A PROTOTYPE HELMET FITTING SYSTEM
FOR CONCUSSION PROTECTION

by

Xingcheng Cai

A thesis submitted to the Graduate Program in Computing
In conformity with the requirements for
the degree of Master of Science

Queen’s University
Kingston, Ontario, Canada
January, 2015

Copyright ©Xingcheng Cai, 2015
Abstract

Helmets are widely used as protection against sports-related concussions. The degree of concussion protection offered by a helmet may be related to the fit between the helmet and head. This thesis discusses different approaches that could be used for helmet fitting, and presents the design and implementation of a prototype helmet fitting recommendation system. The prototype system uses a Kinect sensor to scan a client’s head and then compares the head shape to helmet shapes from a database of off-the-shelf helmets. A slice extraction method is used to compare a standard reference slice extracted from the head to a corresponding slice from the helmet. The degree to which the helmet fits the client’s head is calculated and displayed to the user. This thesis describes the scanning procedure that was conducted to obtain 3D head shapes from a number of participants, and reports results about the measured head and helmet shapes; results show there is significant variation in both head and helmet shapes. The prototype system could potentially help a concussion expert make recommendations about helmet fit to clients, if more research about the effects of helmet fitting on concussion protection becomes available.
Acknowledgements

I would like to thank my co-supervisor Dr. Dorothea Blostein, professor in the School of Computing, for her mentorship and support throughout my experience as a Master’s student. She put a lot of effort towards giving me advice on my thesis and helping me develop as a researcher. I would like to thank my co-supervisor Dr. Fraser Saunders, neurosurgeon in the Department of Surgery, for his mentorship and suggestions for my thesis including my research topic, and technical advice on helmets and concussions. I would also like to thank David Adams for his advice on scanning and providing the helmet scans, and Paul St. John for suggesting the idea of using pressure sensing strips.
Table of Contents

Abstract ................................................................................................................................. ii
Acknowledgements ........................................................................................................... iii
List of Figures ...................................................................................................................... vi
List of Tables ....................................................................................................................... viii
Chapter 1 Introduction ....................................................................................................... 1
  1.1 Contributions ............................................................................................................... 6
Chapter 2 Literature Review .............................................................................................. 7
  2.1 Helmets ....................................................................................................................... 7
    2.1.1 Comparison of Related Work with Our System ...................................................... 8
  2.2 Concussion Protection ............................................................................................... 10
  2.3 Existing Helmet Standards ...................................................................................... 11
Chapter 3 Design of Helmet Recommendation Systems ............................................... 13
  3.1 Types of Helmet Recommendation Systems ........................................................... 14
  3.2 Workflow of Helmet Recommendation Systems ....................................................... 16
  3.3 Scanning ...................................................................................................................... 23
    3.3.1 Kinect Sensor ........................................................................................................ 23
      3.3.1.1 3D Reconstruction and User Interaction with Kinect .................................. 25
      3.3.1.2 Pose Estimation using Kinect ................................................................. 27
    3.3.2 Other Scanning Methods .................................................................................... 27
  3.4 Data Types .................................................................................................................. 28
  3.5 Helmet Fitting ............................................................................................................ 30
    3.5.1 Slice Extraction Approach .................................................................................. 30
    3.5.2 Surface Registration Approach ......................................................................... 32
    3.5.3 Slice Sets Approach .......................................................................................... 35
    3.5.4 Fitting Using Pressure Regions ......................................................................... 36
      3.5.4.1 Measuring Pressure with Pressure Sensing Strips ..................................... 37
      3.5.4.2 Estimating Pressure Points Using Shape Data and Helmet Material Layers ... 38
  3.6 Results and Recommendations of Helmet Fitting ..................................................... 39
Chapter 4 Design and Implementation of the Prototype System ........................................ 42
  4.1 Design Using the Slice Extraction Approach .......................................................... 42
    4.1.1 Anatomical Landmarks for Locating Head Slices .............................................. 44
    4.1.2 Head Slice Location .......................................................................................... 45
List of Figures

Figure 1-1: (a) Head impact that results in linear acceleration. (b) Head impact that results in rotational acceleration. ........................................................................................................... 2

Figure 1-2: High-level overview of a helmet fitting recommendation system. ........................................... 5

Figure 2-1: The Kingston Impact Simulator (KIS) unit. ........................................................................... 12

Figure 3-1: Diagram showing the different categories and types of helmet recommendation systems. ..... 14

Figure 3-2: Design of a shape fitting helmet recommendation system using a slice extraction approach. 18

Figure 3-3: Design of a shape based helmet recommendation system using a surface registration approach. .................................................................................................................. 19

Figure 3-4: Design of a shape based helmet recommendation system using a slice sets approach. ....... 20

Figure 3-5: Design of a pressure fitting helmet recommendation system using a pressure sensing approach. .................................................................................................................. 21

Figure 3-6: Design of a pressure fitting helmet recommendation system using a pressure estimation approach. .................................................................................................................. 22

Figure 3-7: A Kinect sensor for XBox 360 which can act as a 3D scanner ........................................... 24

Figure 3-8: Close-up of a 3D helmet model represented as a mesh ........................................................... 28

Figure 3-9: Close-up of a 3D helmet model represented as a point cloud ................................................ 29

Figure 3-10: A typical head slice (left) and helmet slice (right). ............................................................... 31

Figure 3-11: The interior of a helmet with its foam liner layer ............................................................... 37

Figure 3-12: Measures of fit between the helmet and head ................................................................. 40

Figure 3-13: Alignment with posterior of the helmet fixed onto the posterior of the head ............... 41

Figure 4-1: A typical axial head slice (left) and axial helmet slice (right) ................................................. 43

Figure 4-2: Left (red): an axial slice. Middle (yellow): a sagittal slice. Right (green): a coronal slice. ..... 43

Figure 4-3: The position of two helmet slices ....................................................................................... 47

Figure 4-4: A slice taken after the helmet is manually placed on the head in Slicer ......................... 48

Figure 4-5: Components of the implementation of the prototype system ........................................... 53

Figure 4-6: Fiducials on the surface of the head .................................................................................. 57

Figure 4-7: Slice plane of the head that is defined by 3 fiducials. .............................................................. 57

Figure 4-8: The red slice viewer in Slicer, showing the extracted head slice and fiducials ....................... 58

Figure 4-9: Left: placement of 3 fiducials on the helmet. Right: the helmet slice plane generated from the fiducials .............................................................................................................. 59

Figure 4-10: Removing the outer boundary of the helmet slice ............................................................ 60
Figure 4-11: Left: A helmet slice with a gap due to missing data. Right: part of a slice boundary with gaps (missing pixels). ........................................................................................................................................61

Figure 4-12: Screenshot of the Helmet Fit Viewer program. ........................................................................................................64

Figure 4-13: Dragging the helmet in the head and helmet viewing panel. ........................................................66

Figure 4-14: Helmet alignment that shows a positive top AP distance and left lateral mismatches, and negative bottom AP distance and right lateral mismatches. This alignment also shows a positive coronal matching area. ...............................................................................................................................69

Figure 4-15: The head info tab of the information panel. ........................................................................................................71

Figure 4-16: Left: a minimal 4-connected diagonal line segment. Right: an 8-connected line segment. ...72

Figure 4-17: Converting an outline to a pixel segment matrix, then calculating the length from the midpoints of consecutive segments................................................................................................................72

Figure 4-18: Four pressure points on the CCM helmet.............................................................................................................74

Figure 5-1: Plot of head length vs. head width among the 15 heads in the database.................................................80

Figure 5-2: CCM helmet slice showing large coronal matching area .........................................................................................86

Figure 6-1: System that is automated for head, but semi-automated for helmet (not yet implemented). ...92

Figure 6-2: Fully automated commercial system (not yet implemented) .................................................................93

Figure A-3: Screenshot of Slicer showing an axial slice. ........................................................................................................99
List of Tables

Table 5-1: Intra-operative slice extraction measurements on Head #14. ................................................................. 77
Table 5-2: Summary of intra-operative slice extraction measurements on Head #14. .................................................. 77
Table 5-3: Helmet slice extraction measurements from the 3 helmets in the database................................................. 78
Table 5-4: Head slice extraction measurements on all 15 heads in database.............................................................. 79
Table 5-5: Summary of head slice extraction measurements on all 15 heads in database............................................. 80
Table 5-6: Standard deviations of measurements from the set of 15 head shapes vs. 9 intra-operative fiducial placement measurements (to 4 significant digits)................................................................................................................................. 81
Table 5-7: Differences between head circumference measurements from head slices obtained using 3D data, and physical measurements of the head. ........................................................................................................................................................................... 83
Table 5-8: Mean and standard deviation of head circumference measurements from tape measurements and Kinect scans (to 4 significant digits). ........................................................................................................................................................................ 83
Table 5-9: Head measurements from multiple scans of one participant............................................................................. 84
Table 5-10: Standard deviations of measurements from 6 scans of one participant, compared to the set of 15 head shapes and 9 intra-operative fiducial placement measurements (to 4 significant digits). .......... 85
Table 5-11: Measurements of helmet fitting comparing the head with the Bauer, Easton and CCM helmets. ........................................................................................................................................................................................................... 87
Chapter 1

Introduction

Concussions and head injuries are major health concerns that affect an estimated 300,000 people in the United States [10] and every 110 out of 100,000 Canadians annually [8]. Some researchers believe that many concussions go underreported and that there are approximately 1.8 million to 3.6 million sports-related traumatic brain injuries (TBIs) annually in the United States, most of which are concussions [20]. Helmets are widely used as protection against sports-related head injuries, but it is not well understood how effective helmets are at preventing concussive injuries. The initiative to reduce the incidence of concussions in sports has resulted in rule changes, arena construction changes, player awareness initiatives and better equipment. Helmets are one aspect of this multifactorial approach.

At present, helmet testing and acceptance by standards organizations such as the Canadian Standards Association (CSA) is based on linear acceleration testing, which assesses helmets by their ability to reduce forces resulting from linear acceleration [27]. Concussions, on the other hand, are currently thought to be caused by rotational acceleration. Studies are ongoing regarding the impact of rotational acceleration on head injuries [18] [19], which may lead to new guidelines for helmets to protect against rotational acceleration as well as linear acceleration. Figure 1-1 shows a comparison of linear acceleration versus rotational acceleration.

The mechanism in which a helmet reduces rotational acceleration may be related to its size and shape compared to each individual’s head, materials such as foam layers, and pressure points. These are all aspects that may be considered during helmet fitting.
Today, consumers who purchase athletic and recreational helmets, including hockey helmets, generally select helmets subjectively based on perceptions such as appearance, comfort and brand name, or by simply trying on a helmet. Consumers that are more knowledgeable may refer to ratings from helmet impact tests, but these do not give information about rotational acceleration protection. There is need for a helmet recommendation system that can give customers an objective assessment of which helmets on the market are likely to offer the best concussion protection. This system should give more accurate and objective recommendations than the informal methods customers currently use to choose helmets.

Helmets can be recommended based on their helmet fit. Currently, hockey helmets are purchased with little instruction as to how they fit; typically, the instructions are to put on the helmet so that it is tight across the forehead and does not shake with head movement. Unfortunately, this may not be ideal for rotational acceleration protection. The tighter the fit, the more force is transmitted to the skull and brain. However, a helmet that is too loose may obscure vision and result in other

Figure 1-1: (a) Head impact that results in linear acceleration. (b) Head impact that results in rotational acceleration [13]. Permission for figure reproduction obtained from Copyright Clearance Center (copyright.com).
injuries. Little is currently known about concussion prevention and force transmission to the head, but a helmet that is too tight or too lose would be inherently a bad fit.

Since all heads are of different shapes and each helmet has a different interior structure, a helmet recommendation system that measures a client’s head and matches it to existing helmets would be an advantage over how consumers currently choose helmets, since it would offer some objective basis for helmet purchase decisions.

Our objective is to design a **helmet recommendation system** that recommends the best fitting helmet to a client (customer) after the client’s head is scanned using a Kinect sensor which produces a 3D model of the head. The system matches the client’s head shape to helmet shapes from a database containing information from a selection of off-the-shelf helmets, and finally outputs information about helmet fit for the client. The client can receive an evaluation from this system that offers some objective basis for helmet purchase decisions based on concussion reduction, and can use this evaluation along with trying on helmets to make a decision about which helmet to purchase. (Figure 1-2)

This thesis describes the design and implementation of a **prototype helmet recommendation system** that demonstrates helmet fitting without fully automating all of the steps. This prototype is geared towards helping a concussion researcher formulate recommendations about helmet fit. This system extracts 2D slice images from 3D scans of a number of helmets along with the scan of a person’s head. It aligns each helmet to the head to determine the degree to which the helmet fits, and displays statistics that are of use to the researcher.
Currently, research still needs to be done on the effects of helmet fit on rotational acceleration. A commercial helmet recommendation system would only become viable when there is enough experimental evidence for a concussion researcher to be able to make recommendations.
Figure 1-2: High-level overview of a helmet fitting recommendation system.
1.1 Contributions

This thesis makes the following contributions:

1. Describe the overall design of a helmet recommendation system, including comparisons of different approaches to helmet fitting. (Chapter 3).

2. Create initial databases of head and helmet shapes for the prototype system, by scanning with a Kinect sensor and ReconstructMe software (Section 4.3).

3. Design and implement a helmet fitting recommendation system using a slice extraction approach.
   a. Sections 4.4 - 4.5 define the method that is used for extracting head and helmet slices.
   b. Section 4.6 describes the implementation of Helmet Fit Viewer, a program that allows a user to select a head slice and compare its shape to helmet slices in the database, and view statistics indicating the degree of fit between the head and helmet.

4. Test the accuracy and repeatability of the slice extraction method (Sections 5.1 - 5.2).

5. Measure the shape differences between head slices and between head and helmet slices (Sections 5.3 - 5.4).
Chapter 2

Literature Review

This chapter provides a survey of related work pertaining to helmet fitting, including comparisons to the prototype helmet fitting project reported in this thesis. There is also discussion of concussion research and the current status of testing standards for sports-related helmets.

2.1 Helmets

One problem which is often studied in literature is helmet sizing, where the goal is to identify a small number of standard helmet sizes that best represent a large proportion of the population. Meunier et. al. studied methods for the sizing of ballistic helmets for the Canadian Forces by using a 3D laser scanner to scan the heads of a number of subjects as well as the same subjects wearing a helmet that was thought to be their size according to manufacturer guidelines [23]. Each helmet by itself was also scanned. Nineteen facial landmarks were identified and marked on each subject by an expert, along with the head length and breadth. Head circumference was also measured, but was discarded since it was found to be highly correlated with head length. The researchers measured standoff distance — the distance between the inside of the helmet and skull — and helmets were defined to fit if the standoff distance was greater than 12.5 mm. The standoff distance was calculated at 13 points on the helmet. The distance of 12.5 mm was chosen because it was believed to allow enough air circulation for head cooling as well as protect against the effects of projectile impact. Results from the scanned 3D data were compared to physical measurements made by drilling a caliper through the helmet [23].
Meunier continued this research by developing a helmet sizing strategy for the AMMPHS (Advanced Modular Multi-threat Protective Headwear System), a new military helmet [22]. Using head length and breadth data from members of the Canadian Forces, principal component analysis was conducted to determine 3 representative head shapes which would allow the manufacture of 3 standard helmet sizes (small, medium, large). This was compared to the sizing of the existing Gallet helmet. The author noted that helmet geometry can be compared with different reference points: using the headband on the inside of the helmet as a reference point, which better reflects the wearer’s perspective, is different than placing different sized helmets concentrically.

Guo et. al. studied head modelling with the goal of producing standard headforms for helmet design [9]. Head scans were obtained using MRI (magnetic resonance imaging), and head slices were taken at 5mm intervals between the gnathion (bottom of jaw) and vertex (top of head). The boundary of each head slice was extracted and represented in polar coordinates where each point on the boundary is defined by its distance and angle from an origin at the centre of the slice. The boundary was then fit by the Fourier transform and represented as a mathematical model. Ten characteristic head slices were defined corresponding to anatomical landmarks. The authors proposed 9 standard headforms defined by 3 groups of head breadth / length and 3 groups of height / length aspect ratios.

2.1.1 Comparison of Related Work with Our System

Our helmet fitting system is similar in some ways to existing literature on head shape modelling and helmet sizing. Head shape data is collected using a 3D scanner (Kinect, in our case) and compared with helmet data. The differences include the following:
Most existing literature focus on *helmet sizing* as opposed to *helmet fitting* – the purpose is to find a small number of typical headforms in order to manufacture a small number of standard helmet sizes [9] [22] [23] [34]. Our goal is to determine how a helmet fits on a particular individual’s head. Note that this is not simply a matter of looking at a manufacturer’s size label and assuming it will fit on a head, as different helmets of a particular size will have different shapes, interior padding, etc.

Our project uses a Kinect sensor whereas other studies use other devices including higher-end 3D laser scanners, MRI and even CT [9] [23]. These produce more accurate scans than the Kinect, but since we have in mind a final system that can be used in a retail setting, it is important that the scanning device is familiar and comfortable to clients. Clients may find visible light lasers too intrusive (the Kinect only uses invisible infrared light) and medical imaging procedures such as MRI are far too expensive and not portable.

Most existing studies are focused on military or aviation helmets, while our system focuses on athletic helmets for sports such as football and hockey [22] [23] [34]. The helmets used in our prototype system are all hockey helmets. Military and aviation helmets have different considerations such as projectile impact and often cover the jaw and side of the head, while our focus is concussive head injuries to the cranium.

Positioning of the head was often less of a concern in existing studies. Some studies used MRI where subjects lie in a supine position, and therefore head orientation would not vary. Others assumed the head was oriented horizontally [9]. In this thesis, subjects were scanned in a sitting position and head orientation varied; Section 4.4 describes how this is taken into account during head slice extraction.
2.2 Concussion Protection

Concussions are the most common form of traumatic brain injury (TBI) and are also known as mild traumatic brain injury (MTBI) [7]. Helmets are used as protection against TBI in situations where there is an elevated risk of injury, including in sports and recreational settings such as hockey, football and cycling. Helmets have been shown to reduce the risk of major traumatic brain injury, in particular from skull fracture. They are also effective in reducing head impact forces and recovery time from injuries. However, there is little evidence that helmets are effective in protecting against concussions, and reported concussions are becoming more frequent despite the increasing widespread use of helmets in professional and amateur sports [11] [15].

The exact mechanisms under which concussions occur is not well known, but some researchers have suggested that head rotation and movement are a contributing factor towards concussive injuries [18] [19]. Some studies have found, using physical and finite element models, that there is a relationship between rotational acceleration and brain tissue strains which cause concussions [31], although both linear and rotational acceleration are involved in causing strains [17].

Finite element models of the brain are one technique used to simulate traumatic brain injuries, including concussions. The Wayne University Head Injury Model (WSUHIM) is one finite element model that is used to study brain response from head impact. It can assess predictive factors for concussions, such as from head collisions in the National Football League (NFL) [35]. It found that concussions occur during the rapid rotation and displacement of the cranium [33].
2.3 Existing Helmet Standards

Currently, hockey helmets are subject to linear acceleration tests under the auspices of the National Operating Committee on Standards for Athletic Equipment (NOCSAE) and the Canadian Standards Association (CSA). CSA certification is mandatory for all hockey helmets sold in Canada. These tests involve dropping a helmet fitted onto a phantom headform from a prescribed distance and measuring the linear acceleration from a single central accelerometer.

In 2013, Kis and Saunders et. al. developed the Kingston Impact Simulator (KIS), a system that provides a repeatable and precise technique to test the rotational acceleration of helmets [18]. The KIS uses a pneumatic piston that can deliver various amounts of impact forces, and measures rotational acceleration upon impact on both helmeted and unhelmeted headforms. The system records measurements at 12 impact locations on each headform, and measures rotational acceleration for each plane (horizontal or axial, sagittal, and coronal). The study found that among 10 hockey helmets, rotational acceleration was reduced by 6.4% to 84% compared to unhelmeted headforms.
At the present, no standards organization requires rotational acceleration testing for helmets, but in June 2014 NOCSAE announced draft standards for rotational acceleration testing for football helmets, which may be in effect as early as June 2016 [24]. These standards would ensure that the peak rotational acceleration of the helmet from a pneumatic ram test would not exceed 6,000 rad/sec$^2$ [26]. These standards, however, do not immediately apply to hockey or other types of helmets. Helmet manufacturers may also choose to certify their helmets through any number of other standards organizations besides NOCSAE, including the CSA, CE (Conformité Européenne) and HECC (Hockey Equipment Certification Council) which have not yet announced proposals for rotational accelerating testing requirements.

Figure 2-1: The Kingston Impact Simulator (KIS) unit [17]. Permission for figure reproduction obtained from Copyright Clearance Center (copyright.com).
Chapter 3

Design of Helmet Recommendation Systems

This chapter describes the overall design of helmet recommendation systems: the factors and issues to consider, and alternative choices that could be made in designing a system. At a high level, a helmet recommendation system consists of input head and helmet data, the core helmet fitting method, and output measurements and recommendations.

- Section 3.1 describes the different types of helmet recommendation systems, each of which is based upon a different helmet fitting approach.
- Section 3.2 outlines the overall workflow of a helmet recommendation system, showing the different steps that are taken for different types of systems. The rest of the chapter is organized by the order in which the component appears in the workflow of the system.
- Section 3.3 describes the scanning procedures used to obtain data from heads and helmets. It mentions different scanning methods and gives reasons why Kinect is chosen as the scanning method for the prototype system.
- Section 3.4 discusses the different data types that could be used to represent a 3D model.
- Section 3.5 describes the different approaches to helmet fitting that could be used, given input head and helmet shape data. The helmet fitting approach is core to the design of the helmet recommendation system. This section describes the different helmet fitting approaches and explains the choice of the slice extraction approach for our prototype system.
- Section 3.6 discusses the measurements and recommendations that can be displayed to the user as a result of helmet fitting.
The implementation of our prototype system will be discussed in Chapter 4.

### 3.1 Types of Helmet Recommendation Systems

The following diagram shows a categorization of different types of helmet recommendation systems. These are design alternatives proposed by the author of this thesis; we do not claim that this is an exhaustive list of all possible types of systems.

![Diagram showing the different categories and types of helmet recommendation systems.](image)

**Figure 3-1**: Diagram showing the different categories and types of helmet recommendation systems.

We discuss two main categories of types of helmet recommendation systems:

- **Shape fitting**: This category contains types of systems that use only head and helmet shape data in helmet fitting. In other words, only geometry is used as the input data – no mechanical properties of the head or helmets are known.
• **Pressure fitting.** This category contains types of systems that base helmet fit on mechanical properties – areas of the helmet that may exert pressure on the head, or stiffness of layers of padding. This information may be directly measured, or indicated by a user with knowledge of areas with different mechanical properties, or estimated based on shape data. These types of helmet fitting may be used in conjunction with shape fitting.

Shape fitting encompasses the following types of helmet recommendation systems, based on their approach to using shape information:

• **Slice extraction** approach (Figure 3-2, Section 3.5.1). A 2D standard slice is defined for both the helmet and head. The standard head slice is defined by the neurosurgeon advising on this project to be located 1 inch (2.54 cm) above the eyes and passing through the inion at the back of the head. The helmet recommendation system extracts head and helmet slices from the 3D data, and compares these slices. A key issue with this approach is defining how to locate the 2D slices on the head and helmet. Slices may be extracted after landmarks are manually placed by a user, or by algorithmically identifying slice locations.

• **Surface registration** approach (Figure 3-3, Section 3.5.2). The helmet recommendation system performs 3D matching of the inner contour of the helmet to the head shape.

• **Slice sets** approach (Figure 3-4, Section 3.5.3). The helmet recommendation system extracts a stack of 2D slices from the head and helmet, and compares them.

Pressure fitting encompasses the following types of helmet recommendation systems, based on their approach to acquiring pressure information:

• **Pressure sensing** approach (Figure 3-5 and Section 3.5.4.1). Specially instrumented helmets or skull caps are mounted with pressure strips. As the client wears each helmet, data about the pressure between the head and helmet is collected.
• **Pressure estimation** approach (Figure 3-6 and Section 3.5.4.2). The helmet recommendation system is given information about the stiffness, thickness and other properties of the helmet material layers. The computation of helmet fit takes this information into account, and combines this with shape information to estimate pressure.

### 3.2 Workflow of Helmet Recommendation Systems

The workflow of each type of helmet recommendation system is shown in Figures 3-2 to 3-7. These figures illustrate the steps involved in each type of system. At an abstract level, helmet recommendation systems in general consist of the following components:

- **The input** component. Input to a helmet recommendation system generally consists of:
  - **3D head data** of a client’s head, scanned using an imaging device capable of capturing 3D data.
  - **3D helmet data** from a collection of helmets. These are also scanned with an imaging device that may be different from the device used for capturing head data.

  Systems that also use pressure fitting may have input consisting of:
  - Pressure point data
  - Helmet material layer data

The key factors involved in the input component are the choice of *scanning* device (Section 3.3) and the data types (Section 3.4). Our protocol for head scanning is discussed in Section 4.3.
• The **helmet fitting** component. This component processes the input data as needed and does comparisons between the head and helmet data. Each type of helmet fitting is discussed in Section 3.5.

• The **output** component. This component displays information about the degree of fit of the helmets to the head. The choice of information to report and definition of a proper helmet fit are discussed in Section 3.6.
3D scanner

Client’s head is scanned

Helmets scanned prior to system use

3D scanner

3D head data

3D helmet data

Slice extraction (Section 3.5.1)

- Locate standard head and helmet slices
- Extract and compare slices

Results and recommendations

- Helmet recommendations based on gap distance between the head and helmet in 2D slices.

Figure 3-2: Design of a shape fitting helmet recommendation system using a slice extraction approach.
Client’s head is scanned

Helmets scanned prior to system use

3D scanner

Input component

3D head data

3D helmet data

Helmet fitting component

Surface registration (Section 3.5.2)
- Match the 3D interior helmet surface with 3D head surface

Results and recommendations
- Helmet recommendations based on gap distance between 3D head and helmet models.

Output component

Figure 3-3: Design of a shape based helmet recommendation system using a surface registration approach.
Client’s head is scanned

Helmets scanned prior to system use

**Input component**

- 3D head data

**Helmet fitting component**

- **Slice sets** (Section 3.5.3)
  - Match sets of slices close to and parallel to the standard head and helmet slices

**Output component**

- **Results and recommendations**
  - Helmet recommendations based on weighted gap distance between head and helmet slices.

Figure 3-4: Design of a shape based helmet recommendation system using a slice sets approach.
Pressure is measured while the client is wearing a helmet or skull cap configured with pressure sensing strips. Data indicating location of pressure sensors on helmet.

Pressure points data

- Pressure data from pressure sensing strips is used

Fitting using pressure sensing

- Helmet recommendations based on pressure distribution

Results and recommendations

Figure 3-5: Design of a pressure fitting helmet recommendation system using a pressure sensing approach. Permission for reproduction of top left image (pressure sensing cap) obtained from Copyright Clearance Center (copyright.com) [13].
Client’s head is scanned

Helmets scanned prior to system use

Input component

3D scanner

3D head data

3D helmet data

Material properties of helmet layers are measured

Helmets scanned prior to system use

3D scanner

3D helmet data

Material properties of helmet layers are measured

Helmet material layers such as foam liners are segmented in the 3D helmet data

Fitting using helmet material layers and shape data
- The location and properties of different materials on the interior of the helmet (foam liner vs. helmet shell) is taken into account along with shape data.

Results and recommendations
- Helmet recommendations based on pressure estimation, a weighted value that takes into account both gap distance and material properties. A snug fit is allowed when there is compressible material (padding).

Output component

Figure 3-6: Design of a pressure fitting helmet recommendation system using a pressure estimation approach. Pressure is estimated using a combination of shape information and information about mechanical properties of helmet material layers.
3.3 Scanning

This section describes the scanning procedures used to obtain head and helmet shape data. It mentions different scanning methods and gives reasons why Kinect is chosen as the scanning method for the prototype system.

Both head and helmet shape data may be obtained using a 3D scanner that generates a 3D model of the object that is being scanned. Section 3.3.1 describes the Microsoft Kinect motion sensing device which can be used as a 3D scanner, along with some of its features. Section 3.3.2 briefly discusses alternate scanning devices and the reasons why Kinect was chosen for our project. Our protocol for head scanning is discussed in Chapter 4.

3.3.1 Kinect Sensor

Surface data of real objects (also known as depth or range data) is collected using depth cameras (also known as depth sensors). Depth cameras detect the distance of objects from the camera, a process known as range imaging. Depth cameras that can detect enough information to produce 3D models of sufficient detail also act as 3D scanners. While there are various commercial devices that can scan 3D objects, Microsoft’s Kinect sensor (Figure 3-7) is the first handheld low-cost depth camera using commodity hardware. The Kinect sensor also serves as a motion detector that can detect the movement of objects and estimate the pose (body position) of a moving person. Version 1 of the Kinect system was first released in 2010 and while it is usually coupled with the Xbox 360 gaming system, the Kinect device itself is also sold separately (as of 2014). Version 2 was released with the Xbox One system in 2013 and sold as a standalone in 2014. Kinect remains the most widely available depth sensor in its class (compared to the Asus Xtion and PrimeSense Carmine).
The Kinect has a depth accuracy of about 2 mm at a distance of 1 m, which is approximately the maximum distance in which heads and helmets are scanned for the prototype system [16].

![Image of a Kinect sensor for Xbox 360](image)

**Figure 3-7: A Kinect sensor for Xbox 360 which can act as a 3D scanner.**

The Kinect sensor is used as the scanning device for this project due to its advantages:

- Inexpensive: costs about $150 or less (for the standalone Kinect device – the Xbox system is not needed for scanning purposes).
- Widely available and can be bought in most electronic stores, having sold over 24 million units as of February 2013.
- Non-invasive: the device is always a distance away from the person, and the depth sensor uses an infrared light laser that is invisible. Some other 3D scanners use red visible light lasers which may make users feel uncomfortable.
- Safe to use on a person.
- Lightweight and portable, so that it can be moved around a person’s head.
- Can produce a scanned 3D model quickly using ReconstructMe or similar software.

Limitations:

- Scanning results are not as detailed as some more expensive 3D scanners.
- Has a range of only 8 metres.
- The infrared sensor is affected by sunlight and works best in indoor conditions.

### 3.3.1.1 3D Reconstruction and User Interaction with Kinect

Kinect is used to scan and reconstruct 3D objects in conjunction with software: Microsoft’s KinectFusion as well as third-party software ReconstructMe and Skanect. ReconstructMe is used for this project due to its ease of use and faster reconstruction speed compared to KinectFusion, although KinectFusion can produce more detailed scans. Both ReconstructMe and KinectFusion produce more detailed scans than Skanect [5].

The Kinect must be rotated around the object in order to generate depth images at all different angles in order to reconstruct the entire 3D model of the object. Kinect records a single 2D depth image every frame (1/30 of a second) which can be represented in 3D, but only the visible surface seen by the camera at that angle. Scanning is conducted either by a user holding and moving the Kinect camera around the person to be scanned, or by rotating the person in a lazy Susan or revolving chair, in which case the camera can be stationary.

KinectFusion can also track user interaction and add virtual reality effects, which is used for the Xbox gaming system [12] [28].

The main steps in using the KinectFusion are [12] [28]:

- **Depth map conversion**: the raw depth image data from each frame is converted to a 3D point cloud with normals.
- **Camera tracking**: as the camera is moved around the object or scene, it must track the changing position of the object relative to the camera by computing the transformation matrix between each consecutive frame. This is done by using ICP (iterative closest point). In this case ICP is not used to align or register images but only to compute the transformation.

- **Volumetric integration**: the point clouds generated from each frame are fused into a volumetric surface representation using truncated signed difference functions (TSDF) in which each voxel contains a number indicating its distance to the nearest physical surface. A positive number indicates the voxel is in front of the surface towards the camera, a negative number indicates it is behind, and a number close to zero indicates it is on the surface. As information from each new frame is collected, the volumetric data is updated using a running average, with more weight given to recent data. This implicitly encodes the 3D surface along with uncertainty in the data.

- **Raycasting and 3D rendering**: in addition to rendering the 3D model, this produces a simulated depth map that is fed back into the camera tracking stage. The software compares the previous frame’s simulated depth image to the current frame’s real depth image instead of using the previous real depth image. This stabilizes the camera tracking.

- **ICP Outliers**: the previous four steps are enough for 3D reconstruction of still scenes, but in order to track novel objects inserted into the scene or a user’s movements (e.g. people waving their arms), the camera tracking step is modified to output outliers from the ICP algorithm. A large group of outliers indicates a novel object which is segmented from the rest of the scene and recorded as a separate foreground object. This also allows for augmented reality, for example a teapot inserted and then removed can be recorded as a virtual teapot and then picked up again by a user even without the real teapot being there.
3.3.1.2 Pose Estimation using Kinect

Kinect can be used to estimate the pose of a moving person [32]. This can be done using a two-step body part classification (BPC) technique. First, the input depth image from the Kinect sensor is converted into a body part label map comprised of 31 body parts. Then the labels are used to locate the body joints which indicates the pose. Alternatively, offset joint regression (OJR) can be used which directly converts depth images to body point positions.

In both approaches, training data consists of real mocap (motion capture) as well as synthetic data of people in various poses with correct body part labels, and a large number of simple depth image features is automatically generated for the dataset. These features record the difference in depth between two randomly selected points in the image. Then a random forest classifier is generated, and real and synthetic test data is used to evaluate the classifier [32].

Pose estimation can be run in real-time since the random forest can be read as input instead of having to be regenerated again. Since there are a large number of frames (30 per second) errors in predicting pose in a single frame can be diluted due to aggregation over a period of time.

3.3.2 Other Scanning Methods

Higher-end 3D structured light scanners include the Artec Spider, Artec Eva and DAVID SLS. These give higher precision and resolution than the Kinect, but are significantly more expensive. Although they are safe to use on human subjects, they emit flashing visible light, which may feel irritating to participants while the Kinect only uses invisible infrared light. Kinect is also very widely used as an off-the-shelf consumer electronics device, so it is more familiar to a general audience. For these reasons, Kinect was chosen in this study as the 3D scanner for scanning heads.
Kinect is also used to scan helmets in this study, but with available funds and equipment, helmet scanning could be done with higher-end visible light 3D scanners or with medical imaging devices such as fluoroscopy scanners.

3.4 Data Types

This section discusses different data types that are commonly used to represent a 3D model, and software for viewing 3D data.

- **Meshes** (Figure 3-8). Surfaces may be represented by a collection of flat polygons – in most cases, triangles - known as facets or faces. The .STL file format stores each facet by their three vertices and its surface normal [3] while the .PLY file format stores separate lists of vertices and facets (along with other optional properties) [2].

![Figure 3-8: Close-up of a 3D helmet model represented as a mesh.](image)
• **Point clouds** (Figure 3-9). Surfaces may be represented by point clouds – a set of points and their Cartesian coordinates. This is typically encoded by the .XYZ file format which may either contain just the coordinates of each point, or the surface normal of each point as well as the coordinates.

![Point Clouds](image)

**Figure 3-9: Close-up of a 3D helmet model represented as a point cloud.**

• **Volumetric data.** 3D medical image data is often represented as 3D raster data consisting of a grid of voxels (3D pixels) or a stack of 2D images. Common data formats include DICOM and NRRD.

3D data scanned by Kinect is stored by ReconstructMe in a 3D polygon mesh format (.ply, .stl, .obj or .3ds). A number of software packages such as MeshLab can read these files, but 3D Slicer (often referred to as just “Slicer”) is frequently used in the medical imaging community to process 3D data and view and extract 2D slices. Slicer can be used on mesh file formats, but reads them as “Models” rather than “Volumes” (which refers to volumetric data types such as DICOM and NRRD). This is disadvantageous since much of the functionality in Slicer only works on volumes.
Volumes can be readily converted into models through volume rendering, including in Slicer, but voxelization, the process of converting a model to a volume, is more difficult. There are tools for voxelization but they often do not convert into a format that Slicer reads. One command line utility, “binvox”, converts models to volumes in NRRD format, but the conversion is lossy as the volume is limited to a 1024 x 1024 voxel resolution [25] [29].

**3.5 Helmet Fitting**

This section describes the different approaches to helmet fitting that were introduced in Section 3.1. The helmet fitting approach is core to the design of the helmet recommendation system. Sections 3.5.1 to 3.5.4 describe the different helmet fitting approaches. Section 3.5.1 motivates the choice of the slice extraction approach for our prototype system.

**3.5.1 Slice Extraction Approach**

In this approach, the key is to extract an image slice – a 2D image from a 3D model – from both the 3D head model and 3D helmet model that are to be compared. A slice can be seen as the intersection of a plane with the 3D model. 3D mesh models normally have an empty interior and therefore slices display boundaries indicating where the plane intersects the surface of the model. For head models, slices that go through the head show the outline of the surface of the head at that particular orientation. For helmet models, slices that go through both the exterior and interior of the helmet display two outlines, indicating both the outer surface and inner surface of the helmet. This is illustrated in Figure 3-11.
A helmet fitting system utilizing the slice extraction approach is given the following input:

1. A set $H = \{h_1, \ldots , h_n\}$ of scanned heads
2. A set $L = \{l_1, \ldots , l_m\}$ of scanned helmets

The slice extraction approach extracts a *standard head slice* $h_i^S$ and a *standard helmet slice* $l_j^S$ for each head $h_i$ and helmet $l_j$. The standard slices of the head and helmet are then compared to each other to determine helmet fit.

Helmet fitting based on slice extraction has advantages over helmet fitting based on 3D surfaces. The main advantages are simplicity and computational efficiency. In particular, for the prototype system, it is easier for the user to analyze fit while looking at a 2D slice of the head along with its corresponding helmet slice, than it is to view the entire 3D models. The prototype should offer a simpler and easier to use interface than a 3D imaging program such as Slicer. A number of measurements such as head length, width, aspect ratio and area can be determined from slices. Other researchers have used similar measurements; for instance, Meunier measured head length and width, and Guo et. al. measured length, width and aspect ratio in their studies. [22]

![Figure 3-10: A typical head slice (left) and helmet slice (right).](image)
A disadvantage of the slice extraction approach is that the fit of the helmet outside of the extracted slice is not compared – it is possible for a helmet to not fit on a person’s head even if it fits at that slice position. (A solution to this could be the use of a stack of slices, see Section 3.5.3). Our objective, however, is to investigate helmet fitting for the specific purpose of reducing rotational acceleration, with hopes of reducing concussion proneness. Helmets rotate on the head when they are hit laterally [18]. Therefore, it seems likely that the degree of helmet fit at a specific, near-axial standard slice, is much more important than fit in the rest of the helmet. The location and extraction of the standard slice, upon recommendation of neurosurgeon Dr. Saunders, will be described in Sections 4.1.2 and 4.1.3.

Key to the success of the slice extraction approach is to accurately locate the plane of intersection and slice on the head and helmet. The head slice should correspond to the standard slice that is most relevant to rotational acceleration, and its plane of intersection should be at the same position as the helmet’s plane when the helmet is worn.

We choose the slice extraction approach to helmet fitting for the prototype system due its simplicity compared to surface registration, time constraints of thesis research, and following the suggestions made by neurosurgeon Dr. Saunders. Section 4.1 describes the slice extraction approach in more detail.

3.5.2 Surface Registration Approach

Surface registration, also known as surface matching, refers to the alignment of at least two 3D surfaces such that the difference between the surfaces is minimized [1]. This is similar to image registration except surface registration is generally only concerned with the geometry and location
of surface points rather than other features of images such as colour and textures. Surface registration techniques are intended to work on free-form surfaces, which are not described by a simple algebraic function [1].

Surface registration usually involves point set registration which finds the spatial transformation between two point clouds [1]. The most common technique is iterative closest point (ICP) which minimizes the difference between a source and a reference point cloud using a mean squared error cost function [21]. For each iteration, the closest reference point is found for each source point, and the optimal transformation is computed. The source points are then transformed and the process is repeated until the stopping criterion is met. There are many variants of ICP such as using a point-to-plane error metric instead of point-to-point, where each source point is compared to the tangent plane of a reference point [21].

Genetic algorithms have been used as a surface registration technique [4]. While slower than ICP, genetic algorithms are more robust: ICP tends to not work well with noisy data or multiple surface registration, and needs a good initial guess for the actual solution and a corresponding reference point for almost all of the source points. The genetic algorithm method is an iterative technique in which the locally best transformation is computed using chromosomes comprised of the 6 rigid transformation parameters (3 rotation and 3 translation). Many chromosomes representing candidate solutions are generated and genetic operators – selection, crossover and mutation – are applied to them in order to select chromosomes that improve fitness (or minimize the distance between all pairs of source and reference points) [4].

The following steps could be taken to apply surface registration to helmet fitting:

- Extract only the inner surface of the helmet.
- Extract only the top of the head model surface from above the eyes and neck.
- Convert the helmet and head models from meshes to point clouds, since surface registration algorithms generally compare sets of points.

After the helmet and head are registered, the mean squared error cost function can be used to determine how well the helmet and head are aligned with each other. However, this alone does not determine whether the helmet is a good fit, because part of the head may be outside the helmet. One way to test if the head is inside the helmet is to use the corresponding mesh model of the helmet, and define an interior point, such as the centre of the bounding box enclosing the head. Then use a ray-triangle intersection test where a ray is launched from the centre point to each point on the head. If the ray intersects a triangle or polygon on the helmet before it reaches the head point, then part of the head is outside the helmet.

Since helmet fit is more important at the standard head slice, a band around the standard head slice could be extracted from the head and helmet after alignment, so only the band is considered and not the top of the head and helmet. One disadvantage of using surface registration to measure helmet fit is that statistics such as mean squared error are more difficult to interpret. Surface registration could be used to only align the head and helmet – the slice extraction approach in Section 3.5.1 could then be used to extract the 2D standard head and helmet slices and determine measurements from the 2D slices (or a set of slices as described in Section 3.5.3).
3.5.3 Slice Sets Approach

This approach is similar to the slice extraction approach in Section 3.5.1, but in addition to extracting the standard slice of the head and helmet, a set of slices near the standard slice is extracted.

A helmet fitting system utilizing the slice sets approach is given the following input:

1. A set $H = \{h_1, \ldots, h_n\}$ of scanned heads
2. A set $L = \{l_1, \ldots, l_m\}$ of scanned helmets

Let $h_i$ be a head model and $l_j$ be a helmet model, and let $h_i^S$ and $l_j^S$ be the standard head and helmet slices. For each standard slice pair $(h_i^S, l_j^S)$, let $s$ be the $z$-coordinate of the point where the standard head slice intersects the $z$-axis. The standard helmet slice is translated so that it also intersects the $z$-axis at $s$. Suppose we define $r$ so that only slices located within the range $\{s - r, s + r\}$ are considered. For every slice located at location $z \in \{s - r, s + r\}$, we define the following functions:

- $f(z)$, the degree of fit of the head and helmet slices at location $z$. This could be defined as any measure of fit, for example the anterior AP mismatch (gap distance) of slices located at location $z$.
- $w(z)$, the weight assigned at each location. This can be any function that returns nonnegative values, but should give the highest weight to the standard slice and possibly lower weights to slices that are further way from $s$. For example, $w(z)$ could be defined as the following, which assigns a weight of 1 at $s$ and a weight of 0 at $s - r$ and $s + r$:

$$w(z) = 1 - \left| \frac{s - z}{r} \right|$$
We then define the overall degree of fit $F(s, r, k)$ at a standard slice location $s$ to be the following, where all slices within the range $[s - r, s + r]$ are taken at an increment $k$:

$$F(s, r, k) = \frac{\sum_{i=0}^{2r/k} f(s - r + ik) \cdot w(s - r + ik)}{\sum_{i=0}^{2r/k} w(s - r + ik)}$$

In other words, the overall degree of fit can be calculated by extracting all slices at an increment $k$, for example every 1 mm, within a particular range such as between 50 mm above and 50 mm below the standard slice. Then the degree of fit is computed for each helmet and head slice pair, using the same measurements as the slice extraction approach, and converted into the overall degree of fit using a weighted average.

### 3.5.4 Fitting Using Pressure Regions

The previously discussed methods are based on shape fitting, where only the geometry of the models are taken into account. However, fitting would be more accurate if it took into account the physical material properties of the helmet in addition to its shape. Hockey helmets often have foam liners as the innermost layer which serve as a cushion over the head, separate from the hard outer shell (Figure 3-11).
3D helmet shape data provides the shape of the inner foam liner layer without any indication of its cushion, so a helmet that appears to be too small may actually fit because the pressure of the head compresses the cushion.

We define **pressure points**, or more broadly **pressure regions**, as areas on the interior of the helmet in which the head exerts more pressure on the helmet.

### 3.5.4.1 Measuring Pressure with Pressure Sensing Strips

Pressure points can be measured by wearing a specially prepared helmet mounted with pressure sensing strips. This would require the client to try on each possible helmet. Alternatively, a pressure sensing skull cap with strips of pressure sensors can be used. These skull caps are placed in-between the head and helmet, and have been used to assess head injuries in football players [13]. Testing using this method would require significant research into developing a customized skull cap or helmets for analyzing helmet fit, and algorithms for computing helmet fit given data from pressure sensors.
3.5.4.2 Estimating Pressure Points Using Shape Data and Helmet Material Layers

To address the portability problem in Section 3.5.4.1, shape data can be used to estimate pressure points. A crude estimate can be obtained by locating regions where the helmet fit is snug.

Pressure estimates can be improved by taking into account the material properties in the different layers of the helmet. These can be measured by physical testing of the foam liner’s compressibility. The compressibility data is integrated into the helmet model and becomes a factor in determining fit. Pressure is estimated using a combination of shape information and material layers information – i.e. if the head is pushed against a highly compressible layer then that may be acceptable, but not if it is pushed against an incompressible layer.

Even without compressibility testing, the identification of padding in the helmet model is useful. Some hockey helmets have foam liners that can be removed from the helmet shell. For those helmets, the layers could be segmented by separately scanning the helmet without foam liner and the foam liner itself, then comparing them with the entire helmet model. For padding that cannot be separated, a user has to manually edit the helmet model in 3D modelling software and segment the regions with the foam layer.

The design and implementation of a system using this method would require significant research into the selection of material properties and algorithms to assess helmet fit given these properties, which requires mechanical engineering expertise.
3.6 Results and Recommendations of Helmet Fitting

This section discusses various measurements and recommendations that can be displayed to the user as a result of helmet fitting.

Using any of the helmet fitting methods, the key measure of helmet fit is gap distance (also known as mismatch or stand-off distance) between the helmet and head. If at some point the head is larger than the inner surface of the helmet (negative gap distance), then the helmet does not fit if the helmet is totally incompressible. However, it is also the case that the gap distance should not be too large – if there is too much of a gap then the helmet fits but leaves the head particularly prone to rotational acceleration from head impact. The ideal fitting helmet is one that does not fit so tightly that it is uncomfortable to the wearer, but is tight enough so that during a head impact most of the force is transferred onto the helmet and head twist is minimized.

Using the slice extraction method, several statistics and measures of fit can be obtained (Figure 3-12):

- **AP (anterior-posterior) distance mismatch**: the distance along the sagittal plane (vertical axis) between the helmet and head. This is the gap at the front (anterior) and back (posterior) of the helmet. The value is negative if the head is larger than the helmet along this axis.

- **Lateral mismatch**: the distance along the coronal plane (horizontal axis) between the helmet and head. This is the gap at the left and right sides of the helmet, and can be divided into the left lateral mismatch and right lateral mismatch. The value is negative if the head is larger than the helmet along this axis.
- **Coronal matching**: this is the area between helmet and head, and can be divided into left coronal matching and right coronal matching areas to indicate the portions to the left and right of the sagittal plane.

- **AP distance to lateral mismatch ratio**: the ratio between the total AP distance mismatch to the total lateral mismatch.

In comparing helmet and head slices, the midpoint of the posterior of the head is fixed to the midpoint of the posterior of the helmet, upon advice from neurosurgeon Dr. Saunders. Therefore there is no “posterior” AP distance mismatch; the AP distance mismatch is approximately double.
the actual gap distance when the helmet is worn, assuming that it is worn with equal spacing on the front and back (Figure 3-13).

![Figure 3-13: Alignment with posterior of the helmet fixed onto the posterior of the head.](image)

Measurements of the head shape itself can also be made:

- Head circumference.
- Head length: can be defined as the length of the bounding box enclosing the head.
- Head width: can be defined as the width of the bounding box.
- Head area: the area of the head slice.
- Aspect ratio: defined as the ratio of head length divided by head width.
Chapter 4
Design and Implementation of the Prototype System

This chapter describes the design, implementation and use of the prototype helmet fitting system that we developed:

- Section 4.1 describes the details of the slice extraction approach to helmet fitting used in the design of the prototype system. This continues the introduction to the slice extraction approach in Section 3.5.1.
- Section 4.2 gives an overview of the prototype system.
- Section 4.3 describes the scanning procedure that was conducted for the prototype, in order to collect head and helmet model data.
- Section 4.4 describes the steps in the slice extraction approach (see Section 3.5.1) that was used for the prototype.
- Section 4.5 lists the image processing steps applied to the extracted slice images before they are read as input to Helmet Fit Viewer, a software program developed for this project.
- Section 4.6 presents the implementation of Helmet Fit Viewer.

4.1 Design Using the Slice Extraction Approach

In anatomy, 3 reference slices can be defined with respect to reference planes that cut through the body (Figure 4-2):

- The axial slice cuts through the body horizontally and divides it into top (superior) and bottom (inferior) portions. This is the reference slice that is of most interest to head
measurements for helmet fitting. It is sometimes referred to as the *transverse slice* or *cross-section* in literature. An example is shown in Figure 4-1.

- The **sagittal slice** is vertical and divides the body into left and right portions.
- The **coronal slice** is vertical and divides the body into front (anterior) and back (posterior) portions.

**Figure 4-1**: A typical axial head slice (left) and axial helmet slice (right). Note that the helmet slice contains two outlines indicating both the outer and inner helmet surfaces.

**Figure 4-2**: Left (red): an axial slice. Middle (yellow): a sagittal slice. Right (green): a coronal slice.
4.1.1 Anatomical Landmarks for Locating Head Slices

Anatomical features on the surface of the head need to be identified in order to locate the standard head slice. It is important to note that taking an *anatomically axial* slice of the head is not the same as simply taking a horizontal slice of the 3D model - the head may be tilted up or down or the body posture of the subject may have oriented the head at an angle. Therefore either an anatomical reference plane must be identified, or the head slice taken should depend on head features without assuming horizontal positioning.

Some head measurement studies do assume horizontal positioning when the subject is scanned with an MRI while lying in a supine position. However, such methods are highly impractical for our purposes, and it is also not realistic to assume that all subjects being scanned will keep their heads in a standard position, so our methodology has to be robust to different head orientations.

The study of body measurements is known as *anthropometry*. Different studies have used different numbers of anthropometric landmarks on the head: reference [9] uses 32 landmarks, and survey reference [6] mentions works that use 27 or 47 landmarks. Most of these landmarks are on parts of the head not covered by hockey helmets, such as on the jaw, nose, etc. (They are however important to other types of head protection such as respirators and flight pilot helmets). The topmost standard landmark on the head is the *glabella*, located between the eyebrows and above the nose; there are no standard landmarks on the forehead above the glabella. The most prominent landmark on the back of the head is the *inion*, which is a bone projection at the lower rear part of the skull.

Many of these landmarks depend on bone structure and therefore are difficult to locate without scans from medical imaging devices. 3D scanners such as the Kinect do not capture enough detail
for many of these anatomical landmarks to be easily located, so visually identifiable facial features such as the eyes are more practical to locate as landmarks.

In anthropometry the horizontal orientation of the head is traditionally identified using *Reid’s base line* and *Frankfurt plane*, which are defined as being from the bottom of the orbit (eye socket) to either the centre (Reid’s) or top (Frankfurt) of the ear canal. However, anthropometric information using these reference lines and planes has been found to be misleading and has led to poor helmet sizing in the past [9].

### 4.1.2 Head Slice Location

The **standard head slice** can be defined to be one of the following:

1. The near-axial slice from 1 inch (2.54 cm) above the eyes to the inion at the back of the head. This is the slice that is recommended by Dr. Saunders because it is normally the longest and widest part of the head, and where the helmet is most likely to be in contact with the skull, therefore this is the slice that is likely to be important for the effects of rotational acceleration. This is similar to the *glabella-inion line* in medical literature but the location at the front of the head is normally above the eyebrows and glabella.

2. The slice where the largest head circumference or area occurs. The slice described in (1) is normally close to the largest lead slice but not exactly.

3. The slice, starting at about 1 inch above the eyes, which is most horizontal or axial. This can be defined anatomically or in reference to the horizontal line of the helmet (see Section 4.1.3).
Since our main concern is rotational acceleration, slice (1) is chosen as the definition of the standard head size. However, this poses a problem in that when the helmet is worn, the point on the forehead 1 inch above the eyes and inion may be barely covered by the helmet, or even not covered at all if the wearer has the helmet higher up on the forehead. The corresponding helmet slice would be located between the bottom of the front of the helmet and bottom of the back of the helmet, and therefore part of the slice would actually be outside of the boundary of the helmet (see Figure 4-3).

This could be resolved in one of the following ways:

A. Use a head slice that is parallel to the standard head plane between 1 inch above the eyes and inion. This slice would be at an offset higher up on the head and compared to a helmet slice that contains the full outlines of the outer and inner helmet surface.

B. Compare the standard head slice to the standard helmet slice, even if the two slices are not exactly coplanar when the helmet is worn. There would be some error in comparing head and helmet slices at different positions, but potentially less error in that the measurement is made at a head slice location that is most relevant to rotational acceleration.

For our prototype system method (B) is used - the standard head slice is compared directly with the standard helmet slice.

### 4.1.3 Helmet Slice Location

Unlike heads, the horizontal plane can be defined with respect to helmets due to their manufacture. For hockey helmets, the base of the front of the helmet is horizontal and can be used as the basis for a horizontal reference plane.
The standard helmet slice is the slice that is to be compared with the standard head slice. It can be defined as one of the following:

- A horizontal helmet slice that is at, or an offset above, the reference horizontal slice. The advantage of this is that it can be most consistently extracted, including manually, with less error. (See Figure 4-3, right)

- A near-axial helmet slice that corresponds to the standard head plane. This is hard to define precisely due to the lack of anatomical landmarks on the helmet, but can be estimated as an offset above the plane between a point near the bottom of the front of the helmet and a point near the bottom of the back of the helmet.

The issue with the above two options, especially the first option of extracting a horizontal helmet slice, is that it does not locate the exact position where the helmet fits the head. This is problematic
because different people wear their helmets differently: some wear their helmets at a forward angle so that it covers more of their forehead, while others may wear it at a more backward angle so that the helmet is higher up the forehead but covers more of the back of the head.

The placing of the helmet and head could be done with one of the following:

- Use 3D modelling software such as Slicer to open both the helmet and head model, and manually translate the helmet until it is positioned on top of the head. The disadvantage of this method is that repeatability is an issue – different users may place the helmet differently.

- Create an automated method of placing the helmet and head models. This would essentially be using the *surface registration approach* described in Section 3.5.2.

- Change the scanning procedure so that clients will, in addition to just having their heads scanned, be scanned a second time *while wearing a helmet* that is among the scanned helmets in the database. The helmeted head model is analyzed to determine how the client wore the helmet, and this is used as the basis for fitting the other helmets. Problems with this approach are that this is time consuming, and it is possible that the trial helmet(s) would not fit the client at all (or be too uncomfortable).

Figure 4-4: A slice taken after the helmet is manually placed on the head in Slicer.
4.1.4 Defining Slices via Manual Placement of Fiducials

Planes are 2D surfaces in 3D that can be described in point-normal form, using a point on the plane and an orthogonal normal vector. Another way of stating this is to identify an offset point on the z-axis and a normal vector (the method that Slicer uses to define near-axial slices).

A 3D normal vector is calculated given three points \((p_1, p_2, p_3)\) using the cross product:

\[
n = (p_2 - p_1) \times (p_3 - p_1)
\]

Therefore, in order to locate a plane, and hence slice, 3 landmarks points must be defined either by a user or by an automated algorithm. The landmarks are known as fiducials in medical imaging. A fiducial could be placed, for instance, above the left eye, above the right eye, and at the inion, in order to define a head slice.

Alternatively, a user could specify a plane by placing 2 fiducials, but assumptions would have to be made about the geometry. For instance, it could be assumed that the plane of intersection would not tilt left or right (vary in the x-direction) and then plane location would be reduced to a 2D problem of defining the normal of a line given 2 points.

4.1.5 Defining Slices via Automated Placement of Fiducials

An algorithm that can place 3 fiducials on the head and helmet corresponding to the standard head and helmet slices could automate the process of slice extraction. This was not implemented for this thesis but could be done for future work.
One way in which automated landmark detection could be implemented is through statistical analysis applied to a large amount of head shape data. There exists commercially available anthropometric data, including head shape data, from the CAESAR (Civilian American and European Surface Anthropometry Resource) database. There are also various national sizing surveys from countries including the United States, Mexico, Thailand, United Kingdom and China, but shape data appears to be commercially available only from the Chinese survey (SizeChina). Shape data from these sources are expensive to purchase at about $10,000.

For this project, head scans from 15 participants were obtained on-site at the School of Computing, Queen’s University. We wanted head shape data from our scanning device (Kinect) as this would best reflect head shape accuracies that would occur in a future commercial helmet recommendation system. The amount of data that could be obtained is limited and is insufficient to support a “big data” approach to learning landmarks.

Given enough resources, a large amount of head shape data could be obtained, either from CAESAR or possibly data sources available from biomedical computing labs at the School of Computing. The head shape data could have landmarks placed by experts as the ground truth. The data would then be divided into training and test sets and a machine learning approach would be used to learn the landmarks. The location of head landmarks would be aggregated into a statistical shape atlas. Then whenever a client’s head is scanned, an automated algorithm could fit the head scan to the statistical shape atlas of the head in order to predict where the landmarks are.
4.2 Implementation Overview

This section gives an overview of the implementation of the prototype system.

The hardware and software packages that were used are:

- **Kinect**: the 3D scanning device that was used to scan both heads and helmets.
- **ReconstructMe**: commercial software that, when running on a computer with an attached Kinect device, does the scanning and saves the scan as a 3D model file.
- **Slicer** (also known as “3D Slicer”): open-source medical imaging software that is used to view 3D models and locate and extract head and helmet slices.
- **Helmet Fit Viewer**: software developed for this project that allows the user to view head and helmet slices and make assessments about helmet fit.

The implementation for the prototype is shown in Figure 4-5. The system consists of the following components:

1. **Scanning heads and helmets to create a database of head and helmet shapes.** We first collect 3D head and helmet data by scanning a number of participants’ heads and a number of helmets, using a Kinect sensor attached to ReconstructMe software. (Section 4.3)
2. **Extraction of 2D head and helmet slices.** We extract the 2D standard slice of the head and helmet by placing 3 fiducials (landmarks) on the head and running Python scripts in Slicer. This is done given knowledge of where the standard head and helmet slices are located. (Section 4.4)
3. **Viewing slices using Helmet Fit Viewer.** This program takes in as input a set of head and helmet slice images and displays them to the user. The program provides a user interface that reads in as input:

   a. A head slice \( h_i^S \)

   b. A set of helmet slices \( L^S = \{ l_1^S, \ldots, l_m^S \} \).

The program allows for the user to select a head slice and compare its shape to helmet slices in the database. The user can manipulate the placement of slices to see where the head slice would fit on the helmet at different locations. Helmet Fit Viewer calculates and displays updated helmet fit statistics as the head slice is repositioned. (Section 4.6)
Kinect

Client’s head is scanned

Helmets scanned prior to head scans

Kinect

3D head data

Slicer (existing software)

Place fiducials (landmarks) on head and helmet to locate standard slices.

Slice planes are generated from the fiducials.

Slice images extracted from Slicer.

Image preprocessing

Helmet Fit Viewer (new software) compares helmet and head slice images, displays results for the user to assess helmet fit.

Figure 4-5: Components of the implementation of the prototype system.
4.3 Scanning Procedures to Create Head and Helmet Databases

The first step in the helmet fitting system is the collection of head and helmet shape data. For our project, we obtained the following input data:

- 15 head scans from participants in the School of Computing
- 3 helmet scans from medium sized hockey helmets:
  - Bauer BHH3500
  - CCM HT06
  - Easton E600

Both heads and helmets were scanned using a Kinect 3D scanner and ReconstructMe software, and saved as 3D models in .ply format.

4.3.1 Head Scanning

We obtained head scans from participants using the following procedure, which was conducted with the General Research Ethics Board (GREB) ethics approval shown in Appendix B.

- The Kinect sensor is mounted horizontally on a support at a height of about 1.4 metres from the ground, in order to scan participants in a sitting position. The height can be adjusted accordingly for individual participants. The Kinect is tilted slightly downwards to better scan the top of the head. It is connected with a USB cable to a lab computer that contains licensed ReconstructMe software. The lab room is covered by dark curtains in order to prevent sunlight interference which can affect Kinect scans.
• After reading and agreeing to the GREB Letter of Information and Consent, participants are requested to wear a wig liner over their head in order to compress their hair so that the scans indicate head shape more accurately without the interference of hair. They are then asked to sit in a revolving chair while facing the Kinect at a distance of about 0.7 metres away from it. They are told to keep their head position consistent throughout the scan.

• ReconstructMe is run with standard settings except for Scan Duration = 30 seconds and Device → Optimization Settings = Maximize quality. After pressing Start, the participant slowly rotates in a chair until the 30 second procedure is finished. The participant must be able to complete at least one full rotation within 30 seconds.

• After the scan is completed, ReconstructMe generates the 3D model and the operator saves it as a .ply file.

As an alternative, the head scanning could also be completed by moving the Kinect sensor around a stationary participant, but our experience is that this is more difficult to do without causing “tracking lost” errors in ReconstructMe.

The 3D models generated by ReconstructMe are not watertight, and hole filling algorithms may be applied to them afterwards. ReconstructMe has a “selfie mode” option that generates watertight models but it shrinks models to a 20cm volume and loses accuracy in the process. Watertight models can be generated using the ReconstructMe SDK but that requires the additional purchase of the SDK license.
4.3.2 Helmet Scanning

Helmets can be scanned in a similar fashion using Kinect and ReconstructMe, but the interior of the helmet must be completely scanned, so a moving Kinect sensor should be used to scan a stationary helmet, with the helmet interior facing the Kinect.

The helmet data used for our prototype system was obtained in January 2014 from Dave Adams, a Ph.D. student from the Department of Mechanical and Materials Engineering, Queen’s University.

4.4 Extraction of Semi-Automated 2D Slices

4.4.1 Extraction of 2D Slices from 3D Head Models

This section provides an overview of the semi-automated procedure that was used to extract 2D slices from 3D head models of each of the 15 participants. Details on how to execute all of the steps in Slicer and Python code is provided in Appendix A.

2D standard slices of the 3D head models are extracted in Slicer. After some preliminary steps (Appendix A, Steps 1-3), in order to extract the standard head slice, the plane in which the standard slice is located should be identified. In Slicer, a plane is defined by its normal vector (with correct orientation) and offset (intercept on the z-axis). Three points can also mathematically define planes. Therefore, the procedure is to identify 3 landmark points – known as fiducials – on the surface of the 3D head model, and run a Python script that converts the 3 points to the normal and z-intercept form of the plane. (Appendix A, Step 4)
Three fiducials are manually placed about 1 inch (25.4 mm) above each eye and at the back of the head (about where the inion is). The 3 fiducials define the plane intersecting the head that contains the head slice image of interest.

The fiducials are the red dots in the following pictures:

![Figure 4-6: Fiducials on the surface of the head.](image)

Given the 3 fiducials, a Python script is run to calculate the plane of intersection by calculating the normal to the plane and slice offset. The plane of intersection is aligned with the 3 fiducials:

![Figure 4-7: Slice plane of the head that is defined by 3 fiducials.](image)
The result is a display of the standard head slice in the Red Slice node:

Figure 4-8: The red slice viewer in Slicer, showing the extracted head slice and fiducials.

The head slice images are captured in Slicer and saved as a .PNG image file. (Appendix A, Step 6)

If the head slice image is skewed – in other words, the major axis of the slice does not lie on the y-axis – then it should be adjusted through rotation of the head slice image. This can be done manually in Slicer (Appendix A, Step 7), or algorithmically by rotating the head slice by various amounts to find the rotated slice that best fits an ellipse defined by vertical and horizontal axes. The rotation may introduce image dithering and small gaps in the head outline, which can be corrected using mathematical morphology (Section 4.5.2)
4.4.2 Extraction of 2D Slices from 3D Helmet Models

Helmet slices can be extracted in Slicer in a similar fashion to the extraction of head slices. The difference is that the fiducials must be placed on the standard helmet plane. There are no anatomical features on the helmet, so instead the fiducials should be placed so that the standard helmet plane is horizontal to the helmet. Three fiducials can be marked by placing 2 fiducials on the front of the helmet and 1 fiducial on the back of the helmet. They can be anywhere as long as they are on the standard helmet plane. Once the fiducials are placed, the helmet slice is extracted in the same way by running the Python code (Appendix A), capturing the helmet slice image as a Scene View, and saving it to a file.

Figure 4-9: Left: placement of 3 fiducials on the helmet. Right: the helmet slice plane generated from the fiducials.
4.5 Pre-processing of Images

This section describes operations applied to the 2D head and helmet slice images extracted from Slicer, before they can be read as input into Helmet Fit Viewer.

4.5.1 Helmet Slice Pre-processing

The helmet slice images have to be pre-processed before viewing in order to display only the inner boundary of the helmet and not the outer boundary:

For the prototype system, this was done manually by the author of this thesis so that the input helmet slices used by Helmet Fit Viewer consist of only the inner boundary. For future work, this could be automated by an algorithm (within the Helmet Fit Viewer program, a Slicer module or script, or an intermediate program). If the helmet slice images are assumed to consist of a clear inner and outer boundary, one algorithm would be to start at the centre of the image and find the closest point to the centre, then use a path following algorithm to find the entire inner boundary.

Figure 4-10: Removing the outer boundary of the helmet slice.
The slice images are binary (monochrome) images with two colours - the foreground colour of the outline plus the background colour - as long as they have been saved in a lossless file format such as PNG or BMP. Although they are not noisy images, the boundaries may have gaps so they are not necessarily closed loops. While the slice images ideally consist of closed paths (two boundaries for the helmet slice, and one for the head slice), it is possible that there is missing data. In addition, if rotation is applied to the images, dithering may occur which introduces gaps in the boundary. (Figure 4-11)

![Image](image.png)

**Figure 4-11:** Left: A helmet slice with a gap due to missing data. Right: part of a slice boundary with gaps (missing pixels).

If there is a large gap or a gap involving both inner and outer helmet contours, such as in the left image in Figure 4-11, then the gap could be manually closed by an operator since a closing algorithm (Section 4.5.2) may not be robust in this situation. This is acceptable for helmet slices since the helmet data can be provided beforehand, but is problematic for head slice images since they should be processed quickly after a client’s head is scanned.
4.5.2 Mathematical Morphology Operations

For cases where there are small gaps, such as in the right image in Figure 4-11, mathematical morphology can be applied to close the gaps [30]. This was not implemented for the prototype system, but could be implemented for future work.

Let $A$ be the head or helmet slice image. The support of $A$, denoted as $\text{supp}(A)$, is the set of all foreground pixels in the image.

Let $B$ be a structuring element, a binary image that is applied to the input image $A$. $B$ can be defined as an $n \times n$ unit square, for some odd positive integer $n$, centred at the origin (0,0).

Let $E$ denote the image plane containing images $A$ and $B$.

The dilation of $A$ and $B$ is defined by the union of copies of $B$, translated to each pixel location in $\text{supp}(A)$. The addition $B + p$ means that the origin of $B$ is placed at pixel location $p$:

$$A \oplus B = \bigcup_{p \in \text{supp}(A)} (B + p)$$

The erosion of $A$ and $B$ is defined by the set of all pixels $p$ such that $B + p$ is contained within $A$:

$$A \ominus B = \{ p \in E \mid B + p \in A \}$$

The closing of $A$ by $B$ is defined by the dilation of $A$ and $B$ followed by erosion using the same structuring element:
\[ A \bullet B = (A \oplus B) \ominus B \]

The closing operator can be used to repair gaps in image \( A \), by first expanding \( A \) (dilation) and then contracting it (erosion). The closing of \( A \) should use a structuring element \( B \) the size of the largest gap encountered in \( A \), for instance an \( n \times n \) unit square if the largest gap is \( n \) pixels.

### 4.6 Viewing Slices Using Helmet Fit Viewer Program

The Helmet Fit Viewer is a program that allows a user, the concussion researcher, to compare a standard head slice with standard helmet slices in order to assess helmet fit and make helmet recommendations. As input, the Helmet Fit Viewer is given a set of helmet slice images and a head slice image. It allows the user to compare any helmet with the head.

#### 4.6.1 User Interface

The Helmet Fit Viewer program displays results in a window with of 904 by 874 pixels and is designed for computers with standard screen resolutions of 1280 by 960 or above. The program is developed for Windows, but since it is developed using Qt, a cross-platform application framework, it can run on many different operating systems.
The user interface has the following primary components:

- **Helmet list** across the top. This is a list of available helmet slice images. The user may select one of the helmets to compare it with the head.

- **Information panel** at the lower right. This contains measures of helmet fit, head shape information, and lists of pressure points and regions defined by the user. (Section 4.6.3)
• **Helmet and head viewing panel** at the lower left. When no helmet is selected, this panel just shows the head slice image. When the user selects one of the helmets, the helmet slice image is superimposed onto the head. The user may drag around the helmet slice to alter its position relative to the head.

To drag the helmet, hold down the mouse and drag it to anywhere inside the viewing panel (Figure 4-13). The values in the information panel changes to reflect the helmet’s new position. The position of the head slice is unchanged.

The front (anterior) of the head and helmet is towards the top of the image and the back (posterior) is towards the bottom of the image. By default, the head and helmet slices are aligned so that the posterior point along the midline of the bounding box enclosing the head meets the posterior point of the helmet. After the helmet is dragged out of position, the **Align helmet** button can be used to realign the head and helmet at their posterior points.

The appearance of annotations in the viewing panel can be modified under the menu option **Settings→Color and line width**.
4.6.2 Input and Output (Config Files)

The Helmet Fit Viewer program pre-loads the head and helmet images from a configuration file (text file) in a predefined directory. During execution, a different config file can be loaded through **File ➔ Open Config File.** The config files are in the following format:

```
BackgroundColor,<RGB Red>,<RGB Green>,<RGB Blue>
Head, <Head file path>
Helmets
<Helmet 1 file path>,<Helmet 1 name>
...
```

For example:

```
BackgroundColor,255,255,255
Head, C:\Heads\head1.png
Helmets
"C:\Helmets\Bauer.png",Bauer
"C:\Helmets\CCM.png",CCM
```
Helmets can also be added using the Add Helmet button. If an existing helmet in the list is chosen it can be removed using the Remove Helmet button. The Change Head button switches to another head image. This does not modify the config file that was loaded. File → Generate and save config file saves the current list of helmets and head to a config file.

The input head and helmet slice images are assumed to be in the correct format - the head and helmet outlines should be 1 pixel wide closed paths with no gaps, since certain algorithms such as “flood fill” and “pressure point regions” depend on this assumption. The images should also have the correct orientation, with the posterior of the head and helmet towards the bottom of the image.

The image from the head and helmet viewing panel, including any annotations, can be saved by File → Save head + helmet image.

4.6.3 Statistics from the Information Panel

The information panel is comprised of the following sections:

- **Helmet fit** tab. This displays statistics for a concussion researcher to assess helmet fit, and allows annotations to be turned on or off in the head and helmet viewing panel. (Figure 4-14)
- **Head info** tab. This displays information about the head slice. (Figure 4-15)
- **Pressure points** tab – see Section 4.6.4.
- **Pressure regions** tab – see Section 4.6.4.
- **Slice offset.** If there are multiple slices per head and helmet, then this allows the user to select another head and helmet slice that is at an offset above or below the standard head
and helmet slice. Currently this is unused, but allows the program to work if a set of head and helmet slices are provided.

The **Helmet fit** tab (Figure 4-12) has the following features:

- **Sagittal plane** displays the vertical axis, defined as the midpoint of the bounding box of the head.

- **Coronal plane** displays the horizontal axis, defined as the midpoint of the bounding box of the head.

- **AP distance mismatch** highlights segments of the sagittal plane (appearing as a vertical line) between the helmet and head. If the helmet is outside the head either at the anterior (top of image) or posterior (bottom of image), the distance is a positive value and the corresponding segment of the sagittal plane is highlighted in red. This can be seen in Figure 4-14 at the top of the head and helmet image. If the helmet is inside, the distance is negative and the segment of the sagittal plane is highlighted in blue. The total AP distance mismatch is the sum of the top and bottom AP distance mismatches.

- **Lateral mismatch** highlights segments of the coronal plane (appearing as a horizontal line) between the helmet and head. If the helmet is outside the head either at the left or right, the distance is a positive value and the corresponding segment of the coronal plane is highlighted in red. If the helmet is inside, the distance is negative and the segment of the coronal plane is highlighted in blue. The total lateral mismatch is the sum of the left and right lateral mismatches.

- **Area: coronal matching** displays a flood fill of the region in-between the helmet and head, at the midpoint of the left/right lateral mismatch between the helmet and head and to the
left or right of the sagittal (vertical) plane. This is shown in green in Figure 4-14. The area is also calculated in square millimetres. This is only done if the helmet is outside the head at either the left or right. The total coronal matching is the sum of the left and right coronal matching areas.

- **AP distance to lateral mismatch ratio** is the ratio of the total AP distance mismatch to the total lateral mismatch.

![Helmet alignment diagram](image)

**Figure 4-14:** Helmet alignment that shows a positive top AP distance and left lateral mismatches, and negative bottom AP distance and right lateral mismatches. This alignment also shows a positive coronal matching area.

The AP distance mismatch is an indicator of the tightness of helmet fit at the front and back of the head, while the lateral mismatch is an indicator of the tightness of fit at the sides of the head roughly above the ears. This is important because it is hypothesized, though currently unproven, that differences in fit at the anterior and posterior of the head compared to the lateral (sides) of the head
are factors for reducing rotational acceleration. Therefore, a low AP distance or lateral mismatch, or a particularly low or high AP distance to lateral mismatch ratio, may be useful indicators. The effects of helmet fit at different parts of the head is currently under research, so the mismatch information in Helmet Fit Viewer provides a framework for concussion researchers to make helmet recommendations as research results become available.

If all of the top/bottom AP distance mismatches and left/right lateral mismatches are positive, then the system states that the **Helmet fits**, otherwise **Helmet does not fit**. Note that this is not the final recommendation of a helmet – the message is to exclude cases where the helmet does not fit, assuming the helmet is rigid, because parts of it are inside the head. In cases where the message says “helmet fits”, the concussion researcher may decide that it is not a good fit for the head if the gap (AP distance and lateral mismatches) is too large or if the AP distance to lateral mismatch ratio is not within a desired interval. In a later version of this program, the criteria for displaying the message “helmet fits” could be modified to take this into account. It may display “snug fit” if all AP distance and lateral mismatches are small and “loose fit” otherwise, or it may instead display a summary statistic indicating the degree of helmet fit.

The **Head info** tab (Figure 4-15) displays the following information:

- **Head circumference** – the perimeter of the head as estimated from the head slice image.
- **Head length** – the length of the head, defined by the length of the bounding box enclosing the head.
- **Head width** – the width of the head, defined by the width of the bounding box enclosing the head.
• **Head area** – the area of the head slice in square millimetres. This is calculated using a flood fill algorithm.

• **Aspect ratio** – the ratio of the length to width of the bounding box enclosing the head.

![Head circumference calculation](image)

**Figure 4-15: The head info tab of the information panel.**

### 4.6.3.1 Head Circumference Algorithm

The head circumference is not simply calculated by counting the number of pixels on the outline of the head (and then converting to millimetres). As shown in Figure 4-16, a diagonal line may be either 4-connected or 8-connected. A diagonal of a square with side length $n$ has a length of $\sqrt{2}n$. If the length of the diagonal is estimated by counting pixels, the 4-connected chain of pixels would have $2n$ pixels and overestimate the true length, and the 8-connected chain of pixels would have $n$ pixels and underestimate the true length. The outlines of head slices as extracted from Slicer are mostly comprised of 8-connected chains of pixels, so the actual circumference in pixels is greater than the number of pixels.
In order to more accurately estimate the perimeter, the head outline is converted into a series of 
*pixel segments* – consecutive horizontal or vertical pixels - which are stored in an \( n \times 2 \) matrix, 
where \( n \) = the number of pixel segments. Each row of the matrix contains the dimensions (width, 
height) of the pixel segment.

Given the pixel segment matrix, the length of the outline is calculated as the sum of the lengths of 
line segments connecting the midpoints of successive segments. Let \( n \) be the number of segments, 
\([X_1 \ldots X_n]\) be the list of segment widths (first column in matrix) and \([Y_1 \ldots Y_n]\) be the number of 
segment heights (second column in matrix). Then the length \( L \) of the outline is calculated as:

\[
L = \sum_{i=1}^{n-1} \sqrt{X_i^2 + Y_i^2}
\]
\[ L = \sum_{i=1}^{n} \sqrt{\left( \frac{X_i}{2} + \frac{X_{(i+1) \text{ mod } n}}{2} \right)^2 + \left( \frac{Y_i}{2} + \frac{Y_{(i+1) \text{ mod } n}}{2} \right)^2} \]

For example, the length of the section highlighted in red in Figure 4-17 is calculated by:

\[ L = \sqrt{(4 + 2.5)^2 + (0.5 + 0.5)^2} + \sqrt{(2.5 + 0.5)^2 + (0.5 + 0.5)^2} \]
\[ + \sqrt{(0.5 + 0.5)^2 + (0.5 + 1.5)^2} + \ldots \]

### 4.6.4 Manually Defining Pressure Points

The user can mark a point on the helmet by enabling the **Select point on helmet** button, and then clicking on the viewing window. This draws a point on the viewing window and adds an entry to the table under the **Pressure Points** tab. The table displays the X and Y coordinates of the point drawn (as well as previous points) along with its distance to the closest head point. The selected points will always be on the helmet – if the user clicks on a point not on the helmet, then the program will place it on the closest part of the helmet.
A point can also be marked using **Add Point** and specifying the X and Y coordinate, which snaps to the closest point on the helmet. **Edit Point** modifies the X and Y coordinates of the first point selected in the table and **Remove Point** removes all points that are selected.

**Closest Points** will automatically mark the points on the helmet closest to the head – one point in each quadrant as defined by the sagittal and coronal axes.

Currently, it is up to the user to identify a set of pressure points given shape data. In the future, an automated algorithm to detect pressure points could be devised. Some possible definitions of all pressure points on a helmet include:

---

**Figure 4-18:** Four pressure points on the CCM helmet.

<table>
<thead>
<tr>
<th>Helmet</th>
<th>X</th>
<th>Y</th>
<th>Distance to head</th>
</tr>
</thead>
<tbody>
<tr>
<td>106</td>
<td>180</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>385</td>
<td>174</td>
<td></td>
<td>2.82843</td>
</tr>
<tr>
<td>139</td>
<td>357</td>
<td></td>
<td>5.38516</td>
</tr>
<tr>
<td>378</td>
<td>375</td>
<td></td>
<td>4.24264</td>
</tr>
</tbody>
</table>
• Calculate the distance between each part of the helmet and the head, and return all the local minima of distances as pressure points.

• Find the closest point in each quadrant. The quadrants could be defined by the sagittal and coronal axes. Alternatively, they could be defined by the two main diagonals between the sagittal and coronal axes so that the helmet is split into regions in the vicinity of the left lateral, right lateral, anterior and posterior sides of the helmet and head.

These definitions only apply if the helmet is outside the head. If part of it is inside, then a method of calculating pressure points could be to expand the helmet outline (or shrink head outline) until the helmet outline is entirely outside the head. An implementation challenge is that this could introduce image dithering or gaps in the helmet outline.

The user can similarly add a pressure region on the helmet by enabling Select region on helmet. A pressure region is defined as the shortest portion of the helmet outline between two points designated by the user. The regions are listed in the table under the Pressure Regions tab.
Chapter 5

Measurements and Test Results

This chapter discusses the repeatability and accuracy of using the slice extraction method documented in Section 4.4. In this method, operators manually place 3 fiducials on the head in order to locate the standard head slice, and similarly for the standard helmet slice. This would lead to some intra-operative measurement error from an operator placing the fiducials in slightly different locations each time. Section 5.1 discusses test results from the placement of fiducials on the head models. Section 5.2 discusses measurements of slices from the helmet models.

In addition to assessing helmet fit by comparing head and helmet slices, head models are compared to each other among the 15 heads that were scanned. Measurements from slices extracted from different heads are presented in Section 5.3, showing the differences in head shape.

Section 5.4 summarizes helmet fitting results from the 15 heads compared to the 3 hockey helmets.

As mentioned in Section 3.3.1, the Kinect has a depth accuracy of about 2 mm at a distance of 1 m, which is approximately the maximum distance in which heads and helmets are scanned for the prototype system [16].

5.1 Head Slice Results

Head shapes can be compared by measuring the dimensions and area of 2D head slices. The length and width of head slices can be denoted by the dimensions of the bounding box enclosing the head slice. Aspect ratio is defined as the ratio between length and width.
5.1.1 Repeatability of Head Slice Extraction

The accuracy and repeatability of head slice extraction is tested using the intra-operative method on Head #14. The intra-operative method involves an operator manually placing 3 fiducials 9 different times.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Circumference (cm)</th>
<th>Length (cm)</th>
<th>Width (cm)</th>
<th>Area (cm²)</th>
<th>Aspect ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test #1</td>
<td>55.5</td>
<td>19.8</td>
<td>15.2</td>
<td>233</td>
<td>1.30</td>
</tr>
<tr>
<td>Test #2</td>
<td>55.3</td>
<td>19.4</td>
<td>15.4</td>
<td>230</td>
<td>1.26</td>
</tr>
<tr>
<td>Test #3</td>
<td>55.8</td>
<td>19.9</td>
<td>15.3</td>
<td>234</td>
<td>1.30</td>
</tr>
<tr>
<td>Test #4</td>
<td>55.5</td>
<td>19.8</td>
<td>15.1</td>
<td>232</td>
<td>1.31</td>
</tr>
<tr>
<td>Test #5</td>
<td>55.6</td>
<td>19.8</td>
<td>15.2</td>
<td>232</td>
<td>1.30</td>
</tr>
<tr>
<td>Test #6</td>
<td>55.5</td>
<td>19.6</td>
<td>15.3</td>
<td>232</td>
<td>1.28</td>
</tr>
<tr>
<td>Test #7</td>
<td>55.7</td>
<td>19.9</td>
<td>15.3</td>
<td>234</td>
<td>1.30</td>
</tr>
<tr>
<td>Test #8</td>
<td>55.5</td>
<td>19.7</td>
<td>15.3</td>
<td>233</td>
<td>1.29</td>
</tr>
<tr>
<td>Test #9</td>
<td>55.4</td>
<td>19.7</td>
<td>15.4</td>
<td>232</td>
<td>1.28</td>
</tr>
</tbody>
</table>

Table 5-1: Intra-operative slice extraction measurements on Head #14.

The following table shows a summary of the intra-operative measurements. “Error” is defined as the difference between the maximum and minimum value of the range of each measurement variable. “Expected error” is defined as the mean of the absolute value of the difference between the value of each sample (test) and the median value, for each measurement variable.

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Median</th>
<th>Error</th>
<th>Expected error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>55.3 to 55.8 cm</td>
<td>55.5 cm</td>
<td>± 0.5 cm error</td>
<td>0.1 cm</td>
</tr>
<tr>
<td>Length</td>
<td>19.4 to 19.9 cm</td>
<td>19.8 cm</td>
<td>± 0.5 cm error</td>
<td>0.1 cm</td>
</tr>
<tr>
<td>Width</td>
<td>15.1 to 15.4 cm</td>
<td>15.3 cm</td>
<td>± 0.3 cm error</td>
<td>0.1 cm</td>
</tr>
<tr>
<td>Area</td>
<td>230 to 234 cm²</td>
<td>233 cm²</td>
<td>± 4 cm² error</td>
<td>1 cm²</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>1.26 to 1.31</td>
<td>1.30</td>
<td>± 0.05 error</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 5-2: Summary of intra-operative slice extraction measurements on Head #14.
For future work, the repeatability of head slice extraction can also be measured using an interoperative method, which involves multiple operators manually placing 3 fiducials on a head.

### 5.2 Helmet Slice Results

The measurements of each of the 3 helmets, according to their standard helmet slices, is shown in Table 5-3.

<table>
<thead>
<tr>
<th></th>
<th>Circumference (cm)</th>
<th>Length (cm)</th>
<th>Width (cm)</th>
<th>Area (cm²)</th>
<th>Aspect ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bauer BHH3500</td>
<td>56.0</td>
<td>20.1</td>
<td>14.9</td>
<td>236</td>
<td>1.35</td>
</tr>
<tr>
<td>CCM HT06</td>
<td>61.3</td>
<td>19.7</td>
<td>18.6</td>
<td>263</td>
<td>1.06</td>
</tr>
<tr>
<td>Easton E600</td>
<td>58.1</td>
<td>20.3</td>
<td>15.2</td>
<td>249</td>
<td>1.34</td>
</tr>
</tbody>
</table>

**Table 5-3: Helmet slice extraction measurements from the 3 helmets in the database.**

Compared to retail specifications:

- **CCM HT06 Medium circumference:** 54 – 58 cm
- **Easton E600 Medium circumference:** 55.5 – 59 cm
- **Bauer (other models) Medium circumference:** 55 – 60 cm

The scans of the Bauer and Easton helmets appear to be within the manufacturer’s circumference range. However, the CCM helmet appears larger than it is due to contours caused by gaps in the shape of the padding, as seen in Figure 4-18. This shows that it would be more appropriate to compare ellipses fitted to the helmet shapes rather than compare the helmet shapes directly.
5.3 Head Shape Comparison from Head Slices

The measurements of each of the 15 standard head slices in the database is recorded using the Helmet Fit Viewer program. This shows the variation in head shape:

<table>
<thead>
<tr>
<th></th>
<th>Circumference (cm)</th>
<th>Length (cm)</th>
<th>Width (cm)</th>
<th>Area (cm²)</th>
<th>Aspect ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head #1</td>
<td>57.6</td>
<td>19.6</td>
<td>17.3</td>
<td>257</td>
<td>1.13</td>
</tr>
<tr>
<td>Head #2</td>
<td>58.5</td>
<td>20.4</td>
<td>16.9</td>
<td>264</td>
<td>1.21</td>
</tr>
<tr>
<td>Head #3</td>
<td>59.9</td>
<td>21.3</td>
<td>16.6</td>
<td>273</td>
<td>1.28</td>
</tr>
<tr>
<td>Head #4</td>
<td>59.3</td>
<td>20.7</td>
<td>16.9</td>
<td>270</td>
<td>1.22</td>
</tr>
<tr>
<td>Head #5</td>
<td>58.5</td>
<td>20.6</td>
<td>16.3</td>
<td>262</td>
<td>1.27</td>
</tr>
<tr>
<td>Head #6</td>
<td>59.6</td>
<td>20.9</td>
<td>16.8</td>
<td>273</td>
<td>1.24</td>
</tr>
<tr>
<td>Head #7</td>
<td>56.6</td>
<td>20.1</td>
<td>15.8</td>
<td>245</td>
<td>1.27</td>
</tr>
<tr>
<td>Head #8</td>
<td>57.2</td>
<td>19.9</td>
<td>16.8</td>
<td>252</td>
<td>1.19</td>
</tr>
<tr>
<td>Head #9</td>
<td>58.4</td>
<td>20.9</td>
<td>16.2</td>
<td>258</td>
<td>1.29</td>
</tr>
<tr>
<td>Head #10</td>
<td>61.0</td>
<td>21.3</td>
<td>17.1</td>
<td>285</td>
<td>1.24</td>
</tr>
<tr>
<td>Head #11</td>
<td>54.3</td>
<td>18.4</td>
<td>16.1</td>
<td>228</td>
<td>1.14</td>
</tr>
<tr>
<td>Head #12</td>
<td>57.1</td>
<td>19.9</td>
<td>16.3</td>
<td>252</td>
<td>1.22</td>
</tr>
<tr>
<td>Head #13</td>
<td>63.7</td>
<td>22.2</td>
<td>18.0</td>
<td>312</td>
<td>1.23</td>
</tr>
<tr>
<td>Head #14</td>
<td>55.5</td>
<td>19.8</td>
<td>15.2</td>
<td>233</td>
<td>1.30</td>
</tr>
<tr>
<td>Head #15</td>
<td>59.4</td>
<td>20.8</td>
<td>16.7</td>
<td>270</td>
<td>1.25</td>
</tr>
</tbody>
</table>

*Table 5-4: Head slice extraction measurements on all 15 heads in database.*

The following table summarizes the head slice measurements. “Variation” is defined as the difference between the maximum and minimum value of the range. “Expected variation” is the mean of the absolute value of the difference between the each sample (head) and the median.
<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Median</th>
<th>Variation</th>
<th>Expected variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>54.3 to 63.7 cm</td>
<td>58.5 cm</td>
<td>± 9.4 cm variation</td>
<td>1.6 cm</td>
</tr>
<tr>
<td>Length</td>
<td>18.4 to 22.2 cm</td>
<td>20.6 cm</td>
<td>± 3.8 cm variation</td>
<td>0.7 cm</td>
</tr>
<tr>
<td>Width</td>
<td>15.2 to 18.0 cm</td>
<td>16.7 cm</td>
<td>± 2.8 cm variation</td>
<td>0.5 cm</td>
</tr>
<tr>
<td>Area</td>
<td>228 to 312 cm²</td>
<td>262 cm²</td>
<td>± 84 cm² variation</td>
<td>15 cm²</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>1.13 to 1.30 cm</td>
<td>1.24</td>
<td>± 0.17 variation</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 5-5: Summary of head slice extraction measurements on all 15 heads in database.

This shows the variation between head shapes is much larger than the measurement error from fiducial placement in Section 5.1. The length and width dimensions of the different head shapes can be seen in Figure 5-1.

![Figure 5-1: Plot of head length vs. head width among the 15 heads in the database.](image)

The variation between the 15 head shapes is shown to be statistically different than the measurement error from fiducial placement, by comparing the standard deviation of measurements from both data sets (Table 5-1 and Table 5-4). The standard deviations are shown in Table 5-6.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>15 heads</td>
<td>2.2768</td>
<td>0.8943</td>
<td>0.6633</td>
<td>20.579</td>
<td>0.05</td>
</tr>
<tr>
<td>9 fiducial</td>
<td>0.15</td>
<td>0.1581</td>
<td>0.0972</td>
<td>1.236</td>
<td>0.0154</td>
</tr>
</tbody>
</table>

Table 5-6: Standard deviations of measurements from the set of 15 head shapes vs. 9 intra-operative fiducial placement measurements (to 4 significant digits).

For each measurement, a chi-square test is used to test for whether the standard deviations are equal. For circumference, let $\sigma$ be the standard deviation from the 15 head shapes, and $s$ be the standard deviation from the 9 fiducial placement measurements.

Let the null hypothesis $H_0 = \sigma = 2.2768$.

Let the alternate hypothesis $H_a = \sigma \neq 2.2768$

Let the significance level $\alpha = 0.01$

The degrees of freedom for the Chi-Squared distribution is $df = n - 1 = 8$

The test statistic is:

$$X^2 \ast = \frac{(n - 1)s^2}{\sigma^2} = \frac{8 \times 0.15^2}{2.2768^2} = 0.0347$$

The p-value $P$ is:

$$\frac{1}{2} P = 1 - P(X^2 > 0.0347, df = 8)$$

Since $P(X^2 > 0.0347, df = 8) = 1.0000$ when rounded to 4 significant digits,

$$\frac{1}{2} P < 1 - 0.99995$$

$$P < 0.0001$$

Since $P < \alpha = 0.01$, this shows shown evidence against $H_0$. Therefore, the standard deviations are significantly different.
Similarly, for length, width and area, $P < 0.0001$. Therefore, the standard deviations are significantly different.

For aspect ratio,

$$X^2 = \frac{(n - 1)s^2}{\sigma^2} = \frac{8 \times 0.1537^2}{0.05^2} = 0.7551$$

$$\frac{1}{2}P = 1 - P(X^2 > 0.7551, df = 8)$$

$$\frac{1}{2}P = 1 - 0.9992$$

$$P = 0.0012$$

Since $P < \alpha = 0.01$, this shows the standard deviations are significantly different.

5.3.1 Comparison of Head Scans to Physical Head Shape Measurements

Head slice measurements from the 3D scans can be validated by comparing them to physical head measurements. The head circumference of 8 participants is obtained using a measuring tape and compared to the circumference of head slices extracted from 3D Kinect data (Table 5-7).

This shows there is an error of up to ±2.4 cm, and median error of ±0.7 cm, between physical head circumference measurements and measurements obtained using the prototype system.
Table 5-7: Differences between head circumference measurements from head slices obtained using 3D data, and physical measurements of the head.

The head circumference from the 8 tape-measured heads (Table 5-7) is shown to be significantly different than from the corresponding 8 Kinect scans, by testing for whether the means are equal using a Student’s t-test (Table 5-8):

<table>
<thead>
<tr>
<th></th>
<th>From 3D data (cm)</th>
<th>From measuring tape (cm)</th>
<th>Difference (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head #1</td>
<td>57.6</td>
<td>58.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Head #2</td>
<td>58.5</td>
<td>59.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Head #3</td>
<td>59.9</td>
<td>57.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Head #5</td>
<td>58.5</td>
<td>60.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Head #8</td>
<td>57.2</td>
<td>58</td>
<td>0.8</td>
</tr>
<tr>
<td>Head #9</td>
<td>58.4</td>
<td>58.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Head #10</td>
<td>61.0</td>
<td>60.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Head #15</td>
<td>59.4</td>
<td>59.6</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The head circumference from the 8 tape-measured heads (Table 5-7) is shown to be significantly different than from the corresponding 8 Kinect scans, by testing for whether the means are equal using a Student’s t-test (Table 5-8):

<table>
<thead>
<tr>
<th></th>
<th>Mean (cm)</th>
<th>Stdev. Circumference (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) 8 Kinect scans</td>
<td>58.8125</td>
<td>1.2392</td>
</tr>
<tr>
<td>(B) 8 tape measurements</td>
<td>59.0</td>
<td>1.1364</td>
</tr>
</tbody>
</table>

Table 5-8: Mean and standard deviation of head circumference measurements from tape measurements and Kinect scans (to 4 significant digits).

Let the null hypothesis $H_0 = \mu_B - \mu_A = 0$

Let the alternate hypothesis $H_a = \mu_B - \mu_A \neq 0$

Let the significance level $\alpha = 0.01$

The degrees of freedom for the t distribution is $df = n - 1 = 7$

The test statistic is:

$$t^2 = \frac{(x_B - x_A) - (\mu_B - \mu_A)}{\sqrt{\frac{s_A^2}{n_A} + \frac{s_B^2}{n_B}}} = \frac{59.0 - 58.8125}{\sqrt{\frac{1.2392^2}{7} + \frac{1.1364^2}{7}}} = 0.2951$$
The P-value $P$ is:

$$P = P(t^2 > 0.2951, df = 7) = 0.7756$$

Since $P \gg \alpha = 0.1$, there is no evidence against $H_0$. Therefore, the means of the head scans vs. tape measurements are statistically different.

### 5.3.2 Multiple Scans from a Single Participant

Multiple head scans can also be taken from a single participant on different occasions. The following results are obtained from 6 scans of one participant (Head #14):

<table>
<thead>
<tr>
<th></th>
<th>Circumference (cm)</th>
<th>Length (cm)</th>
<th>Width (cm)</th>
<th>Area ($cm^2$)</th>
<th>Aspect ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan #1</td>
<td>55.5</td>
<td>19.8</td>
<td>15.2</td>
<td>233</td>
<td>1.30</td>
</tr>
<tr>
<td>Scan #2</td>
<td>55.6</td>
<td>20.0</td>
<td>14.9</td>
<td>230</td>
<td>1.34</td>
</tr>
<tr>
<td>Scan #3</td>
<td>55.9</td>
<td>20.1</td>
<td>15.1</td>
<td>237</td>
<td>1.33</td>
</tr>
<tr>
<td>Scan #4</td>
<td>56.2</td>
<td>20.2</td>
<td>15.5</td>
<td>239</td>
<td>1.30</td>
</tr>
<tr>
<td>Scan #5</td>
<td>56.3</td>
<td>19.9</td>
<td>15.4</td>
<td>240</td>
<td>1.29</td>
</tr>
<tr>
<td>Scan #6</td>
<td>56.1</td>
<td>20.0</td>
<td>15.3</td>
<td>238</td>
<td>1.31</td>
</tr>
</tbody>
</table>

**Table 5-9: Head measurements from multiple scans of one participant.**

The variation from the multiple head scans of a single participant is compared to the 15 head scans and 9 intra-operative fiducial placement measurements in Table 5-11. This shows that the standard deviation of measurements from different scans of one head is generally larger than from the intra-operative fiducial placements of one scan, but much smaller than between different heads.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6 scans of same head</td>
<td>0.3266</td>
<td>0.1414</td>
<td>0.2160</td>
<td>3.2700</td>
<td>0.0194</td>
</tr>
<tr>
<td>15 heads</td>
<td>2.2768</td>
<td>0.8943</td>
<td>0.6633</td>
<td>20.579</td>
<td>0.05</td>
</tr>
<tr>
<td>9 fiducial placement measurements</td>
<td>0.15</td>
<td>0.1581</td>
<td>0.0972</td>
<td>1.236</td>
<td>0.0154</td>
</tr>
</tbody>
</table>

Table 5-10: Standard deviations of measurements from 6 scans of one participant, compared to the set of 15 head shapes and 9 intra-operative fiducial placement measurements (to 4 significant digits).

5.4 Helmet Fitting Results

The results of helmet fitting between the 15 scanned heads and 3 helmets (Bauer BHH3500, CCM HT06 and Easton E600), as determined by the Helmet Fit Viewer program, is shown in Table 5-11. In this table, “AP” is short form for AP distance mismatch; “Lateral” is lateral mismatch, and “Coronal” is coronal matching area.

For both the Bauer and Easton helmets, none of the 15 heads fit. In all cases the helmet is narrower than the head at the sides, leading to a negative lateral mismatch.

For the CCM helmet, 2 of the 15 heads fit the helmet as determined by the AP distance and lateral mismatches both being positive. For 5 heads, the lateral mismatch is positive, leading to a positive coronal matching area that indicates the area of the gap between the head and helmet.
Note that the CCM helmet (Figure 4-18) has large gaps with empty space, so the coronal matching area is significantly larger than what would be expected with the amount of lateral mismatch distance. (Figure 5-2)

To verify these results, one of the participants (Head #15) tried wearing each of the helmets. According to the Helmet Fit Viewer, there is an AP distance or lateral mismatch of between -4.5 to -17 mm for each of the helmets on the participant’s head. Upon wearing the helmets, it turns out the Bauer helmet is too tight to fit without discomfort, but the CCM helmet does fit tightly on the participant’s head, although it is not particularly comfortable. The Easton helmet is between the Bauer and CCM helmets in terms of comfort.

This shows the need for helmet fitting to take into account more than shape information. The CCM helmet in particular is lined with a ridged padding layer that shows up in the 2D helmet slice, but shape information alone does not show that this layer is quite compressible. It seems that the CCM helmet would have fit many of the participants as the padding layer of the helmet compresses against the skull, but this was not captured by the prototype helmet recommendation system. For future work, incorporating helmet material layer information into the system would be a significant improvement.

Figure 5-2: CCM helmet slice showing large coronal matching area.
<table>
<thead>
<tr>
<th></th>
<th>Bauer helmet</th>
<th></th>
<th>Easton helmet</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AP (mm)</td>
<td>Lateral (mm)</td>
<td>AP (mm)</td>
<td>Lateral (mm)</td>
</tr>
<tr>
<td>Head #1</td>
<td>6</td>
<td>-25.5</td>
<td>8</td>
<td>-25.5</td>
</tr>
<tr>
<td>Head #2</td>
<td>-2.5</td>
<td>-20.5</td>
<td>-0.5</td>
<td>-20</td>
</tr>
<tr>
<td>Head #3</td>
<td>-11</td>
<td>-16</td>
<td>-9</td>
<td>-13.5</td>
</tr>
<tr>
<td>Head #4</td>
<td>-5.5</td>
<td>-17.5</td>
<td>-3.5</td>
<td>-16.5</td>
</tr>
<tr>
<td>Head #5</td>
<td>-5</td>
<td>-13.5</td>
<td>-3</td>
<td>-12.5</td>
</tr>
<tr>
<td>Head #6</td>
<td>-7.5</td>
<td>-19</td>
<td>-5.5</td>
<td>-17</td>
</tr>
<tr>
<td>Head #7</td>
<td>1</td>
<td>-9.5</td>
<td>3</td>
<td>-9.5</td>
</tr>
<tr>
<td>Head #8</td>
<td>3</td>
<td>-18</td>
<td>5</td>
<td>-17.5</td>
</tr>
<tr>
<td>Head #9</td>
<td>-5.5</td>
<td>-6</td>
<td>-5.5</td>
<td>-6</td>
</tr>
<tr>
<td>Head #10</td>
<td>-11</td>
<td>-20.5</td>
<td>-9</td>
<td>-18</td>
</tr>
<tr>
<td>Head #11</td>
<td>19.5</td>
<td>-20.5</td>
<td>19.5</td>
<td>-13.5</td>
</tr>
<tr>
<td>Head #12</td>
<td>2</td>
<td>-14</td>
<td>4</td>
<td>-14</td>
</tr>
<tr>
<td>Head #13</td>
<td>-20.5</td>
<td>-31</td>
<td>-18.5</td>
<td>-29</td>
</tr>
<tr>
<td>Head #14</td>
<td>4.5</td>
<td>-4</td>
<td>6.5</td>
<td>-4</td>
</tr>
<tr>
<td>Head #15</td>
<td>-7</td>
<td>-17</td>
<td>-5</td>
<td>-15.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>CCM helmet</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AP (mm)</td>
<td>Lateral (mm)</td>
<td>Coronal (mm²)</td>
<td>Fits?</td>
</tr>
<tr>
<td>Head #1</td>
<td>1.5</td>
<td>-10.5</td>
<td>0</td>
<td>DNF</td>
</tr>
<tr>
<td>Head #2</td>
<td>-7</td>
<td>-7</td>
<td>0</td>
<td>DNF</td>
</tr>
<tr>
<td>Head #3</td>
<td>-15.5</td>
<td>-3</td>
<td>0</td>
<td>DNF</td>
</tr>
<tr>
<td>Head #4</td>
<td>-10</td>
<td>-4.5</td>
<td>0</td>
<td>DNF</td>
</tr>
<tr>
<td>Head #5</td>
<td>-9.5</td>
<td>0</td>
<td>0</td>
<td>DNF</td>
</tr>
<tr>
<td>Head #6</td>
<td>-12</td>
<td>-6</td>
<td>0</td>
<td>DNF</td>
</tr>
<tr>
<td>Head #7</td>
<td>-3.5</td>
<td>4</td>
<td>1876</td>
<td>DNF</td>
</tr>
<tr>
<td>Head #8</td>
<td>-1.5</td>
<td>-3</td>
<td>0</td>
<td>DNF</td>
</tr>
<tr>
<td>Head #9</td>
<td>-12</td>
<td>5</td>
<td>1703.8</td>
<td>DNF</td>
</tr>
<tr>
<td>Head #10</td>
<td>-15.5</td>
<td>-7.5</td>
<td>0</td>
<td>DNF</td>
</tr>
<tr>
<td>Head #11</td>
<td>13</td>
<td>4</td>
<td>3242.8</td>
<td>Fits</td>
</tr>
<tr>
<td>Head #12</td>
<td>-2.5</td>
<td>0.5</td>
<td>1498.5</td>
<td>DNF</td>
</tr>
<tr>
<td>Head #13</td>
<td>-25</td>
<td>-21</td>
<td>0</td>
<td>DNF</td>
</tr>
<tr>
<td>Head #14</td>
<td>0</td>
<td>11</td>
<td>2751</td>
<td>Fits</td>
</tr>
<tr>
<td>Head #15</td>
<td>-11.5</td>
<td>-4.5</td>
<td>0</td>
<td>DNF</td>
</tr>
</tbody>
</table>

Table 5-11: Measurements of helmet fitting comparing the head with the Bauer, Easton and CCM helmets. (DNF = “did not fit”)
Chapter 6

Conclusion

6.1 Summary

Concussion prevention continues to be an important research goal for reducing the incidence of sports-related head injuries. Helmet fitting is one approach that may show promise in helping to limit concussions, if future research shows that a properly fitting helmet can reduce rotational acceleration from lateral head impact. We have demonstrated the development of a prototype helmet fitting recommendation system that contributes towards the long-term research goal of creating a system capable of producing helmet recommendations that are tailored for each client. The prototype system shows the difference between head and helmet shapes and measurements of fit based on comparisons between 2D head and helmet slices. The proper helmet fit with respect to reducing concussions is not currently known. However, the prototype system shows that helmet fit can be assessed given shape information from head and helmet scans.

We have made the following contributions in this thesis:

- Descriptions of the overall design of a helmet recommendation system, and comparisons of different approaches to helmet fitting (Chapter 3).
- Creation of the initial databases of 15 head and 3 helmet shapes for the prototype system, by scanning with a Kinect sensor and ReconstructMe software (Section 4.3 and Appendix B).
- Design and implementation of a helmet recommendation system using a slice extraction approach (Chapter 4). This involves two key steps:
  - Extraction of head and helmet slices (Section 4.4 and Appendix A).
Implementation of the Helmet Fit Viewer, a program that allows a user to compare head and helmet slices, and view statistics indicating the degree of fit between the head and helmet (Section 4.6).

- Tests showing the accuracy and repeatability of the slice extraction method.
- Measurements of the shape differences between head slices (Section 5.3) and between head and helmet slices (Section 5.4). This shows the variation between head shapes is much larger than the measurement error from fiducial placement in Section 5.1.

### 6.2 Prototype System In This Thesis vs. Commercial System

The long-term goal is to create a **commercial helmet recommendation system** that can be readily used in a retail setting. During use of this system, the operator (an employee at the retail outlet) scans the client’s head shape with a Kinect. The system then automatically recommends which helmet model(s) best fit the client and are therefore most likely to offer the client the best concussion protection. The recommendation would be based upon the latest concussion information provided by an expert in concussion research.

Both the prototype system, which was detailed in Chapter 4, and the envisioned commercial helmet recommendation system are based on the same overall design. However, there are some key differences:

- **Degree of automation.** The commercial helmet fitting system is aimed at users in a retail setting, with full automation of the pipeline from head scanning to helmet fitting. Software quickly captures 3D head data from the scanner, converts it to a format that can be compared with helmet data, and then automatically determines helmet fit with minimal
intervention required from the operator. The entire process should be fast enough to be desirable for the client.

Note that it is not essential for the processing of helmet scans to be fully automated. The helmet database is created prior to system use; therefore this data may be manually processed by experts without affecting the waiting time of a client.

In contrast, the prototype system is intended to be a demonstration of the first steps towards a commercial system. It involves some manual steps, as described in Chapter 4 and Appendix A.

- **Results to be displayed.** The prototype system is primarily intended to assist a concussion researcher in developing helmet fit recommendations while the commercial system is intended for operators at the retail outlet. The prototype can produce a result as to which helmet is the best fit for the head, but also allows the user to select each helmet individually and compare it with the head. The prototype displays statistics that indicate the degree of fit, and also displays measurements that might aid in the researcher’s assessment of helmet fit. It is configured to allow comparison of heads with other heads, or helmets with other helmets if needed, so that the researcher can assess head or helmet shape differences.

A commercial helmet recommendation system would have a simpler interface that only indicates which helmet(s) are the best fit for the client, or perhaps gives a ranking of the best fitting helmets.
6.3 Future Work

The long-term goal is the development of a fully automated helmet recommendation system for commercial use that would recommend helmet(s) to clients after the client’s head is scanned by a Kinect sensor. In order to make further progress towards creating a full commercial helmet recommendation system, research is needed in several areas:

- The science of helmet fitting for reducing rotational acceleration. This is the most important contribution that must be made before a commercial system can be developed. Currently, it is hypothesized but not proven that proper helmet fit reduces rotational acceleration, and it is not known what degree of fit is ideal. It is hypothesized that lateral and AP distance mismatch have different effects on rotational acceleration, but this has not been proven. Also, further research should be conducted on the relationship between rotational acceleration and incidence of concussions.

- Include material properties of helmets. It is clear that shape information alone is not sufficient to accurately determine helmet fit. For future work, the compressibility of different materials in the helmet – in particular, foam padding layers – should be measured, and this information along with the location of material layers on the helmet interior should be added to the helmet database.

- Automation of helmet fitting – in particular, automating the slice extraction procedure by algorithmically detecting the fiducials on the head, which would require a large database of head shapes. A workflow showing a helmet recommendation system based on the prototype but with more automation is shown in Figure 6-1. This version is automated for the head but not for the helmet – since helmet data can be provided beforehand, it is acceptable for it to be manually processed.
Figure 6-1: System that is automated for head, but semi-automated for helmet (not yet implemented).
Client’s head is scanned

Helmets scanned prior to head scans

Kinect

3D head data

3D helmet data

Helmet Fit Viewer (new software) automatically calls Slicer at runtime and extracts 2D slices from the head and helmet. It then determines helmet fit by aligning the head and helmet images, along with additional information such as the location of pressure regions.

Helmet Fit Viewer compares helmet and head slice images and displays information for the operator: a recommendation about whether or not the helmet is suited for the client.

Figure 6-2: Fully automated commercial system (not yet implemented)
• Automation of the entire system, from Kinect scans to helmet recommendation. A fully automated commercial helmet recommendation system is shown in Figure 6-2. The system should automatically read in 3D head shape data after the client is scanned by the Kinect sensor, and return as output the helmet recommendation through a user interface.

The helmet recommendation system could also be improved by incorporating information from helmet manufacturers about the design of helmets – how the helmets are intended to fit, the pressure points at which the manufacturers expect the helmet to touch the skull, and how the shape of the outer helmet shell layer is intended to fit head shapes.

Many helmets also have an adjustable fit system. Some helmets allow the length to be adjusted by loosening screws on the sides of the helmet and then pulling apart the front and back sections. Similarly, the width of the helmet may be adjustable. Other helmets have side flaps that can be pushed up in order for the helmet shell sections to be adjusted. The helmet recommendation system could be expanded to take into account the range of helmet sizes possible with adjustment.

In the longer term, it may become practical to develop a system to design custom made helmets for clients based on Kinect scans of their heads, rather than just recommend existing helmets on the market. Alternatively, this system could recommend custom foam liners that best fit the client. Future research may also investigate different shapes of foam besides flat layers of padding, similar to the design of tire treads, and their effects on reducing rotational acceleration.
Bibliography


Appendix A
Slice Extraction Procedure Using Slicer

This appendix is a continuation of Section 4.1 and describes the details of the extraction of 2D slices from 3D head models using Slicer and Python code.

**Step 1: Open and view the head model in Slicer**

Open the head models (given as .ply files) using File → Open. The models can be viewed under the Models module.

First, display the head model by selecting it under Scene (in the Modules module) and turning on both Display → Visibility → Visible and Slice Intersections Visible. Make sure no other model has its visibility turned on.

Note that in the default (Conventional) view, the 3D model of the head is displayed at the upper right section, and the lower right section contains 3 panes showing the red (axial), yellow (sagittal) and green (coronal) slices. The slices do not have to be axial, sagittal or coronal however – they can be adjusted to be at an oblique angle. This is called a reformat slice in Slicer and can be set by the Reformat module.
Step 2: Use scripts in the Python console

This is preliminary code that should be executed in order for the other steps starting at Step 3 to work. Open the Python console in Slicer through View → Python Interactor. Run the following code by pasting it into the console and press Enter:

```python
lm = slicer.app.layoutManager()
red = lm.sliceWidget('Red')
redLogic = red.sliceLogic()
redSliceNode = redLogic.GetSliceNode()
reformatLogic = slicer.modules.reformat.logic()
```
Step 3: Determine pixels to distance ratio

The distance per pixel of an image extracted from Slicer is important, since this allows the Helmet Fit Viewer program to compute distance measurements. Slicer measures units of distance in millimetres. The distance that corresponds to each pixel on the slice images is determined by the Dimensions and Field of View in Slicer. The formula for calculating pixels to distance ratio is:

\[
\frac{\text{Pixels}}{\text{Distance (mm)}} = \frac{\text{Dimensions}}{\text{Field Of View}}
\]

These parameters can be seen under View Controllers Module → Slice Information with the Red slice node selected, and also by using the following code in the Python console (after Step 2 has been completed):

```python
redSliceNode.GetDimensions() # e.g. = (500, 500, 1)
redSliceNode.GetFieldOfView()
```

For our purposes, the images are to be 500 by 500 pixels in size – the value of this parameter could be changed to any image size. To set the dimensions, resize the window of the Slicer program so that the Red slice pane is also resized, until the dimensions as displayed in the View Controllers module or Python console is of the desired size (here, 500 by 500 by 1). If needed, set the view in Slicer to Red Slice Only so that the Red slice takes up the entire display window.

This can also be set in Python using `redSliceNode.SetDimensions(500, 500, 1)`, but the dimensions may be set to different values than the size of the red slice window. For example, if the dimensions are set to (500, 500, 1) in Python and the red slice window size is 400 by 400 pixels, then only the
central 400 by 400 pixel section of the 500 by 500 pixel image is displayed on the screen (and captured by SceneView screenshots).

The field of view is set in Python:

```python
redSliceNode.SetFieldOfView(250, 250, 1)
```

If the field of view is set to the same values as the dimensions, then 1 pixel is equal to 1 millimetre. This is most convenient for calculations, but for our purposes we want a higher resolution of 0.5 mm per pixel, since head (and helmet) sizes are roughly 20 cm or 200 mm in length and a larger image is preferred. Therefore, set the field of view to be (250, 250, 1), making 1 pixel be 0.5 mm.

**Step 4: Locate the standard head slice plane**

Slicer allows for head slices to be viewed within the RAS (Right, Anterior, Superior) coordinate system in which each slice can be defined by its z-axis value. Units in Slicer are measured in millimetres, and by default, axial spacing is set to 1.0 so that slices are viewed at 1 mm intervals (ex. z = 37.0, z = 38.0, etc.)

In order to extract the standard head slice, the location of the standard head slice plane is indicated by placing 3 fiducials (landmarks).

First, do the following in Slicer to display the slice plane:

- In the View Controllers module, turn on Slice Visible and Widget Visible for the red (Axial) slice.
• In the Model To Label Map module, select Output Volume → Create and Rename New Volume (which is called “Output Volume” by default). Then select the newly created volume name (“Output Volume”) for both Input Volume and Output Volume, and press Apply.

If the slice plane is not located on the head model, drag it so that it is in position. The up and down position (offset) can only be set using the Python console:

```
redLogic.SetSliceOffset(offset) # ex. offset = 100
```

Now place 3 landmarks (fiducials) about 1 inch (25 mm) above the eyes and at the back of the head (about where the inion is). They can be placed using the Fiducial button and viewed in the Markups module in Slicer. The Ruler annotation can be used to measure distances and place the fiducial 25 mm above the eyes.

**Step 5: Extract the head slice**

Given the 3 fiducials, run the following Python script. This script produces the plane of intersection by calculating the normal to the plane and slice offset. The plane of intersection is aligned with the 3 fiducials, as shown in Figure 4-7.

(Note: the following Python script assumes the fiducials list under Markups is called “vtkMRMLMarkupsFiducialNode1” – this may be different if multiple lists were made. Check the Data module with “Display MRML ID’s” on.)
import math

p1 = [0, 0, 0]; p2 = [0, 0, 0]; p3 = [0, 0, 0]

fiducials = slicer.util.getNode("vtkMRMLMarkupsFiducialNode1")

fiducials.GetNthFiducialPosition(0, p1)
fiducials.GetNthFiducialPosition(1, p2)
fiducials.GetNthFiducialPosition(2, p3)

plx = p1[0]; ply = p1[1]; plz = p1[2]
p2x = p2[0]; p2y = p2[1]; p2z = p2[2]
p3x = p3[0]; p3y = p3[1]; p3z = p3[2]

# calculate the normal as the cross product of two vectors on the plane
vector1 = [p2x - plx, p2y - ply, p2z - plz]
vector2 = [p3x - p2x, p3y - p2y, p3z - p2z]

vector1x = vector1[0]; vector1y = vector1[1]; vector1z = vector1[2]
vector2x = vector2[0]; vector2y = vector2[1]; vector2z = vector2[2]

nx = vector1y*vector2z - vector1z*vector2y
ny = vector1z*vector2x - vector1x*vector2z
nz = vector1x*vector2y - vector1y*vector2x

# orient normal so that positive z is upwards
if nz < 0:
    nx = -nx
    ny = -ny
    nz = -nz

normal = [nx, ny, nz]

reformatLogic.SetSliceNormal(redSliceNode, nx, ny, nz)

# normalize normal, then get z-intercept based on equation of plane in form
nx_n = nx / math.sqrt(pow(nx, 2) + pow(ny, 2) + pow(nz, 2))
ny_n = ny / math.sqrt(pow(nx, 2) + pow(ny, 2) + pow(nz, 2))
nz_n = nz / math.sqrt(pow(nx, 2) + pow(ny, 2) + pow(nz, 2))

z_intercept = nx_n*p1x + ny_n*p1y + nz_n*p1z
redLogic.SetSliceOffset(z_intercept)

The result should be the display of the standard head slice in the Red Slice node, as illustrated in Figure 4-8.

**Step 6: Save the slice images**

The extracted standard slice images are captured using the Scene Views module. The following Python code captures the images as Scene Views with a white background:

```python
# extract just the standard slice
offset = redLogic.GetSliceOffset()
sceneViewsLogic = slicer.modules.sceneviews.logic()
qPixmap = qt.QPixmap().grabWidget(red)
# removes the top slider bar
qPixmap2 = qPixmap.copy(0, 15, qPixmap.width(), qPixmap.height())
qImage = qPixmap2.toImage()
imageData = vtk.vtkImageData()
slicer.qMRMLUtils().qImageToVtkImageData(qImage,imageData)
sceneViewsLogic.CreateSceneView("Slice_" + str(offset), "", 1, imageData)
```

The Scene Views can then be saved to file as .PNG images.
If a slice sets approach is used (Section 3.5.3), then a stack of slices around the standard slice should be captured, for instance at every 1 mm above and below the standard slice. This can be done using the following Python code:

```python
# capture stack of slices for every 1 mm (50 mm above and below plane) and save as Scene Views
offset = redLogic.GetSliceOffset()
min = -50
max = 50
for inc in range(min, max):
    redLogic.SetSliceOffset(offset + inc)
    sceneViewsLogic = slicer.modules.sceneviews.logic()
    qPixmap = qt.QPixmap().grabWidget(red)
    qPixmap2 = qPixmap.copy(0, 15, qPixmap.width(), qPixmap.height())
    qImage = qPixmap2.toImage()
    imageData = vtk.vtkImageData()
    slicer.qMRMLUtils().qImageToVtkImageData(qImage, imageData)
    sceneViewsLogic.CreateSceneView("Slice_" + str(offset + inc), "", 1, imageData)

redLogic.SetSliceOffset(offset)  # restore slice position
```
Step 7: Adjust rotation of head slice (if necessary)

Rotation of the head slice image (not the head slice plane itself) can be adjusted manually in the Reformat module ➔ IS slider. Alternatively, this can also be done algorithmically by iteratively rotating the head slice (for instance by every 1° of rotation) and finding the rotated slice that best fits an ellipse with vertical and horizontal axes. This can be done in Slicer after modifying the Reformat module source code to allow rotation to be set using the Python console. (As of Slicer v4.3.1, this can only be done using the Reformat module GUI).
Appendix B
GREB Ethics Application

The following section contains the General Ethics Research Board (GREB) application that we submitted in order to conduct head scanning on participants. GREB approval is required for any experiment that involves human participants. The GREB application consists of both the main application form and the Letter of Information given to all participants prior to the head scanning experiment. Also included is the letter we received from GREB that approved our application.
General Info

File No: 6013597
Title: GCISC-078-14 A prototype helmet fitting system for concussion protection
Start Date: 17/09/2014
End Date: 
Keywords: concussion protection, computer science, helmet fitting

Project Members

Principal Investigator
Prefix: Dr.
Last Name: Blostein
First Name: Dorothea
Affiliation: Faculty of Arts and Science\School of Computing
Rank: Professor
Gender: Female
Email: blostein@queensu.ca
Phone1: 613 533-6537 x6537
Phone2: 
Fax: 
Mailing Address: Goodwin Hall 
Institution: Queen's University
Country: Canada
Comments: 

Others

<table>
<thead>
<tr>
<th>Rank</th>
<th>Last Name</th>
<th>First Name</th>
<th>Affiliation</th>
<th>Role In Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research Administrator</td>
<td>Whiteway</td>
<td>Karilee A</td>
<td>Faculty of Arts and Science\School of Computing</td>
<td>Research Coordinator</td>
</tr>
<tr>
<td>Master's Student</td>
<td>Cai</td>
<td>Xingcheng</td>
<td>Faculty of Arts and Science\School of Computing</td>
<td>Co-Investigator</td>
</tr>
</tbody>
</table>

Common Questions
1. CORE Completion

<table>
<thead>
<tr>
<th>#</th>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Applicant: CORE Completion *Students and staff submitting ethics applications must also attach their CORE certificate. To complete CORE go to <a href="http://pre.ethics.gc.ca/eng/education/tutorial%7B-%7Ddidacticiel/">http://pre.ethics.gc.ca/eng/education/tutorial{-}didacticiel/</a> If desired, CORE can appear on your transcript as SGS804. (Click Info tab for further details).</td>
<td>N/A</td>
</tr>
</tbody>
</table>

2. Project details

<table>
<thead>
<tr>
<th>#</th>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Level of Research</td>
<td>Faculty research</td>
</tr>
<tr>
<td>2.2</td>
<td>If you are a student, please add your Supervisor's name in the box below. Also, make sure to add you Supervisor to PROJECT INFO TAB under Other Project Member info. If you are a Faculty member indicate N/A in the field below.</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Abstract (300-500 words) See Info tab for further details.</td>
<td></td>
</tr>
</tbody>
</table>

Helmets are widely used as protection against sports-related concussions. Our eventual goal is to construct a helmet-fitting recommendation system that can be readily used in a retail or clinical setting. During use of this system, the operator (an employee at the retail outlet or clinic) uses a Kinect sensor to scan the client's (customer's) head shape. The system matches the client's head shape to helmet shapes from a database containing information from a selection of off-the-shelf helmets. Finally, the system recommends which helmet model(s) are most likely to offer the client the best concussion protection. The recommendation is based upon the latest concussion information provided by an expert neurosurgeon.

The objective of this project is to create a prototype system that helps the neurosurgeon make recommendations about helmet fit. The system takes as input images extracted from 3D scans of a number of helmets along with the scan of a person's head. It then aligns each helmet to the head to determine the degree to which the helmet fits, and displays statistics that are of use to the neurosurgeon.
Method (Explain protocols in 1000 words) See Info tab for further details.

The input data required for this project includes the 3D scans of heads from a number of participants. The participants will be informally recruited from students in the School of Computing at Queen's and includes the investigators in this project (Dr. Blostein and Mr. Cai). Each participant will first be given the Letter of Information and the option to either sign the letter to proceed or to decline. The participant will be allowed to decline during the procedure at any time. If the participant agrees to proceed, they will be asked to put on a swim cap. The swim cap serves to compress the hair so that scan will more accurately reflect the participant's head shape.

The participant's head will then be scanned using a Kinect device. Kinect sensors are in widespread use in the videogame industry, with over 24 million units sold as of Feb. 2013. A Kinect device consists of a depth sensor and RGB camera. The depth sensor consists of an infrared laser projector and a monochrome CMOS (complimentary metal-oxide semiconductor) sensor to capture depth images using a structured light technique. The infrared laser projects a speckle light pattern onto the scene. Kinect then analyzes the deformation of the light pattern to produce a depth map that represents a 3D image.

The scanning will be carried out using one of the following two procedures:

(1) The Kinect sensor is placed in a fixed position while the participant sits in a revolving chair. Upon hearing a beep, the participant will slowly rotate themselves in the chair as their head is scanned by the Kinect sensor. The rotation allows the head to be scanned at different angles in order to produce the final 3D head model.

(2) The participant sits in a stationary position while an operator moves the Kinect sensor around the participant's head to scan it.

In both cases the procedure is not invasive as the sensor will never touch the participant's head: the sensor is held at least 20 cm away from the participant's head. Using either procedure, the scanning will take between 30 seconds to 2 minutes to complete. After the scan is completed, the participant removes the swim cap and the scan is saved as a 3D model by the scanning software.
2.5 Conflict of Interest (COI) | NO
2.6 If YES above, please explain
2.7 Funding | Funding Received
2.8 Sponsor agency | NSERC
2.9 Location - Will the data be collected on Queen's campus or affiliated hospitals? (Web-based surveys are considered on campus) | YES
2.10 If NO above, please describe. (NOTE: all off-campus activities require OCASP clearance (See https://webapp.queensu.ca/safety/ocasp).
2.11 Are other approvals or permissions required? e.g. Off Campus Activity Safety Policy (OCASP), School Board Approval, Community or Institutional Approval. | NO
2.12 If YES, above, please identify and describe the necessary authorizations.
2.13 If you will be using archived data from a previous research project, please describe the data source and identify the custodian of the database (if known).

3. Recruitment

<table>
<thead>
<tr>
<th>#</th>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Number of participants</td>
<td>20</td>
</tr>
<tr>
<td>3.2</td>
<td>Sources of Participants - Check all that apply</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Queen's undergrad or graduate students</td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>If OTHER above, please describe. If you selected SCHOOLS above, please identify the School Board(s) from whom permission will be sought.</td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>Description of Study Participants</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Participants must be able to put on a swim cap and rotate themselves in a revolving chair.</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>Will vulnerable population(s) be recruited? (See info (i) tab for description).</td>
<td>NO</td>
</tr>
<tr>
<td>3.6</td>
<td>If YES above, please describe the population and any special measures that will be needed to address their vulnerable status</td>
<td></td>
</tr>
</tbody>
</table>
3.7 Will Aboriginal peoples in Canada be recruited or Aboriginal communities studied?  NO

3.8 If YES above - Has band approval been obtained?  N/A

3.9 Will the findings be reviewed by an Aboriginal community before dissemination?  N/A

3.10 If NO to 3.8 and/or 3.9, please explain

3.11 Describe how and by whom potential participants will be recruited.

Participants will first be informally recruited within the investigator's lab room, the Joints and Connective Tissues lab of the School of Computing. In addition, an email invitation will be sent out to the social mailing list for the School of Computing's graduate students and staff (social@cs.queensu.ca).

3.12 Please describe procedures should someone wish to withdraw?

The participant will be allowed to withdraw immediately at any time before or during the procedure by saying "I wish to withdraw" or similar.

3.13 If remuneration or compensation will be offered, please provide the details. Indicate N/A if not applicable.  N/A

4. Risk Assessment

<table>
<thead>
<tr>
<th>#</th>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Will this study involve any of the following (Check all that apply)</td>
<td>No known risks</td>
</tr>
</tbody>
</table>

Please describe risks selected from above or any other risks. Indicate N/A if not applicable.

Kinect uses an infrared laser projector. The infrared laser meets IEC 60825-1 standards as a Class 1 laser device. Class 1 is the safest of all classes and means the laser is safe under all normal use conditions: the laser emits less than 25 microwatts and the maximum permissible exposure (MPE) cannot be exceeded if viewed by the naked eye or eyeglasses. The procedures in this study last for at most 2 minutes, so the laser projector will not impact participants for any prolonged period of time.
4.3 Please describe your plan to minimize these risks and describe how you will provide support to participants in the context of these risks. Indicate N/A if not applicable.

<table>
<thead>
<tr>
<th>#</th>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N/A</td>
</tr>
</tbody>
</table>

5. Benefits

<table>
<thead>
<tr>
<th>#</th>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Please describe the potential benefits of the research to the participants in your project, the research community and/or to society at large</td>
<td>There are no direct benefits to the participants. The research community would benefit as this helps neurosurgeons researching helmet fitting, and society would potentially benefit if this leads to the recommendation of helmets that reduce the risk of concussions.</td>
</tr>
</tbody>
</table>

6. Privacy and Confidentiality

<table>
<thead>
<tr>
<th>#</th>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Please check all that apply to your project for: (1) data collection, (2) data processing and (3) data storage. For definitions of each category, click the Info (i) tab.</td>
<td>De-identified/coded information (i.e., remove direct identifiers using code names or numbers)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td>Based on 6.1, explain if and how you intend to protect the privacy of your participants. If not, why not?</td>
<td>No identifying information will be collected except the participant's signature on the consent form. The data will be stored in files labelled with anonymous numeric codes.</td>
</tr>
<tr>
<td>6.3</td>
<td>Will information about the participants be obtained from sources other than the participants themselves?</td>
<td>NO</td>
</tr>
<tr>
<td>6.4</td>
<td>Will the information on individual participants be disclosed to others? (Disclosure could be during data acquisition, data reduction or publication).</td>
<td>YES</td>
</tr>
<tr>
<td>6.5</td>
<td>If you answered YES to 6.3 or 6.4, please explain</td>
<td></td>
</tr>
</tbody>
</table>
Images from the head scans could be used in a thesis or publication, or as input for the helmet fitting software that this project aims to develop. Display of a 3D scan of a participant's head could allow for that participant to be identified. However, for this project, only horizontal 2D slices of the 3D scan will be used, and they will only be from parts of the head above the eyes. Participants will see examples of the 2D slices resulting from a head scan, and they will be informed that such 2D slices of their head shape may be published in a thesis or technical papers.

| 6.6 | Will the participants be made aware of this disclosure? | YES |
| 6.7 | Will the confidentiality of the participant's identity be protected to the extent possible? | YES |
| 6.8 | If you answered No above, please explain | |
| 6.9 | Could publication of the research allow participants to be identified? | NO |
| 6.10 | If you answered YES above, please explain | |
| 6.11 | Will anyone other than the principal investigator or co-applicants listed on the application have access to the data during collection or processing? | NO |
| 6.12 | Please identify who will have access? | |
| 6.13 | Will the person identified above (e.g. translator, transcriber, RA, etc.) sign a Confidentiality Agreement? | N/A |
| 6.14 | Will the data or aspects of the data be encrypted? | NO |
| 6.15 | Provide specific details about security procedures for the data, methods of data transcription as well as plans for the ultimate disposal of records/data. | The data will be stored in files with numeric codes as the filenames. The numeric codes would have no indication of the person's name or identity. |

7. Informed Consent

<table>
<thead>
<tr>
<th>#</th>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Will participants be given a written Letter of Information (LOI)?</td>
<td>YES</td>
</tr>
<tr>
<td>7.2</td>
<td>If you answered NO above, please explain</td>
<td></td>
</tr>
<tr>
<td>7.3</td>
<td>Will participants be asked to sign a written consent form (may be combined with LOI)?</td>
<td>YES</td>
</tr>
<tr>
<td>Question</td>
<td>Answer</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------------------------------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>7.4 If you answered NO above, please explain:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5 Does the research project involve deception of the participant?</td>
<td>no deception</td>
<td></td>
</tr>
<tr>
<td>7.6 Describe the deception of the participant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.7 Describe the debriefing procedure for the participant, if applicable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.8 If participants are not in a position to give consent to participate, will written permission be acquired from a person with legal authority?</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>7.9 If participants are children or other population unable to legally provide consent, what procedure will be followed?</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
Letter of Information

1. This research is being conducted by Dr. Dorothea Blostein, Professor at the School of Computing, Queen’s University, Kingston, Ontario, Canada and Xingcheng Cai, Master’s student at the School of Computing.

2. The research topic is “A Prototype Helmet Fitting System for Concussion Prevention”. The project involves the scanning of a number of participants’ heads using a Kinect sensor in order to produce 3D head scans.

3. A computer program will be used to compare the 3D head scans to 3D scans of helmets. The computer program will produce a variety of measurements that characterize the fit between the head and helmet. This information will be given to a neurosurgeon who is researching how to fit helmets in order to reduce the risk of concussions.

4. Participants will be asked to wear a swim cap over their head that may fit tightly and compress the participant’s hair.

5. Participants may be asked to rotate themselves in a revolving chair around the Kinect sensor. This is expected to last for 30 seconds. Participants may also be asked to sit still in a chair while an operator moves a Kinect sensor around the participant’s head.

6. The scanning is expected to last no more than 2 minutes, and the duration of the entire procedure is expected to last no more than 5 minutes.

7. There are no known physical, psychological, economic or social risks involved with the participation in the research. Participants will be scanned by a Kinect sensor, a device with widespread use in the videogame industry that has sold over 24 million units. The Kinect sensor contains an invisible infrared laser projector. The infrared laser is certified as a Class 1 laser product, which means it is safe to the eye under all normal conditions. This off-the-shelf consumer electronics device does not expose participants to any significant amount of radiation and no chemicals are involved.

8. Participation in the research project is completely voluntary and participants are free to withdraw at any point of time during the research for any reason they may deem fit.

9. This research will be part of the M.Sc. dissertation that will be submitted to Queen’s University. The academic community and any other person interested in it will have access to it through Queen’s University. It may also be published in the form of a scholarly article at a later stage and can be thus available to the general public or as a secondary source for other researchers. The M.Sc. thesis and scholarly articles will not contain information that reveals the identity of a participant: we will not publish 3D head shapes of any participants who are not the investigator or co-investigator. We may publish 2D slice images extracted from some of the participants’ head scans. You may ask to see examples of a 3D head shape and 2D slices of this head shape, to verify that a person’s identity cannot be determined from a 2D slice of the head shape.

10. Any ethical concerns about the study may be directed to the Chair of the General Research Ethics Board at chair.GREB@queensu.ca or 613-533-6081.

11. Any questions about study participation may be directed to the graduate student, Xingcheng Cai (cai@cs.queensu.ca) or the supervisor Prof. Dorothea Blostein (blostein@cs.queensu.ca)

12. I have read the Letter of Information and have had all questions regarding it answered to my satisfaction.
September 17, 2014

Dr. Dorothee Blostein  
Professor  
School of Computing  
Queen's University  
Goodwin Hall  
Kingston, ON, K7L 3N6

GREB Ref #: GCISC-078-14; Romeo # 6013597  
Title: "GCISC-078-14 A prototype helmet fitting system for concussion protection"

Dear Dr. Blostein:

The General Research Ethics Board (GREB), by means of a delegated board review, has cleared your proposal entitled "GCISC-078-14 A prototype helmet fitting system for concussion protection" for ethical compliance with the Tri-Council Guidelines (TCPS) and Queen's ethics policies. In accordance with the Tri-Council Guidelines (article D.1.6) and Senate Terms of Reference (article G), your project has been cleared for one year. At the end of each year, the GREB will ask if your project has been completed and if not, what changes have occurred or will occur in the next year.

You are reminded of your obligation to advise the GREB, with a copy to your unit REB, of any adverse event(s) that occur during this one year period (access this form at https://eservices.queensu.ca/romeo_researcher/ and click Events - GREB Adverse Event Report). An adverse event includes, but is not limited to, a complaint, a change or unexpected event that alters the level of risk for the researcher or participants or situation that requires a substantial change in approach to a participant(s). You are also advised that all adverse events must be reported to the GREB within 48 hours.

You are also reminded that all changes that might affect human participants must be cleared by the GREB. For example you must report changes to the level of risk, applicant characteristics, and implementation of new procedures. To make an amendment, access the application at https://eservices.queensu.ca/romeo_researcher/ and click Events - GREB Amendment to Approved Study Form. These changes will automatically be sent to the Ethics Coordinator, Gail Irving, at the Office of Research Services or irvingg@queensu.ca for further review and clearance by the GREB or GREB Chair.

On behalf of the General Research Ethics Board, I wish you continued success in your research.

Yours sincerely,

Joan Stevenson, Ph.D.  
Chair  
General Research Ethics Board

c: Mr. Xingcheng Cai, Faculty Supervisor  
Ms. Karilee Whiteway, Research Coordinator