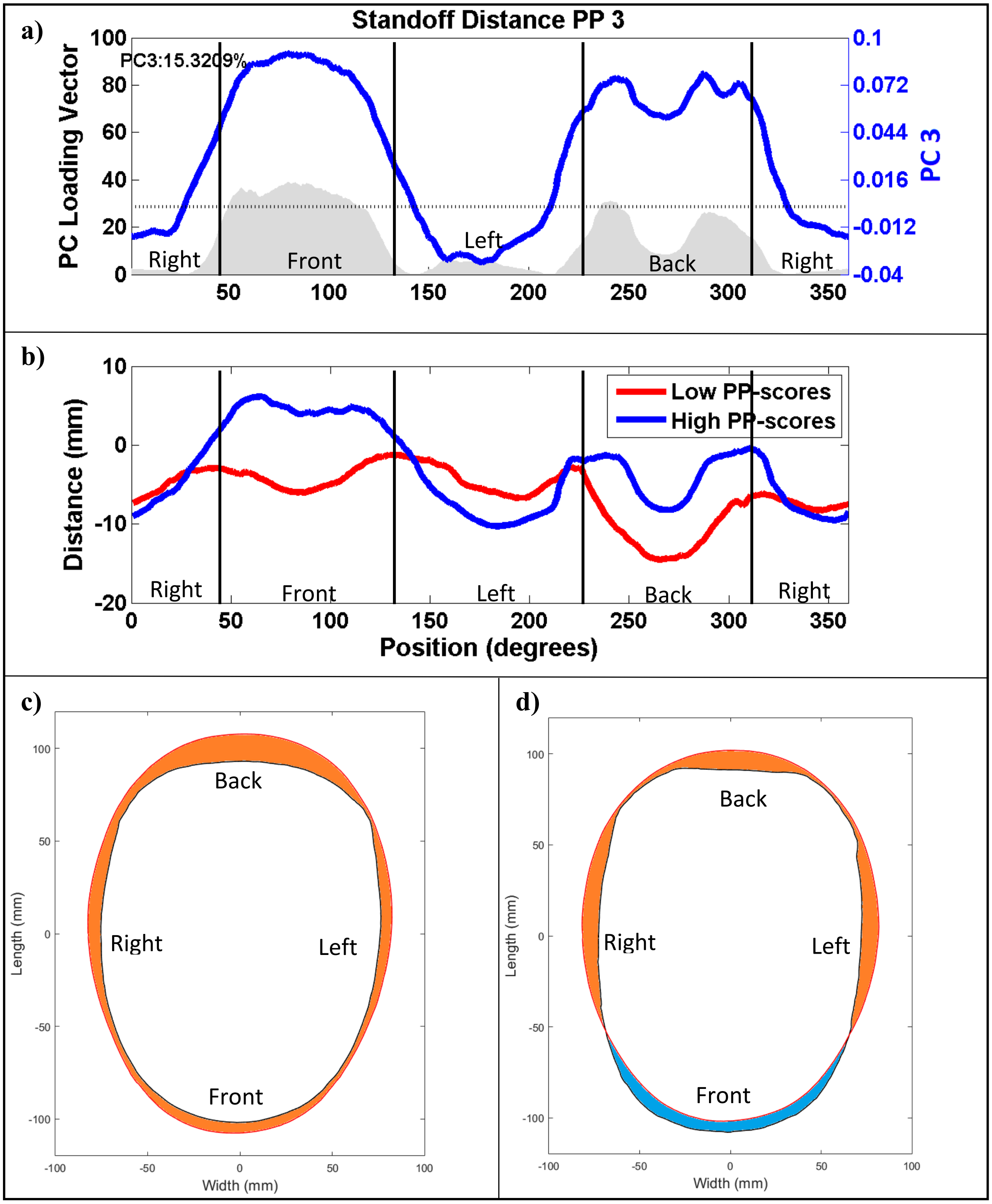


Fig. 18 Principal component 3: a) eigen vector (PC3) represented in blue, variance in the principal component in grey; b) polar coordinate representations of 5^{th} and 95^{th} percentile PC3 Z-scores; c) Cartesian representation of 5^{th} percentile PC3 Z-score, orange marks areas of overlap, blue marks gap regions; d) Cartesian representation of 95^{th} percentile PC3 Z-score, orange marks areas of overlap, blue marks gap regions.

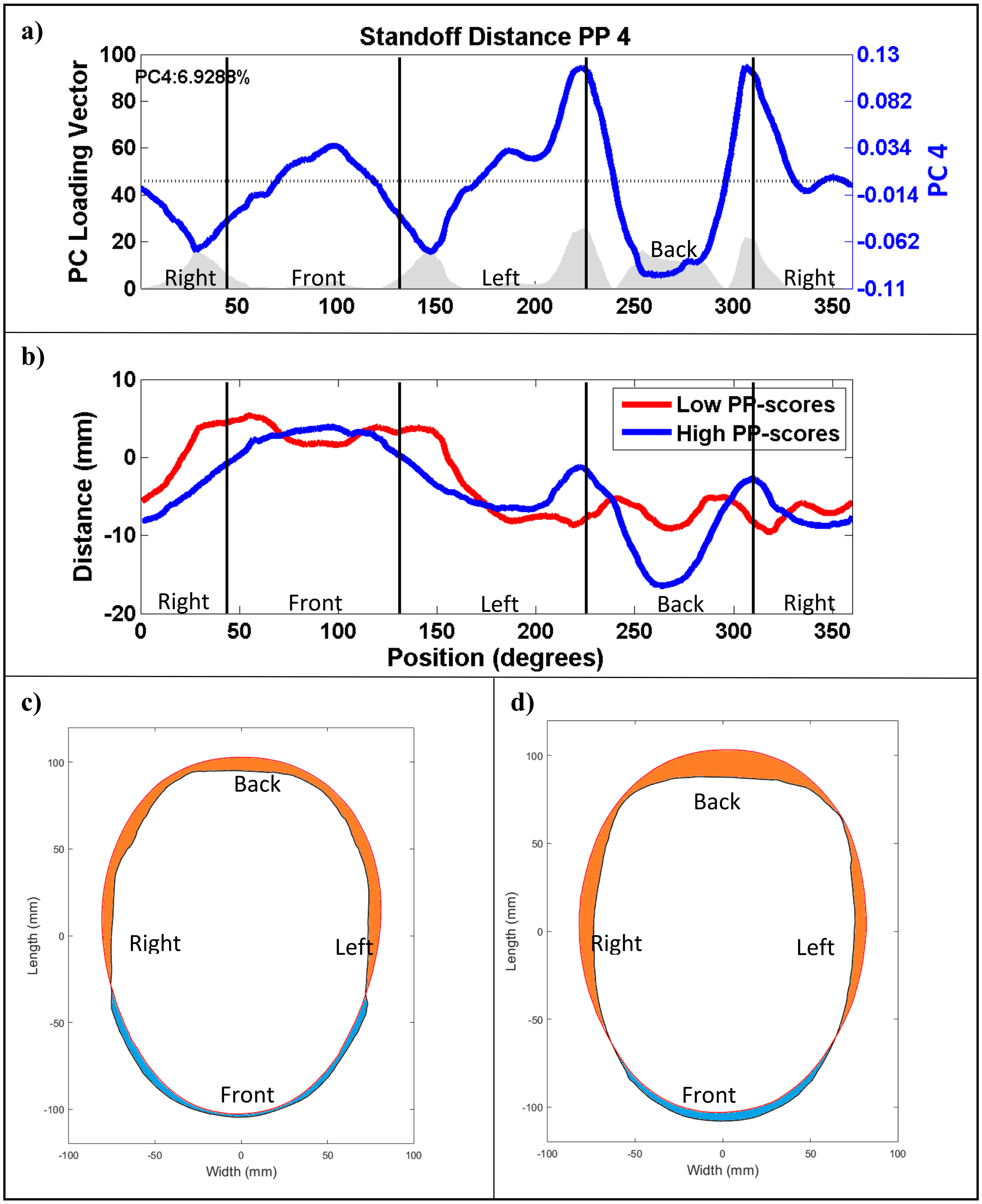


Fig. 19 Principal component 4: a) eigen vector (PC4) represented in blue, variance in the principal component in grey; b) polar coordinate representations of 5th and 95th percentile PC4 Z-scores; c) Cartesian representation of 5th percentile PC4 Z-score, orange marks areas of overlap, blue marks gap regions; d) Cartesian representation of 95th percentile PC4 Z-score, orange marks areas of overlap, blue marks gap regions.

Significant differences were found between the mean PC Z-scores for helmet models (fig. 20):

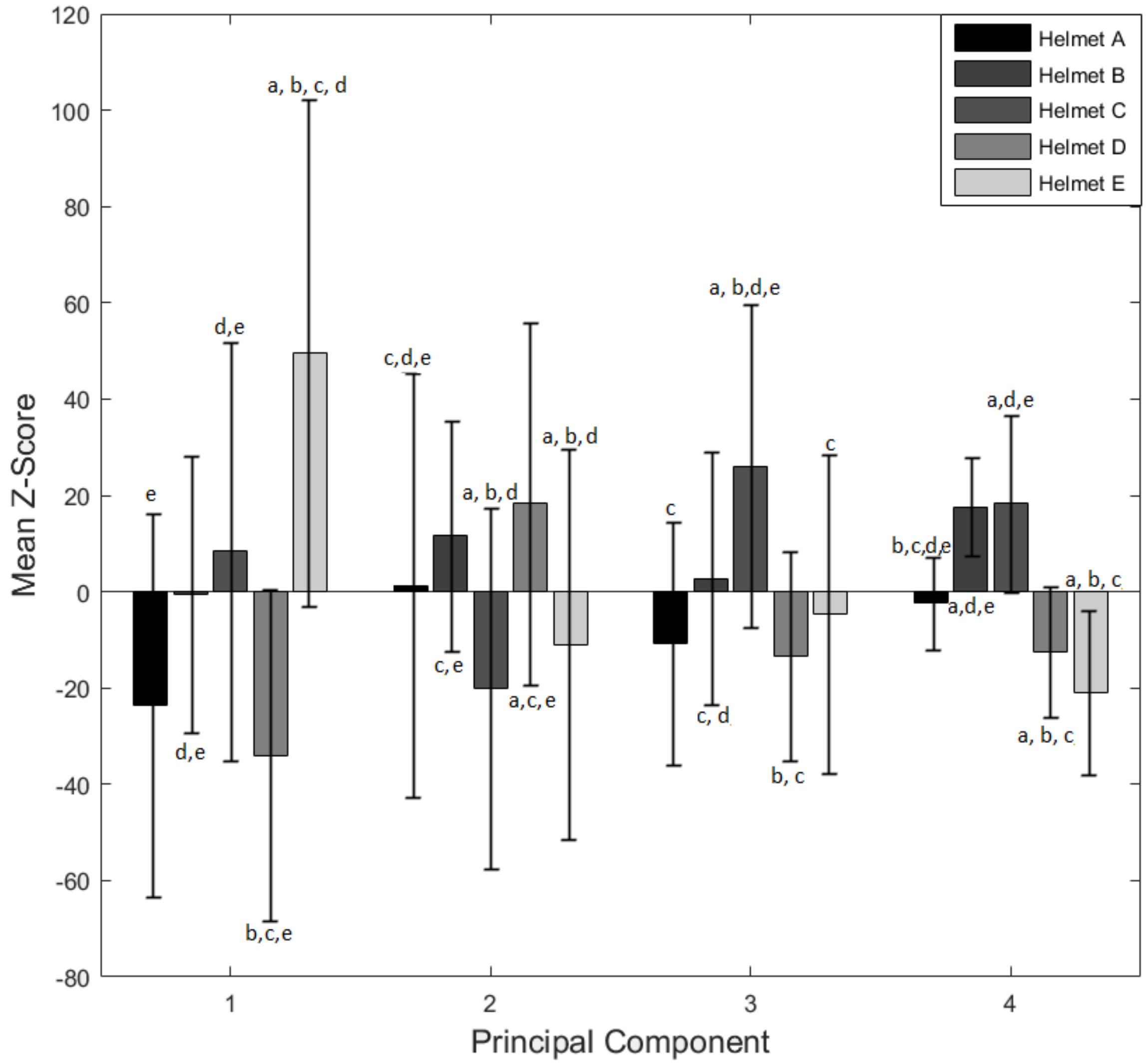


Fig. 20 Mean Z-Scores for principal components by helmet. Significant differences ($p < 0.05$) are denoted by lowercase letters indicating the helmets from which the mean Z-score differs.

3.5 Discussion

This study had two objectives: 1) to develop a protocol for the collection of high resolution 3D models of heads, helmets and head-helmet combinations, and 2) to compute the relative fit geometry between the head's cranium and that of the inner concave helmet surface. Building from works of other research groups on helmet fit, these objectives were achieved [8,60]. Methodological improvements yielded high precision in individual participant head-to-helmet fit descriptions as well as a means to identify group traits of regional head-to-helmet interaction about the principal plane of the head. A third objective was to run a small case study using this fit analysis method on a group of 30 adult males comparing 5 different hockey helmet models, and then to compare these quantitative measures to participants' qualitative perceptions of fit. Collectively, the above results offer new insights on how to quantify and interpret helmet fit. The following sections will explore the merits and limitations of this approach to discern head-to-helmet fit, as well as offer a functional interpretation of the fit traits derived.

3.5.1 3D Model of Helmet-to-Head Alignment

The novel helmet fit analysis method used in this study was the first system to record high-resolution helmet-to-head alignment, estimated foam compression (negative DD), as well as the method's repeatability errors. The 3D model meshes generated had incredible resolution, capable of rendering minute contour details of the complex padding configuration within the helmet interiors. Our methods measured the interface fit between the head and helmet lining of ice hockey helmet, whereas in the study by Ellena et al. [60], the analysis of fit was between the head with respect to the protective shell of a bicycle helmet. The one-time impact energy dissipating materials and shell of a bicycle helmet are one-and-the-same structure that is not in direct contact with the head during regular use; rather, an intermediate suspension mechanism about the head's surface is used. For ice hockey helmets, much of the energy dissipation occurs in the multiple impact energy dissipating foams of the helmet liner that are in direct contact with the user's head.

For ice hockey helmet fit stability, there must be compression of the inner foam for friction to anchor the helmet to the user's head. However, in another ice hockey helmet study, they stated the contrary assumption: that if the outer head boundary exceeded the inner helmet liner (i.e. foam compression) then the helmet did not fit [8]. This misconception likely occurred because Cai et al. used virtual fitting routines of separate helmet and head shape models; in our study, the additional helmet-to-head model scan revealed that negative DD (i.e. foam compression and shell deformation) is actually present. The resolution of the 3D models used in this study as well as the direct alignment measures of helmets to the head's principal plane are major improvements in this study.

3.5.2 Case Study

It was expected that subjective fit scores and DD measures would be related. This, however, was not found. In the one instance of width measures, some relation between subjective perception of helmet fit tightness and lower DD (more compression) was observed. Further, helmet C scored subjectively tighter in width fit than helmets A and D ($p < 0.05$), which corresponded to DD measures. Helmets were all adjustable in length but not in width, so as expected, the length fit had minimal effect on "perfect" subjective fit scores. The poor correlation between geometrical fit and subjective fit scores may be due to many factors: the varied personal preference, experience wearing helmets, and the perception of different material properties (e.g. stiffness) of each helmet model of participants. Additionally, it may be that the range of DD differences were too small to observe tactile pressure "tightness" or "looseness", or that the DD in other planes (not measured) varied substantially, which skewed fit perceptions.

For the perception of fit scoring, the participants had to recall their personal habitual experiences of wearing helmets to assign scores to each helmet. This limits the consistency of the results. For example, a participant who has a very narrow head may assign a width fit score of "perfect" even if there is no contact with the lateral portions of their head due solely to the fact that they have never worn a helmet which contacts that region. If a participant who has a very wide head had no contact in the lateral regions of their head, they would be more likely to rate the helmet at "slightly loose" or even "too loose". The helmets used in this study also ranged in foam properties, in particular the foam stiffness and thickness. The plastic shells of the helmets also have different properties and may deform differently under the same forces. The difference of the helmet's material properties will change the pressures associated with the areas of negative DD. Helmets of different properties may feel to be more or less anchored to the head due to the differences in these properties and in DD.

Lastly, the window of DD was extremely small: the median distribution of the DD for all fit scores were within 2.5 mm. Yet, perception scores were quite variable within and between participants. For example, some participants would score one helmet fit "perfect" and another helmet "slightly loose" despite the latter leaving visible transient skin depression marks on their forehead from that same helmet. In other cases, participants rated the helmets to be a "perfect" fit, although it was visibly loose enough to shift unintentionally. Other subjective factors may come into play; for example, many participants commented that they believed that they preferred their helmet to fit tighter or looser than other players, that they believed that they did not wear their helmets in the safest way, and that what they assumed was the "proper fit" was uncomfortable. Hence, given the small DD window in combination with highly variable preference criteria within and between participants, it is not surprising that these two variables correlated weakly.

3.5.3 Principal Component Analysis of Fit

Given the poor inter-relation found between width, length, average DD and fit perceptions described above, a more detailed analysis was pursued that evaluated the profile of DDs around the full 360° circumference of the head's principal plane. This involved the use of principal component analysis (PCA). Indeed, PCA extracted four principal components that accounted for 85% of the variability in DD within the principal plane. This finding alone suggests the promising use of PCA to describe fit using continuous data rather than the discrete DD measures, and offers a much richer depiction of helmet fit.

PC1 represents the amount of compression in the rear region of the head and the amount of front gapping, as well as how well the helmet contours the head in the principal plane (refer to fig. 16). The variability of this component stems from the different shapes of the helmet interiors, and may also be influenced by the different compression properties of the head and helmet (helmet foams, hair at the back of the head, etc.). Participants who wore the helmets greatly tilted upward would have different areas of the helmet in contact with their forehead, and this may be another cause of the variation in PC1. Seeing that there were differences between helmet models for their Z-score in PC1 may show that some helmets made contact (or anchored) with the front of the head in the principal plane, but others made contact (anchored) in another plane, thus leaving small gaps in the front region of the principal plane.

PC2 represent the absolute magnitude of DD in the lateral regions of the principal plane (refer to fig. 17). From our subjective fit scores, the width fit carried the highest variability in scores. This relates well as PC2 accounts for a relatively large proportion (24%) of the DD variability. Indirectly, PC2 explains the difference in head width, as ice hockey helmets are generally not laterally adjustable. In contrast, PC3 measures the absolute magnitude of the front and back regions of the principal plane (refer to fig. 18) and accounts for a smaller portion of the DD variability (15%). To explain the difference in these variabilities is simple: ice hockey helmets do have adjustable lengths, allowing the user to personalize the fit in the front and back regions, thus leading to a smaller variability in length fit as compared to width fit. PC4 corresponded to the uniformity and the congruency of the head and helmet in the rear region of the head, or more specifically the difference in the DD of the rear of the head compared to the rear lateral boss (refer to fig. 19). Scoring differently in this component, fit may lead to the reduction of pressure points in the rear region of the head leading to a more comfortable fit for the user.

Helmets A and B were chosen as the favourite helmet by the participants ten and nine times respectively, out of 30 participants. These two helmets were quite similar in PC Z-scores and only significantly differed in PC4 Z-scores (see fig. 20). Helmets A and B were overall the most similar in PC Z-scores. It may be inferred that the shapes of the liners of helmets A and B may be lead to the preferred fit for most head shapes.

3.5.4 Limitations

The main errors in this 3D shape analysis of helmet-to-head fit were relatively small, and primarily due to the sum of the rendering/scaling and the alignment errors. Further research to minimize these errors would further improve the analysis method’s precision. The rendering/scaling error may be reduced by having an improved scale setting method for the high-resolution head models. As stated in the methods, the scale was set by using the head length. The landmarks used for the physical measurement were broad which leads to variation in setting the scale. If markers were placed on the participant at a set distance or calipers were attached securely to the participant, the consistency of the scaling would increase, thus decreasing the rendering/scanning error, which is the largest error in the system.

There are many feasible improvements to reduce the alignment error. First, rather than using the lower-resolution video for the intermediate collections, the same high-resolution method that was used for the acquisition of the participant's head should be considered. The higher resolution models have more pronounced landmarks which allow for easier alignment in MeshLab using point based alignments. However, the time per scan would be drastically increased by a factor of 3 to take photos compared to video. To compensate, it would be a simple task to create a multi-camera setup where there are 3 cameras (one at each camera height position) that acquire photos in unison. This would allow for the participant to complete only one full rotation rather than three times with different camera heights; thus, reducing recording time by a factor of 3. Further, using higher quality cameras that can take photos at a higher resolution may be used to further increase the resolution of each render, improving alignment precision. Though these setups and even more elaborate setups using upwards of 120 cameras are available, these custom rigs are very expensive.

Variation for PC1 may also be due to the small amount of alignment error in the system. The front region of the helmet was in contact with the skin of the forehead, a region with negligible hair, whereas the rear region of the helmet was in contact with the region of the head with the most hair. The compressibility of the hair is higher than that of the skin and therefore DD values in the front and back regions of the head may not actually correspond to similar pressures exerted on the head.

This study was delimited by analyzing one two-dimensional plane of helmet and head interaction, but to gain a more complete picture of fit, analysis must be done in three-dimensions. This study delimited the helmet point clouds as rigid, though the helmet shell may too deform due to the outward compression of the foams under head regions, causing buckling of the plastic shell of the helmet.

3.5.5 Future Direction

This study analyzed geometrical fit in a two-dimensional plane for males. The obvious next step is to expand the analysis to describe the fit of ice hockey helmets for males, females, and children using three-dimensional PCA and to determine which principal components define the three-dimensional fit of ice hockey helmets. Furthermore, having foams that are pre-compressed changes the protective capacity of the helmets. During standards testing, helmet foams are pre-compressed when the helmet is put onto test headform, and the impact dissipation standards must be met for that combination. However, in practice, the users' heads may pre-compress the foams in a different manner than was tested, under which the helmet's performance on the standard impact tests may change. There should be work that analyzes how energy dissipation changes for a given ice hockey helmet protecting different head shapes (i.e. under different amounts of pre-compression). With that, optimal fit parameters (Z-scores for the PC) may be found in terms for the main purpose of ice hockey helmets: head injury prevention.

3.6 Conclusion

Helmet fit is important in terms of optimizing player's comfort and head impact protection that occur during a hockey game or practice. Developing a method to quantify ice hockey helmet fit as well as interpreting these fit measures were not a trivial problem. Photogrammetry proved to be a cost-effective way to assess three-dimensional shapes of the head and helmet. This study succeeded in creating a helmet fit analysis method that replicates the helmet to head orientation. Further, the Principal Component Analysis provided a novel means to evaluate the circumferential helmet to head dimensional difference curves. However, contrary to our hypothesis, subjective fit measures varied greatly due to individual preferences and previous experiences and were not correlated to quantitative geometric measures.

3.7 Acknowledgements

The authors would like to thank Dr. Shawn Robbins for his help with the principal component analysis as well as Brian McPhee for allowing his 3D models to be depicted in this work.

4. References

1. Kelly KD, Lissel HL, Rowe BH, Vincenten JA, Voaklander DC (2001) Sport and recreation-related head injuries treated in the emergency department. Clinical Journal of Sport Medicine 11 (2):77-81
2. Black AM, Sergio LE, Macpherson AK (2017) The epidemiology of concussions: number and nature of concussions and time to recovery among female and male Canadian varsity athletes 2008 to 2011. Clinical Journal of Sport Medicine 27 (1):52-56
3. ASTM (2007) F1045-07 Standard performance specification for ice hockey helmets.
4. CSA (2009) Z262.1-09 Ice hockey helmets. Canadian Standards Association,
5. Pearsall DJ, Wall RE, Hoshizaki BT (2000) Comparison of international safety standards for ice hockey helmets. In: Safety in Ice Hockey: Third Volume. ASTM International,
6. Rowson S, Duma SM (2013) Brain injury prediction: assessing the combined probability of concussion using linear and rotational head acceleration. Annals of biomedical engineering 41 (5):873-882
7. Rowson S, Brolinson G, Goforth M, Duma S, Dietter D (2009) Linear and angular head acceleration measurements in collegiate football. Journal of biomechanical engineering 131 (6):061016
8. Cai X, Blostein D, Saunders FW A shape-based helmet fitting system for concussion protection. In: Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE, 2015. IEEE, pp 4615-4618
9. Witana CP, Feng J, Goonetilleke RS (2004) Dimensional differences for evaluating the quality of footwear fit. Ergonomics 47 (12):1301-1317
10. Schmitt K-U, Zürich PFNE, Muser MH, Walz F (2009) Trauma Biomechanics: Accidental injury in traffic and sports. Springer Science & Business Media,
11. Qureshi NH, Harsh G (2015) Skull Fracture. Medscape,
12. Aldman A (1984) A method for the assessment of the load distributing capacity of protective helmets. Chalmers University of Technology, Goteborg
13. Melvin JW, Lighthall JW (2002) Brain-injury biomechanics. In: Accidental Injury. Springer, pp 277-302
14. Sawauchi S, Murakami S, Ogawa T, Abe T (2007) [Mechanism of injury in acute subdural hematoma and diffuse brain injury: analysis of 587 cases in the Japan Neurotrauma Data Bank]. No shinkei geka Neurological surgery 35 (7):665-671
15. Nahum AM, Melvin JW (2012) Accidental injury: biomechanics and prevention. Springer Science & Business Media,
16. Goggio A (1941) The mechanism of contre-coup injury. Journal of neurology and psychiatry 4 (1):11
17. Ward C, Chan M, Nahum A (1980) Intracranial pressure–a brain injury criterion. SAE Technical Paper,
18. King AI, Yang KH, Zhang L, Hardy W, Viano DC Is head injury caused by linear or angular acceleration. In: IRCOBI conference, 2003. pp 1-12
19. Anderson R, McLean J (2005) Biomechanics of closed head injury. Head injury Pathophysiology and management Hodder Arnold, London:26-40
20. Purcell L, Carson J (2008) Sport-related concussion in pediatric athletes. Clinical pediatrics 47 (2):106-113
21. Rousseau P, Post A, Hoshizaki T (2009) The effects of impact management materials in ice hockey helmets on head injury criteria. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology 223 (4):159-165
22. Willer B, Leddy JJ (2006) Management of concussion and post-concussion syndrome. Current Treatment Options in Neurology 8 (5):415-426
23. Williamson I, Goodman D (2006) Converging evidence for the under-reporting of concussions in youth ice hockey. British journal of sports medicine 40 (2):128-132
24. McCrea M, Hammeke T, Olsen G, Leo P, Guskiewicz K (2004) Unreported concussion in high school football players: implications for prevention. Clinical Journal of Sport Medicine 14 (1):13-17

25. Llewellyn T, Burdette GT, Joyner AB, Buckley TA (2014) Concussion reporting rates at the conclusion of an intercollegiate athletic career. Clinical Journal of Sport Medicine 24 (1):76-79
26. Langlois JA, Rutland-Brown W, Wald MM (2006) The epidemiology and impact of traumatic brain injury: a brief overview. The Journal of head trauma rehabilitation 21 (5):375-378
27. Ruhe A, Gansslen A, Klein W (2014) The incidence of concussion in professional and collegiate ice hockey: are we making progress? A systematic review of the literature. Br J Sports Med 48 (2):102-106. doi:10.1136/bjsports-2012-091609
28. Cantu RC (1998) Second-impact syndrome. Clinics in sports medicine 17 (1):37-44
29. Control CfD, Prevention (1997) Sports-related recurrent brain injuries—United States. International journal of trauma nursing 3 (3):88-90
30. McCrory P, Meeuwisse W, Johnston K, Dvorak J, Aubry M, Molloy M, Cantu R (2009) Consensus statement on Concussion in Sport–the 3rd International Conference on Concussion in Sport held in Zurich, November 2008. South African Journal of Sports Medicine 21 (2)
31. Sasaki T, Pasternak O, Mayinger M, Muehlmann M, Savadjiev P, Bouix S, Kubicki M, Fredman E, Dahlben B, Helmer KG, Johnson AM, Holmes JD, Forwell LA, Skopelja EN, Shenton ME, Echlin PS, Koerte IK (2014) Hockey Concussion Education Project, Part 3. White matter microstructure in ice hockey players with a history of concussion: a diffusion tensor imaging study. J Neurosurg 120 (4):882-890. doi:10.3171/2013.12.JNS132092
32. Caron JG, Bloom GA, Johnston KM, Sabiston CM (2013) Effects of multiple concussions on retired national hockey league players. Journal of sport & exercise psychology 35 (2):168-179
33. De Beaumont L, Lassonde M, Leclerc S, Théoret H (2007) Long-term and cumulative effects of sports concussion on motor cortex inhibition. Neurosurgery 61 (2):329-337
34. Stern RA, Riley DO, Daneshvar DH, Nowinski CJ, Cantu RC, McKee AC (2011) Long-term consequences of repetitive brain trauma: chronic traumatic encephalopathy. PM&R 3 (10):S460-S467
35. Schwartz D (2011) Are NHL enforcers' addictions, depression a result of on-ice brain trauma?: A Q&A with neurosurgeon Robert Cantu who studies the brains of dead athletes. Accessed 20/4 2016
36. Daneshvar DH, Baugh CM, Nowinski CJ, McKee AC, Stern RA, Cantu RC (2011) Helmets and mouth guards: the role of personal equipment in preventing sport-related concussions. Clinics in sports medicine 30 (1):145-163
37. Clark JM, Post A, Hoshizaki TB, Gilchrist MD (2016) Protective capacity of ice hockey helmets against different impact events. Annals of biomedical engineering 44 (12):3693-3704
38. Murray TM, Livingston LA (1995) Hockey helmets, face masks, and injurious behavior. Pediatrics 95 (3):419-421
39. Dolan E, Kriz P (2016) Protective Equipment. In: Head and Neck Injuries in Young Athletes. Springer, pp 13-26
40. Newman JA (2015) Design and Testing of Sports Helmets: Biomechanical and Practical Considerations. In: Accidental Injury. Springer, pp 755-768
41. Pearsall DJ, Lapaine P, Ouckama R (2016) Ten years later: Ice hockey helmet impact mechanics change with age. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology 230 (1):23-28
42. Pearsall D, Dowler P A Longitudinal Study of Ice Hockey Helmet Shelf Life. In: Fifth International Symposium on Safety in Ice Hockey, 2009. ASTM International,
43. Pearsall DJ, Hakim-Zadeh R (2002) Durability of Ice Hockey Helmets to Repeated Impacts.
44. Bishop PJ, Norman RW, Kozey JW (1984) An evaluation of football helmets under impact conditions. The American journal of sports medicine 12 (3):233-236
45. Guo F, Wang L, Dong D (2009) Human head 3D dimensions measurement for the design of helmets. In: Digital Human Modeling. Springer, pp 624-631

46. Lemair M, Pearsall D (2007) Evaluation of impact attenuation of facial protectors in ice hockey helmets. Sports Engineering 10 (2):65-74
47. Rowson B, Rowson S, Duma SM (2015) Hockey STAR: a methodology for assessing the biomechanical performance of hockey helmets. Annals of biomedical engineering 43 (10):2429-2443
48. Ouckama R, Pearsall D (2014) Projectile impact testing of ice hockey helmets: Headform kinematics and dynamic measurement of localized pressure distribution. IRCOBI Proceedings:62-71
49. Post A, Karton C, Blaine Hoshizaki T, Gilchrist MD, Bailes J (2016) Evaluation of the protective capacity of baseball helmets for concussive impacts. Computer methods in biomechanics and biomedical engineering 19 (4):366-375
50. Guskiewicz KM, Mihalik JP (2011) Biomechanics of sport concussion: quest for the elusive injury threshold. Exercise and sport sciences reviews 39 (1):4-11
51. Jadischke R, Viano DC, Dau N, King AI, McCarthy J (2013) On the accuracy of the Head Impact Telemetry (HIT) System used in football helmets. Journal of biomechanics 46 (13):2310-2315
52. Pheasant S, Haslegrave CM (2016) Bodyspace: Anthropometry, ergonomics and the design of work. CRC Press,
53. Ball R, Shu C, Xi P, Rioux M, Luximon Y, Molenbroek J (2010) A comparison between Chinese and Caucasian head shapes. Applied ergonomics 41 (6):832-839
54. Au EYL, Goonetilleke RS (2007) A qualitative study on the comfort and fit of ladies' dress shoes. Applied Ergonomics 38 (6):687-696
55. Weerasinghe TW, Goonetilleke RS, Signes GS (2012) Why the optimal fitting of footwear is difficult. Advances in Affective and Pleasurable Design:371
56. Cook CS, Kilgore B, Meschter J (2007) Custom fit system with adjustable last and method for custom fitting athletic shoes. Google Patents,
57. Cook CS (2005) System and method for sizing footwear over a computer network. Google Patents,
58. Choi HJ, Zehner GF, Hudson JA (2009) A manual for the performance of protective equipment fit-mapping. DTIC Document,
59. Meunier P, Tack D, Ricci A, Bossi L, Angel H (2000) Helmet accommodation analysis using 3D laser scanning. Applied Ergonomics 31 (4):361-369
60. Ellena T, Subic A, Mustafa H, Pang TY (2016) The Helmet Fit Index–An intelligent tool for fit assessment and design customisation. Applied ergonomics 55:194-207
61. Wu J, Li Z, Niu J (2009) A 3D Method for Fit Assessment of a Sizing System. In: Digital Human Modeling. Springer, pp 737-743
62. Ball R (2009) 3-D design tools from the SizeChina project. Ergonomics in Design 17 (3):8-13
63. Cavalcanti M, Rocha S, Vannier M (2014) Craniofacial measurements based on 3D-CT volume rendering: implications for clinical applications. Dentomaxillofacial Radiology
64. Collins DL, Neelin P, Peters TM, Evans AC (1994) Automatic 3D intersubject registration of MR volumetric data in standardized Talairach space. Journal of computer assisted tomography 18 (2):192-205
65. Schaaf H, Pons-Kuehnemann J, Malik C, Streckbein P, Preuss M, Howaldt H-P, Wilbrand J-F (2010) Accuracy of three-dimensional photogrammetric images in non-synostotic cranial deformities. Neuropediatrics 41 (01):24-29
66. de González AB, Mahesh M, Kim K-P, Bhargavan M, Lewis R, Mettler F, Land C (2009) Projected cancer risks from computed tomographic scans performed in the United States in 2007. Archives of internal medicine 169 (22):2071-2077
67. Böhler W, Marbs A 3D scanning and photogrammetry for heritage recording: a comparison. In: Proceedings of the 12th International Conference on Geoinformatics, 2004. Gavle University Press, Sweden, pp 291-298
68. AutoDesk® (2016) AutoDesk® ReMake Getting Started Guide. AutoDesk®,

69. Hassan EA, Jenkyn TR, Dunning CE (2007) Direct comparison of kinematic data collected using an electromagnetic tracking system versus a digital optical system. Journal of biomechanics 40 (4):930-935
70. Seel T, Raisch J, Schauer T (2014) IMU-based joint angle measurement for gait analysis. Sensors 14 (4):6891-6909

5. Appendices

Appendix A: Consent Form

Statement of Consent

I, ______________________________________, AGREE TO VOLUNTARILY PARTICIPATE IN THE STUDY DESCRIBED ABOVE ABOUT 3D ANALYSIS OF ICE HOCKEY HELMET FIT.

I HAVE RECEIVED AND READ A DETAILED DESCRIPTION OF THE EXPERIMENTAL PROTOCOL. I AM FULLY SATISFIED WITH THE EXPLANATIONS THAT WERE GIVEN TO ME REGARDING THE NATURE OF THIS RESEARCH PROJECT, INCLUDING THE POTENTIAL RISKS AND DISCOMFORTS RELATED TO MY PARTICIPATION IN THIS STUDY.

I am aware that I have the right to withdraw my consent and discontinue my participation at any time without any prejudices.

I consent, and wish to receive, a URL link to my online 3D Model ☐

SUBJECT

_____________________________________ _____________________________________

(Signature) (Print name)

RESEARCHER

_____________________________________ _____________________________________

(Signature) (Print name)

Date signed: ___________________________

INFORMATION AND CONSENT DOCUMENT
3D Analysis of Ice Hockey Helmet Fit

Investigators:	Daniel I Aponte, Ph.D. Student (Kinesiology)	daniel.aponte@mail.mcgill.ca
	David J Greencorn, M.Sc. Candidate (Kinesiology)	david.greencorn@mail.mcgill.ca
	Supervisor: David J Pearsall, Ph.D	david.pearsall@mcgill.ca

Ice Hockey Research Lab, Department of Kinesiology and Physical Education, McGill University

Statement of Invitation:
You are invited to participate in a research project conducted by the above-named investigators. This research project will be performed at the IHRG laboratory (Room 400, 475 avenue des Pins Ouest, Montreal, QC, Canada, H2W 1S4). You will be entered into a lottery with a 1 in 20 chance to win a $50 gift card, and a 3D file of your scanned head for your participation. You are asked to come to one experimental session that will last approximately 1.5 hours. We greatly appreciate your interest in our work.

Purpose of the Study

The purpose of this study is to determine the ideal fit parameters of ice hockey helmets. In particular, ideal fit parameters for any given head shape.

Your participation in this study involves:
1. Providing informed consent prior to the experimental session,
2. Providing data concerning your physical attributes, hockey experience, and hockey equipment usage (e.g., height, age, number of years playing ice hockey, highest level played, current helmet model, etc.)
3. Being photographed for the 3D models, and filling out fit and comfort questionnaires for each helmet.

Risks and Discomforts

It is anticipated that you will encounter no significant discomfort during these experiments. There is minimal risk associated with these experiments. You may, however, chose to withdraw from the study at any point during data collection.

Benefits

You will receive compensation for your participation in the form of a 3D file of your head scan and a 1 in 20 chance to win a $50 gift card. Benefits of this study may lead to a new helmet fitting system and a better understanding of the geometrical fit of hockey helmets on different head shapes.

Photographs

The technique used to build a 3D model of your head requires that we take multiple photographs of you at many different angles. These photographs will only be used to build 3D models of your head, and will not be used for any other purpose, or disseminated from this laboratory.

Confidentiality

All the personal information collected during the study you concerning will be encoded in order to keep their confidentiality. These records will be maintained at the Biomechanics Laboratory by Dr. David Pearsall for 7 years later the end of the project, and will be destroyed upon the expiration of this me frame. Only members of the research team will be able to access them. In case of presentation, your personal information will remain completely anonymous.

Dissemination of Results

The results of the study will be disseminated through an MSc thesis (Greencorn), PhD thesis (Aponte), journal publications and conference posters (if applicable), and in a formal report to Bauer Hockey Corp.

Sources of Funding

Currently, this study is funded by an NSERC Collaborative Research and Development Grant, in collaboration with the Bauer Hockey Corpora on.

Inquiries Concerning this Study

If you require information concerning the study (experimental procedures or other details), please do not hesitate to contact Daniel Aponte or David Greencorn at the address listed at the top of this document.

Responsibility Clause

In accepting to participate in this study, you will not relinquish any of your rights and you will not liberate the researchers nor their sponsors or the institutions involved from any of their legal or professional obligations.

Consent

Please be advised that your participation in this research undertaking is strictly on a voluntary basis, and you may withdraw at any me.

A copy of this form will be given to you before the end of the experimental session.

Appendix B: Pre-Screening Questionnaire

Date: ______________________________

Participant Information

Participant Information	
Participant #	
Age	
Highest Level Played	
Years of Experience	
Their Current Helmet Model	
Their Current Helmet Size	
Their Current Helmet Colour	

Anthropometrics	
Head Circumference (mm)	
Head Length (mm)	
Head Width (mm)	

Compressions	
Length Compression (mm)	
Width Compression (mm)	

Top Ranked Helmet Fit	
Helmet Code	

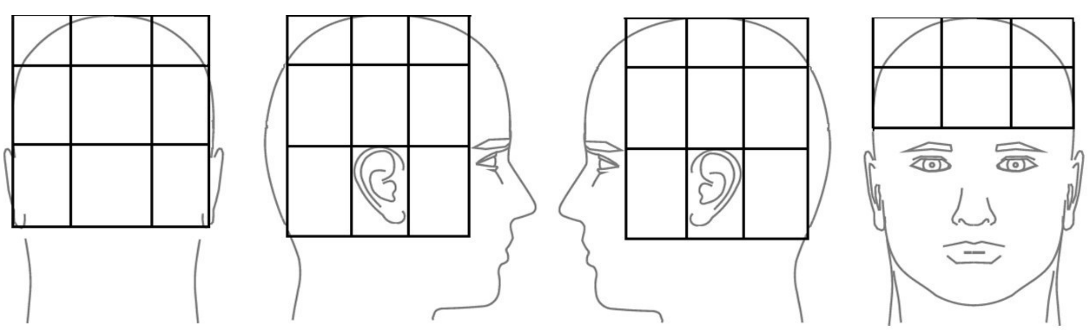
Appendix C: Helmet Fit Questionnaire

Participant: ___________________ **Date: ___________________**

Helmet Fit Questionnaire

Helmet Code: _____________ Order: _____ Size: _____ Adjustment: ____

Fit - Circle one of each							
Overall Helmet Fit	Too Loose	Loose	Slightly Loose	Perfect	Slightly Tight	Tight	Too Tight
Helmet Width Fit	Too Loose	Loose	Slightly Loose	Perfect	Slightly Tight	Tight	Too Tight
Helmet Length Fit	Too Loose	Loose	Slightly Loose	Perfect	Slightly Tight	Tight	Too Tight
Comfort | 1 = Very Poor, 4 = Neutral, 7 = Very Good							
Overall Comfort	1	2	3	4	5	6	7
Front Comfort	1	2	3	4	5	6	7
Back Comfort	1	2	3	4	5	6	7
Side Comfort (R)	1	2	3	4	5	6	7
Side Comfort (L)	1	2	3	4	5	6	7
Stability | 1 = Very Poor, 4 = Neutral, 7 = Very Good							
Overall Stability	1	2	3	4	5	6	7
Front/Back Stability	1	2	3	4	5	6	7
Side/Side Stability	1	2	3	4	5	6	7
Safety | 1 = Very Poor, 4 = Neutral, 7 = Very Good							
Perceived Safety	1	2	3	4	5	6	7



Appendix D: Distribution of Dimensional Differences by Fit Score

Overall fit score	N	Mean average DD	SD	Median overall SOD	Max average DD	Min average DD
-3	2	-3.7	1.2	-3.7	-2.9	-4.6
-2	3	-4.2	0.9	-4.7	-3.2	-4.8
-1	40	-3.4	2.3	-3.2	1.9	-8.4
0	50	-3.5	1.8	-3.4	0.9	-7.0
1	44	-3.1	2.0	-3.0	1.6	-8.0
2	9	-4.0	1.2	-4.3	-2.3	-5.7
3	2	-2.1	1.1	-2.1	-1.3	-3.0
Width fit score	N	Mean Width DD	SD	Median Width DD	Max Width DD	Min Width DD
-3	2	-3.2	0.9	-3.3	-2.7	-3.9
-2	8	-3.0	3.5	-4.0	2.4	-6.8
-1	39	-2.6	2.6	-2.7	2.7	-7.3
0	51	-4.3	2.5	-4.7	2.7	-9.9
1	39	-4.8	2.5	-5.0	3.6	-10.0
2	7	-5.4	2.6	-6.1	-1.1	-8.2
3	4	-6.2	1.9	-6.5	-3.7	-8.2
Length fit score	N	Mean length DD	SD	Median length DD	Max length DD	Min length DD
-3	0					
-2	3	-2.93	0.7	-3.2	-2.1	-3.4
-1	25	-2.82	3.1	-2.9	3.8	-9.3
0	69	-2.92	2.2	-2.9	1.0	-8.8
1	43	-2.83	1.8	-2.7	2.9	-6.6
2	7	-2.71	2.1	-1.8	-0.4	-5.9
3	3	0.49	0.6	0.6	1.1	-0.2