A Shape-Based Helmet Fitting System for Concussion Protection

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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 paper presents the design of a prototype helmet fitting recommendation system using shape-based helmet fitting. The shape-based helmet fitting 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. 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.**

I. INTRODUCTION

Concussions and head injuries are major health concerns that affect an estimated 300,000 people in the United States [2] and every 110 out of 100,000 Canadians annually [3]. Some researchers believe that many concussions go underreported and the actual incidence of concussions is much higher [4]. Helmets are widely used as protection against sports-related head injuries, but the effectiveness of helmets in preventing concussive injuries is still under research.

At present, standards organizations such as the Canadian Standards Association (CSA) test and accept helmets by their ability to reduce linear acceleration forces. 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 [5][6], which may lead to new guidelines for helmets to protect against rotational as well as linear acceleration. Rotational acceleration occurs when an impact force to the head causes it to rotate, which may lead to concussive and diffuse axonal injuries [7][8].

Rotational acceleration can be tested using the Kingston Impact Simulator (KIS), a system developed by one of the authors of this paper (FS). The KIS provides a repeatable and precise mechanism to test the degree to which helmets reduce the rotational acceleration experienced by a head form [5].

The degree to which a helmet reduces rotational acceleration may be related to how well a helmet fits on an individual's head. Helmet fitting can take into account the size and shape of the helmet compared to the head, as well as material properties such as the compressibility of foam layers. Different foam materials can have different levels of energy absorption during head impact [12].

The relationship between concussion prevention and force transmission to the head is still under research, but a helmet that is too tight or too loose would be inherently a bad fit. 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 injuries, or be displaced during a crash [13].

Currently, consumers often do not choose the best fitting helmet due to a lack of information. Studies have shown that cyclists often wear improperly fitted helmets [13], and proper helmet fitting can reduce concussion risk by 41% in motocross riders [11]. Our long-term goal is to design a helmet recommendation system for use in a retail setting that provides software support to improve upon current methods of choosing helmets. In this paper, we show progress towards this goal with our design of a shape-based prototype system. This system recommends the best fitting helmet for a client after the client's head shape is scanned, and displays statistics and information that would help a concussion researcher formulate recommendations about helmet fit. The client's head is scanned using a Kinect sensor, which produces a 3D model of the head. The system also contains a database of pre-scanned helmets. The system extracts 2D slice images from both the head and helmets, and compares the slice images to determine the degree to which the helmet fits.

Figure 1. Left: a Bauer 3500 hockey helmet. Right: the 3D model produced by a Kinect scan of this helmet. Top row shows a side view and bottom row shows an interior view.

II. DESIGN OF THE HELMET FITTING SYSTEM

The main challenge is to design a helmet fitting system that extracts suitable measurements from head and helmet shape data, and presents it in a comprehensible way to a concussion researcher. We address this by designing a system consisting of the following components:

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- *Head and helmet scanning using Kinect*

The input to the helmet fitting system consists of data produced by a Kinect sensor: a 3D head scan of a client's head, and 3D helmet data for a collection of helmets. We chose to use a Kinect sensor because it is a safe, portable, inexpensive and widely used consumer device, and therefore it would be acceptable for use on clients in a retail setting.

We designed a repeatable and safe protocol for scanning head shapes, and the experimental procedures described in this paper were approved by the General Research Ethics Board (GREB) at Queen's University [1]. Figure 1 shows the 3D model of one of the scanned helmets.

- *Helmet fitting using slice extraction*

We developed a slice extraction based method for helmet fitting, after considering alternate approaches [1]. Using this method, the system processes the input data as needed by extracting a 2D slice from the head and helmet models, and uses the slices to make comparisons between the head and helmet.

- *Viewing slices using Helmet Fit Viewer*

We developed a new program, Helmet Fit Viewer, which reads in the 2D slice data and displays information about helmet fit that would be useful for a concussion researcher.

These three components are discussed in more detail in the following sections.

III. HEAD AND HELMET SCANNING USING KINECT

For our project, we scanned heads and helmets using a Microsoft Kinect depth sensor connected to ReconstructMe – commercial software that converts Kinect scans to 3D meshes in .ply format. We created a database of 15 head shapes from scans of participants (10 male and 5 female, ranging in age from 20 to 60) from the School of Computing, and 3 helmet shapes from scans of medium-sized hockey helmets.

The head scans are obtained using the following procedure. First, a 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. Next, each participant wears a wig liner in order to compress their hair so that the scans indicate head shape more accurately without the interference of hair. Each participant then sits in a revolving chair while facing the Kinect at a distance of about 0.7 metres. Upon hearing a command to start, the participant slowly rotates in the chair (in either clockwise or counterclockwise direction) so that at least one full rotation is completed within 30 seconds. During this time, ReconstructMe is able to take a full 360^{o} scan of the participant from all angles and generates the resulting 3D model.

Helmets scans are similarly obtained using Kinect and ReconstructMe, but a moving Kinect sensor is used to scan a stationary helmet since both the inside and outside of the helmet must be scanned.

IV. HELMET FITTING USING SLICE EXTRACTION

We used a slice extraction method for our system. In this method, a near-axial 2D slice image is extracted from both the 3D head model of the participant and 3D helmet model that is 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. (Figure 2)

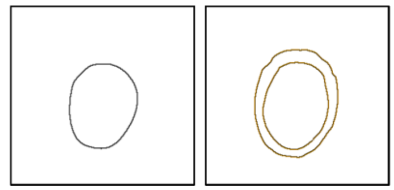

Figure 2. Left: a typical head slice. Right: a typical helmet slice.

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 [1].

We used 3D Slicer, an open-source software package for medical image processing, to read the 3D head and helmet models and extract 2D standard slices. In order to extract the standard head slice, the plane in which the standard slice is located must be identified.

In 3D Slicer, a plane is defined by its normal vector (with orientation) and offset (intercept on the z-axis). Planes are mathematically defined by three points. Our procedure is to identify 3 fiducials (landmark points) 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.

In the prototype system, 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). As shown in Figure 3, the three fiducials define the plane intersecting the head that contains the head slice image of interest. This anatomical location of the fiducials is chosen based on the recommendation of one of the authors (FS).

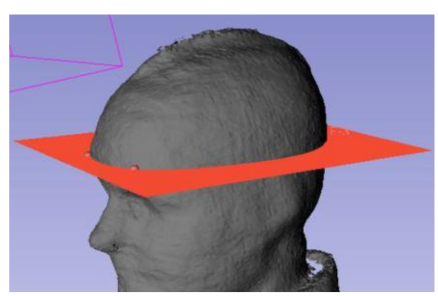

Figure 3. Slice plane of the head that is defined by 3 fiducials.

The result is a display of the standard head slice in 3D Slicer. The head slice images are captured in 3D Slicer with the help of a Python script, along with some manual adjustment to correct the orientation of the slice so that it is aligned with the sagittal and coronal planes. The images are then saved as .PNG files. (Figure 4)

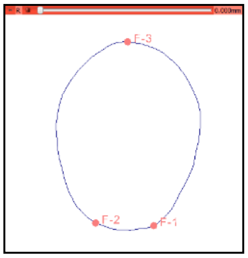

Figure 4. The red slice viewer in 3D Slicer, showing the extracted head slice and fiducials.

Helmet slices are extracted in 3D 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 are placed so that the standard helmet plane cuts through the helmet horizontally, by placing 2 fiducials on the front of the helmet and 1 fiducial on the back of the helmet [1]. Once the fiducials are placed, the helmet slice is similarly extracted in 3D Slicer and saved as an image.

Additional image pre-processing can be done to repair gaps in the slice images by using the closing operator from mathematical morphology, and to remove the outer boundary of the helmet slice (Figure 5). The images must be reduced to closed, single curves before being read by the Helmet Fit Viewer program.

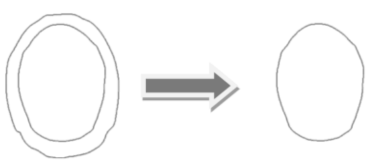

Figure 5. Removing the outer boundary of the helmet slice.

V. VIEWING SLICES USING HELMET FIT VIEWER

Helmet Fit Viewer is a program developed for this project using Qt, a cross-platform application and user interface framework written in C++. This program 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. (Fig. 6)

The user interface contains the following sections:

- *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 the Helmet Fit tab that displays measures of helmet fit. It also contains tabs for head shape information, and a section for user-defined pressure points and regions that would be used after material properties are known (see Future Work section).
- *Helmet and head viewing panel* at the lower left. When the user selects one of the helmets, the helmet slice image is superimposed onto the head. The user can drag around the helmet slice to alter its position relative to the head.

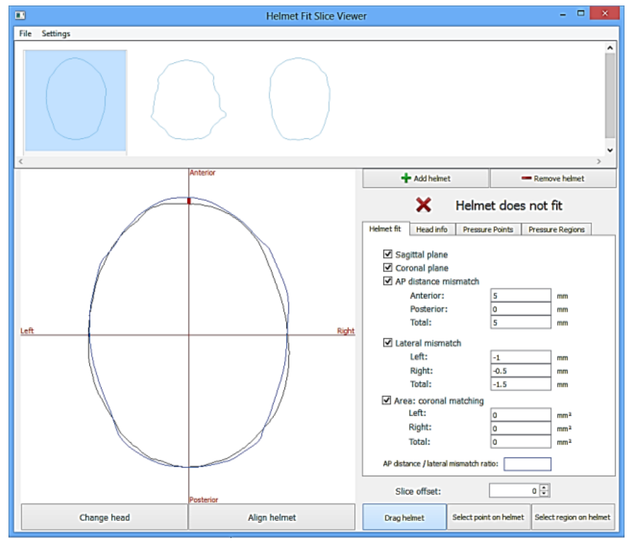

Figure 6. Screenshot of the Helmet Fit Viewer program.

A. Helmet Fit tab

The Helmet fit tab displays the following information, which is updated every time the user drags the helmet to a different position on the viewing panel: (Figure 7)

- *Sagittal plane* displays the vertical axis and *Coronal plane* displays the horizontal axis respectively. The axes pass through 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 at the anterior or posterior, the mismatch is positive, and negative if the helmet is inside the head. The total AP distance mismatch is the sum of the left and right mismatches.
- *Lateral mismatch* is similar to the AP distance mismatch, but instead highlights segments of the coronal plane (appearing as a horizontal line) between the helmet and head.
- *Area: coronal matching* displays the shaded region 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 plane. The area is also shown (in mm^2), if the helmet is outside the head at either the left or right.
- *AP distance to lateral mismatch ratio* is the ratio of the total AP distance mismatch to the total lateral mismatch.

If all of the top/bottom AP distance mismatches and left/right lateral mismatches are zero or positive, then the system automatically determines that it is either a *Snug fit* or *Loose fit*, otherwise it states *Helmet does not fit*. These definitions focus on the mid-sagittal and mid-coronal points – the front and back of the head and sides of the head approximately above the ears. A snug fit refers to a helmet that touches the head at the mid-sagittal and mid-coronal points, and is defined by all mismatches being at least 0 and less than or equal to a small ε, which we defined as 1 cm. A loose fit is defined by all mismatches being at least zero and at least one mismatch greater than ε.

Note that although the program can determine helmet fit, the precise measurements that indicate an ideal helmet fit are still under research. Therefore, the concussion researcher should still make the final assessment which may differ from the program's decision. In cases where the message is "loose fit", the researcher may decide that the helmet is not a good fit for the head if the gaps (mismatches) are too large. In the case of both snug and loose fits, the researcher may judge helmet fit to be poor if the AP distance to lateral mismatch ratio is not within a desired interval. In addition, the "Helmet does not fit" message is generated assuming the helmet is rigid, but in actuality helmet liners are compressible.

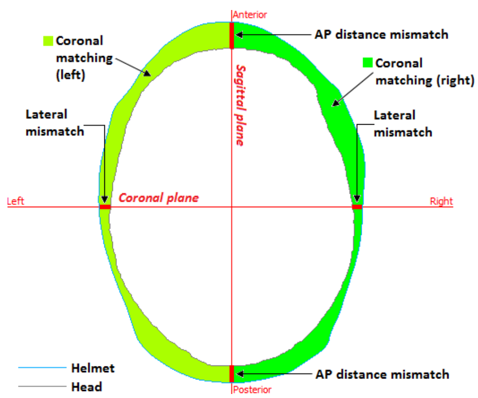

Figure 7. Measures of fit between the helmet and head, as displayed in the Helmet Fit Viewer's viewing panel.

VI. CONCLUSION

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 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, using the Helmet Fit Viewer user interface, shows measurements of helmet 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.

VII. FUTURE WORK

The long-term goal is the development of a fully automated helmet fitting 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 this goal, more research needs to be done on the science of helmet fitting for reducing concussions. Ongoing work in this area uses finite element model simulations of the brain and skull during impact [9][10].

It is important that material properties of helmets are included in software that assists with helmet fitting. We tested our shape-based system by having two participants wear helmets and comparing it to the results generated by the Helmet Fit Viewer. We found that in some instances when the system displayed "Helmet does not fit", the helmet actually was a tight fit that felt acceptable to the participant. This clearly demonstrates that shape information alone is not sufficient to accurately determine helmet fit: the compressibility of the foam padding layers plays a significant role. For future work, we need to collaborate with mechanical engineers to measure and interpret data about the compressibility of the helmet material layers. This information will be integrated with helmet shape data in order to improve the assessment of helmet fit.

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