Helmet Test Protocol

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Preface

This document outlines a procedure for testing football helmets using test conditions based on severe impacts in the National Football League during the 2015-2017 seasons. The test procedure builds upon the protocol developed by Viano et al. (2012) and Biokinetics LTD (Ottawa, Canada).

1. Test Equipment

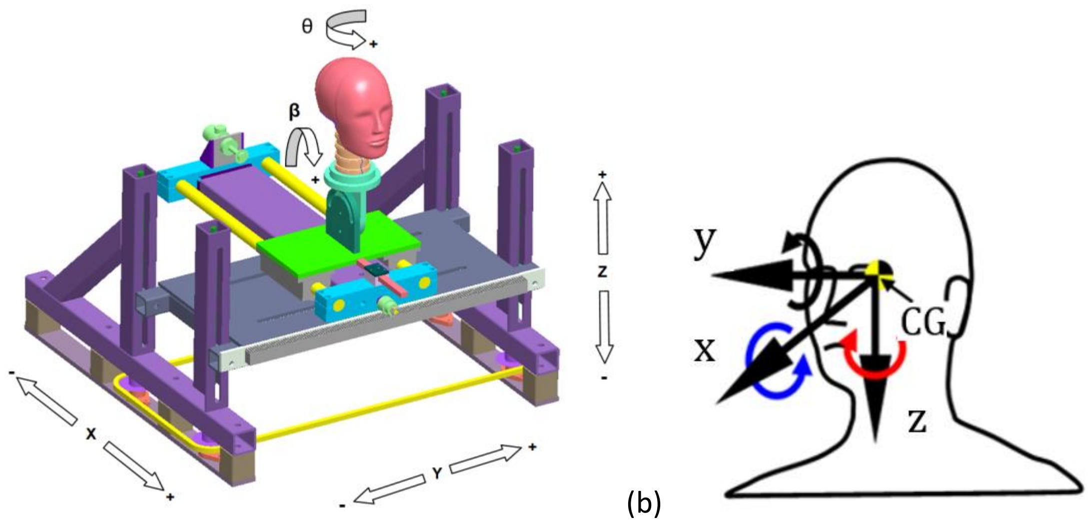
1.1 Impactor

The impactor shall be a linear ram having a total mass of 15.6 kg ± 3%, with the ram constrained to translational movement along its axis. The illustrations in this document are based upon the use of the Biokinetics linear impactor test apparatus, but this document has been written to accommodate other makes of test equipment. A 6-axis Hybrid III femur load cell (N6ACC11A, MG Sensor, Rheinmuenster, Germany, or equivalent) shall be attached in line with the impactor shaft to measure impact force. Note that the total mass (15.6 kg) is the sum of the un-instrumented ram including the end cap (14.5 kg) and the femur load cell (1.1 kg) masses. A load cell blank or a heavier end plate may be used for testing without a load cell, so long as the total impacting mass is 15.6 kg ± 3%. The impactor face shall consist of extruded nylon 6/6 in the shape of a spherical cap (140 mm radius sphere, 203 mm diameter cap) (see drawing in Appendix I). The spherical cap shall be attached with Velcro to a cylindrical piece of vinyl nitrile foam (VN600, DerTex, Inc.) (41.3 mm thick, 127 mm diameter), which in turn shall be attached with Velcro to a circular metal backing plate (127-mm diameter) on the ram.

The ram shall be accelerated to the desired test speed and then disengage from the propulsion source so that it strikes the specimen while at constant velocity. A compressed air supply dumped into a cylinder has been a suitable and repeatable propulsion source; however, other methods may also be used. The impactor ram shall be allowed to travel 17 cm ± 0.5 cm after engaging the headform and before engaging a braking mechanism. Pre-impact ram velocity shall be measured after the ram has disengaged the propulsion source, but prior to the ram impacting the helmet or headform. Laboratory temperature should be 72˚F ± 5˚F (22 ˚C ± 2 ˚C).

1.2 Head Positioning

The head and neck from a certified Hybrid III 50th percentile male anthropomorphic test device (ATD) should be mounted to a sliding carriage having a mass of 17.7 kg ± 5%. The Biokinetics slider table and carriage (Figure 1a) are used for testing, though a similar device with equivalent degrees of freedom, adjustability, and mass may be used. The carriage should be oriented parallel to the ram such that it is free to slide in the direction of impact. For reference, a right-hand laboratory coordinate system has been defined in which –X is the impact direction and +Z is vertically upward (Figure 1). Note that the local head coordinate system has been defined according to the Society of Automotive Engineers J211/1 document (Society of Automotive Engineers 2014).



(a)

Figure 1. (a) Laboratory coordinate system and Biokinetics slider table and carriage with the head in the reference position. The impactor ram travels in the –X direction. (b) Head coordinate system.

The mounting hardware to the carriage is constructed so that the initial position and rotation of the head are adjustable in five degrees of freedom. The sixth degree of freedom is rotation about the lab x-axis, which is arbitrary due to radial symmetry of the impactor face and foam pad about that axis. Therefore, the test apparatus effectively allows complete adjustability of the head in all degrees of freedom. On the Biokinetics slider table and carriage assembly, the head and neck are placed on a pivot that is connected to the carriage and may be rotated through an angle β about an axis parallel to the lab Y-axis. In addition, the head and neck may be rotated on the pivot through an angle θ about the long axis of the neck. These two angular adjustments allow the head to be positioned in a wide range of orientations. The entire table may be raised and lowered to adjust the lab Z position of the head. The table position may also be adjusted laterally (along the lab Y-axis), and the table may slide along the lab X-axis to the desired impact point (just after the ram clears the velocity measurement system while coasting).

Six impact locations are specified in terms of rotational and translational displacements of the Biokinetics slider table and carriage assembly from a head reference position (Table 1, Figure 1). The head reference position is established by, first, positioning the head with the neck vertical (β=0°) and the right side of the head (+Y-axis) facing the impactor (θ=90°). The table position is then adjusted along the Y and Z axes until the centerline of the impactor ram passes through the center of gravity (CG) marks on the dummy skull. Next, the head and neck are rotated 90 degrees through the angle θ so that the head faces the impactor (θ=0°). The head is then in the head reference position and the displacements in Table 1 may be used to orient the dummy head for each of the six impact locations. Note that because the CG of the dummy head is located anterior to the neck axis, rotating the dummy to face the impactor moves the CG of the head away from the centerline of the impactor. Thus, the head CG is not coincident with the impact vector when the head is in the reference position. Further, note that the Hybrid III dummy head is tilted approximately 4.75^{o} rearward (extension) when the neck is vertical. Thus, the head's z-axis is not parallel to the long axis of the neck and the angle θ is not in the head's x-y plane.

Table 1. Rotational and translational table displacements from the head reference position (see Figure 1a) for each of the 6 impact sites, and position of the head CG in the Y-Z plane (i.e., the plane normal to the axis of impactor travel).

	Translational (Table)		**Rotational (Table)**		**Head CG Position**	
Impact Site	**Y_{table} (mm)**	**Z_{table} (mm)**	**θ (deg)**	**β (deg)**	**Y_{CG} (mm)**	**Z_{CG} (mm)**
Side Upper (SU)	1	-18	90	25	1	-47
Oblique Front (OF)	35	-31	-45	25	12	-64
Oblique Rear (D)	27	-2	-157	11	8	-5
Side (C)	27	-2	-95	11	0	-7
Facemask Side (FMS)	-63	38	70	15	-64	26
Facemask Central Oblique (FMCO)	13	35	-20	-5	-5	35

Positioning systems other than the Biokinetics slider table and carriage assembly may be used. Positioning with an alternative system can be accomplished by matching the head/neck orientation and the location of the head CG achieved by each of the sets of table displacements shown in Table 1. The position (Y_{CG}, Z_{CG}) of the head CG in the Y-Z plane from the axis of the impactor travel (defined as Y = Z = 0) can be calculated using the known Hybrid III head/neck geometry as

$$Y_{CG} = (\sin\theta - 1)X_{off} + Y_{table} \quad \text{(Eqn. 1)}$$

$$Z_{CG} = -\cos\theta \sin\beta \, X_{off} + (\cos\beta - 1)Z_{off} + Z_{table} \quad \text{(Eqn. 2)}$$

where

Z_{off} = 310.3 mm is the distance in the Z direction from the head CG to the pivot point on the Biokinetics slider table and carriage assembly at the base of the Hybrid III neck when the head is in the reference position, and

X_{off} = 13.7 mm is that distance in the X direction.

To further define the impact locations, reference lines similar to those on the NOCSAE headform may be marked on the Hybrid III headform. These reference lines can then be used to mark the locations where a laser (or physical pointer) aligned with the center of the face of the ram and pointed in the lab -X direction would intersect the headform for each impact location (Figure 2, Table 2). First, a measuring tape or string should be wrapped around the Hybrid III skull such that its edge intersects the left and right CG marks on the headform and the nasion. By tracing along this line, a transverse plane of the head may be marked. Next, the measuring tape or string should be wrapped over the top of the head such that it intersects the left and right CG marks and the center of the top bolt hole on the head to identify a coronal plane of the head. Lastly, the measuring tape or string can be wrapped from the top of the skull where it intersects the center of the bolt hole and then down through the nasion and rear hole marking the sensor cube attachment point to mark the sagittal plane. Coordinates of the place where the laser mark intersects the headform relative to these reference lines are provided for each of the impact locations (Table 2). The distance measured along the surface of the skull from each reference line is also provided. Note that the directions provided for these distances are curvilinear and that measurements taken along the surface of the headform will not be purely along one coordinate axis.

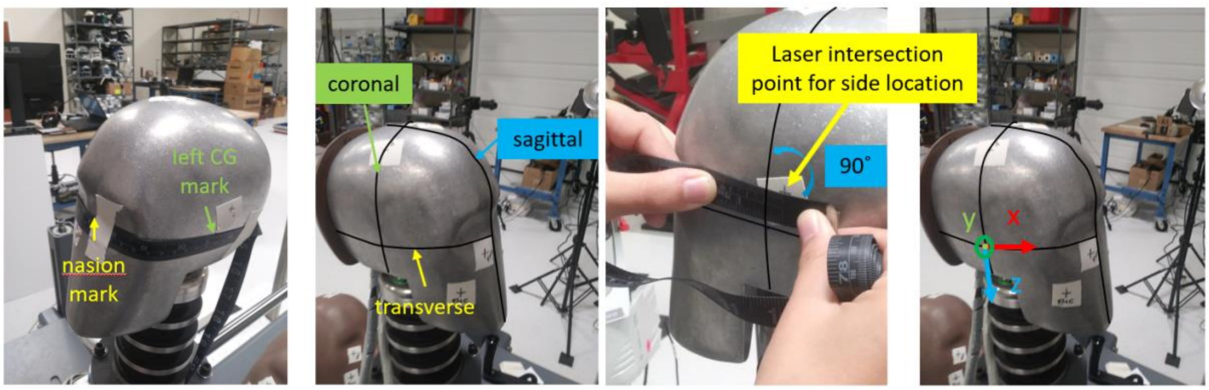


Figure 2. Procedure for marking reference lines and ram centered laser intersection locations on the Hybrid III skull.

Table 2. Coordinates of the ram center projection onto the Hybrid III skull and distances from Hybrid III reference lines marked according to the procedure depicted in Figure 2. The tolerance on these measurements is ±5mm.

Impact Site	Distance from Transverse Plane* (mm)	Distance from Sagittal Plane* (mm)	Distance from Coronal Plane* (mm)
Side Upper (SU)		48 (+y)	0
Oblique Front (OF)		18 (-y)	36 (+x)
Oblique Rear (D)	12 (-z)	50 (-y)	
Side (C)	20 (-z)		9 (-x)
Facemask Side (FMS)	19 (+z)	18 (+y)	
Facemask Central Oblique (FMCO)	54 (+z)	31 (-y)	

*Note that the directions provided for the distances are generalized and that measurements taken along the surface of the headform will not be purely along one coordinate axis.

2. Test Procedure

2.1 Helmet Positioning and Adjustment

For each helmet model, the manufacturer shall be asked to supply fit and positioning instructions to fit the 50^{th} percentile male Hybrid III headform. When provided, these instructions shall be used in place of the default positioning procedure described below, with the caveat that the instructions provided should be consistent with guidelines specified by the National Operating Committee on Standards for Athletic Equipment (NOCSAE). Helmet manufacturers may specify the use of commercially-available user-customizable fit padding for a given helmet model. Examples of this customizable fit padding include jaw pads which are commercially available in different thicknesses, and other comfort liner thickness options which can be used to fill space between the helmet shell and the head. Any instructions or parts submitted with or as part of the helmet should be consistent with the product literature and Components and Materials Description and/or Bill of Materials provided to the Safety Equipment Institute (SEI) as part of the certification process for that helmet model.

A parts list including part numbers or other identifiers for all liners, pads, chin straps, and facemask options shall be submitted for each new helmet model submitted for testing. If multiple sizes are available for the submitted model, parts lists for each individual size should also be submitted.

Prior to testing, helmet fit shall be checked using a TekScan Flexiforce ELF Force Measurement System (TekScan, Inc., South Boston, MA) with B201-L sensors (71 mm^2 sensing area) or equivalent. The pressure shall not exceed 77 kPa (69 kPa + 11% uncertainty) anywhere over the helmet surface interface with the headform. This threshold is based on a discomfort of helmet fit quantified by Jadischke et al. (2013) and the variability estimated from a Biocore study of repeated pressure measurements with a helmet positioned on a Hybrid III headform. The outer geometry of the Hybrid III headform is provided on the Biocore resources page.

Each helmet to be tested requires four (4) identical eye and oral protection-style facemasks and four (4) identical soft cup chin straps. If an eye and oral protection-style facemask style or soft cup chin cup is not offered by the manufacturer, an alternative style may be used at the discretion of the test engineer with guidance from the helmet manufacturer. Due to the potential for damage, the facemask and chin strap shall be replaced after high-speed impacts to the facemask. A nylon stocking shall be placed over the Hybrid III head in order to make it easier to take the helmet on and off the head. Once donned, the helmet shall be positioned squarely on the head to eliminate any left/right asymmetry. Additional measurements may be taken using a center rule or other measurement tool to confirm left/right symmetry of helmet landmarks about the centerline of the headform.

For each helmet, a manufacturer-supplied helmet positioning index (HPI) shall be used to position the brow of the helmet relative to the tip of the Hybrid III nose. An HPI of 75 mm shall be used to position the helmet if the manufacturer does not relay specific instructions. A tool similar to the NOCSAE nose gauge may be used to set the vertical distance from the bottom of the nose to the brow of the helmet (Appendix I and Figure 3). Manufacturers shall also be asked to supply a second measurement between the most inferior and anterior point at the center of the helmet and the outer posterior edge of the table clamp ring to ensure that the helmet is seated on the headform per manufacturer recommendations (Figure 3). If this “back distance” is not specified, the helmet shall be pulled onto the head to eliminate any gap present between the top of the head and the padding in the top of the helmet. The back distance shall then be measured and recorded for use in subsequent tests for repeatability of positioning.

Next, the chin strap shall be routed and adjusted according to manufacturer-specified instructions. Chin straps shall be adjusted in length until each strap is taut but can still be snapped or fastened by hand without undue effort. The adjustment position of the straps shall be recorded either by marking the strap directly or by measuring the distance between the center of the chin cup and the edge of the buckle. After each test, the facemask and chin strap shall be checked for damage and replaced if necessary. The helmet and chin strap shall be repositioned prior to each test, and slippage of the chin strap shall be noted in the test notes. In cases where the chin strap slips significantly or unbuckles, additional repeat tests may be performed to understand the variation in performance with and without the chin strap slippage.

Figure 3. Demonstration of the use of the nose gauge and helmet positioning index (left). A secondary measurement (back distance) between the center of the lower back of the helmet shell and the neck base may be measured using calibers to ensure that the helmet is seated on the head repeatably (right).

A laser positioning system (or alternative mechanism aligned with the center of the ram face) shall be used to indicate the projected center of the ram on the helmet for each impact location. This location shall be marked on the helmet and used with the HPI and back distance to ensure repeatable helmet positioning from test to test. Between each helmet test, the laser intersection mark shall also be checked with respect to the original location marked on the head skin. After testing at each impact location, the head skin shall be removed and the laser intersection point checked with respect to the mark on the Hybrid III skull.

2.2 Test Matrix

Each helmet sample shall be subjected to a total of 18 impact tests comprising the full combination of 3 test speeds and 6 impact locations (Table 1). The test speeds are 5.5 m/s, 7.4 m/s, and 9.3 m/s, with a tolerance of ± 2%. The standard protocol shall be to test 2 samples of each helmet model.

Testing shall be conducted in a sequence to maximize efficiency and minimize the adverse effects of equipment damage. Bare head tests (bolded) shall be intermingled to ensure system repeatability throughout the test matrix. The impact sites on the shell (Side, Oblique Rear, Side Upper, Oblique Front) shall be tested first. Tests shall be conducted one site at a time to minimize the time required to reposition the table and head between sites. Tests shall be conducted at all three speeds from slowest to fastest at each impact site before moving on to the next site. For the test sites that primarily involve contact with the facemask (Facemask Side and Facemask Central Oblique), testing shall be conducted at the two slowest speeds, with facemask and chin strap replacement occurring prior to and after the fastest speed. The testing and facemask replacement shall be performed in the following sequence:

- **2x Side with Bare Head @ 5.5 m/s**
- Side @ 5.5 m/s
- Side @ 7.4 m/s
- Side @ 9.3 m/s
- **2x Side with Bare Head @ 5.5 m/s**
- **2x Oblique Rear with Bare Head @ 5.5 m/s**
- Oblique Rear @ 5.5 m/s
- Oblique Rear @ 7.4 m/s
- Oblique Rear @ 9.3 m/s
- **2x Oblique Rear with Bare Head @ 5.5 m/s**
- **2x Side Upper with Bare Head @ 5.5 m/s**
- Side Upper @ 5.5 m/s
  Side Upper @ 7.4 m/s
- Side Upper @ 9.3 m/s
- **2x Side Upper with Bare Head @ 5.5 m/s**
- **2x Oblique Front with Bare Head @ 5.5 m/s**
- Oblique Front @ 5.5 m/s
- Oblique Front @ 7.4 m/s
- Oblique Front at 9.3 m/s
- **2x Oblique Front with Bare Head @ 5.5 m/s**
- **2x Facemask Side with Bare Head @ 5.5 m/s**
- Facemask Side @ 5.5 m/s
- Facemask Side @ 7.4 m/s, change facemask and chin strap
- Facemask Side @ 9.4 m/s, change facemask and chin strap
- **2x Facemask Side with Bare Head @ 5.5 m/s**
- **2x Facemask Central Oblique with Bare Head @ 5.5 m/s**
- Facemask Central Oblique @ 5.5 m/s

- Facemask Central Oblique @ 7.4 m/s, change facemask and chin strap
- Facemask Central Oblique @ 9.3 m/s
- **2x Facemask Central Oblique with Bare Head @ 5.5 m/s**

A minimum wait time of five (5) minutes shall be required between each test. All testing shall be conducted at room temperature (22 ˚C ± 2 ˚C) in an indoor climate-controlled environment.

2.3 Instrumentation and Data Processing

The Hybrid III head shall be instrumented to measure head kinematics in all six degrees of freedom. The testing may be conducted using a standard nine-accelerometer array package (NAP). The NAP data shall be processed using programming code (e.g., the algorithm supplied by the National Highway Traffic Safety Administration (DiMasi 1995)). A consistency check should be performed on the NAP data to check for erroneous sensor channels prior to and throughout testing (Takhounts 2009). Resources for performing a consistency check are provided on Biocore's software page. Other instrumentation schemes are acceptable so long as they measure head kinematics in all six degrees of freedom. A 6-axis upper neck load cell shall also be installed on the Hybrid III dummy. If the upper neck load cell is not used, a structural replacement should be inserted in its place. The velocity of the ram shall be measured using an optical gate immediately before impact while the ram is coasting.

Instrumentation data shall be collected at 10 kHz. Head accelerometer data shall be low-pass filtered to a frequency cutoff of 300 Hz (CFC180) prior to calculating rotational kinematics from the NAP. Other head instrumentation schemes may require different filtering algorithms in order to perform optimally. Upper neck loads and moments shall be filtered using CFC1000 and CFC600, respectively. Every test shall also be recorded with high-speed video (1000 Hz).

For some test conditions, secondary impacts may occur between the helmet specimen and the Hybrid III neck or neck base. Consequently, care should be taken to truncate the head kinematic response time history after the ram loses contact with the helmet, but before secondary impacts occur. As a rule of thumb, data may be truncated between 30 and 60 ms after first contact, with first contact being defined as the time when the resultant acceleration of the head CG first exceeds 5g. In some cases, use of high speed video and inspection of the ram load cell data may be required to determine the appropriate time of data truncation.

2.5 Helmet Performance Score

Processed head kinematic data should then be used to calculate two injury metrics; the Head Injury Criterion (HIC) and the Diffuse Axonal Multi-Axis General Evaluation (DAMAGE). HIC is based on the resultant translational acceleration time history of the head CG, a(t):

$$\mathrm{HIC} = \max_{(t_1,t_2)} \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} |a(t)| dt \right]^{2.5} \right\} \quad \text{(Eqn. 3)}$$

where the acceleration units are (g), and t_1 and t_2 are upper and lower bound time points that maximize the value of HIC (Versace 1971). A constraint of $(t_2 - t_1) \leq 15$ ms is imposed for the calculation of HIC.

DAMAGE is based on the maximum of the resultant displacement of a coupled three degree-of-freedom multibody model that uses the directionally dependent rotational acceleration time histories of the head as inputs (Gabler et al. 2018). Values for the mass, stiffness, and damping parameters are based on a finite element brain model (Gabler et al. 2018). Resources to calculate HIC and DAMAGE are available on the software page.

Values for DAMAGE and HIC should be used in a linear combination to calculate the head acceleration response metric (HARM) for each impact condition (Eqn. 4):

$$\mathrm{HARM} = C_1 \mathrm{HIC} + C_2 \mathrm{DAMAGE} \quad \text{(Eqn. 4)}$$

where $C_1 = 0.0148$ and $C_2 = 15.6$ are constants that were determined from fits to head kinematics measured in physical dummy reconstructions of on-field football impacts involving an injured player and non-injured collision partner (Pellman et al. 2003, Sanchez et al. 2018). A lower HARM value indicates better helmet performance.

The Helmet Performance Score (HPS) is the sum of weighted HARM values calculated for each of the 18 impact conditions. The target contribution of each impact condition (Figure 4) reflects:

1. The on-field incidence of NFL concussions by impact location (see Lessley et al. 2018) using concussion data from the 2015-16 to 2017-18 seasons, and
2. Prioritization of the highest test speed which is reflective of the average closing velocity of helmet-to-helmet impacts which result in injury. The 9.3 m/s conditions contribute 50% of the total score, while the 5.5 and 7.4 m/s conditions each contribute 25% of the total score.

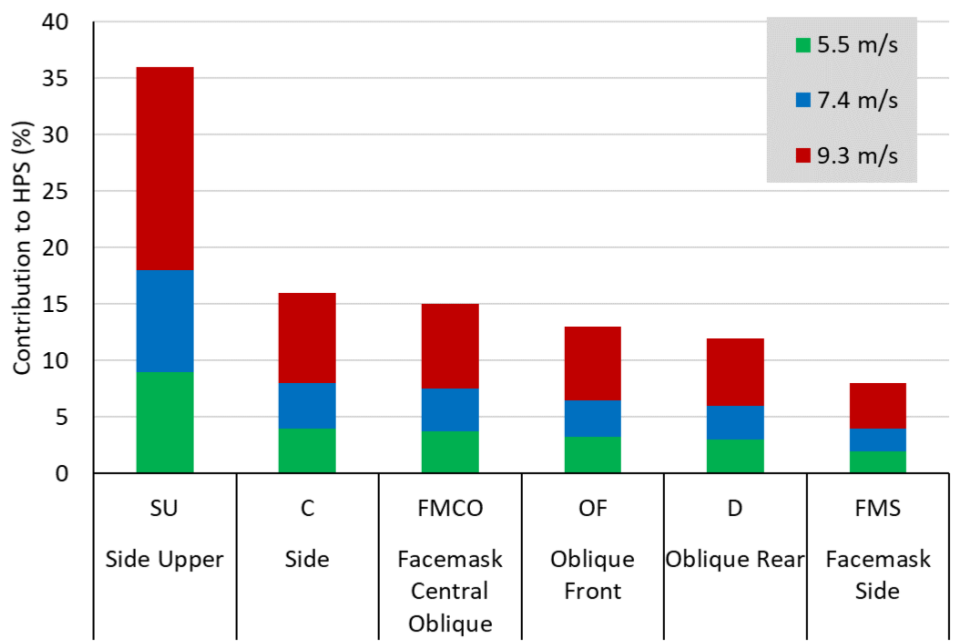


Figure 4. Target contribution of each test condition to the Helmet Performance Score (HPS) by speed and location weighted according to on-field concussion incidence.

To determine the HPS for a helmet model, the HARM calculated for each of the 18 impact conditions is multiplied by the applicable weighting factor (Table 3) and then summed (Eqn. 5). For each impact condition, the weighting factor was determined by dividing the on-field incidence of concussion associated with a given impact condition by the average HARM from a sample of seven helmet models tested in that impact condition. This normalization of the weighting factors was performed to account for differences in the magnitude of HARM by impact condition so that the overall contribution of each impact condition is reflective of the on-field concussion incidence and the impact speed prioritization described above.

$$HPS = \sum_{i=1}^{18} M_i (HARM)_i \quad \text{(Eqn. 5)}$$

Table 3. Weighting factors (M_i) for each test condition used for calculating the Helmet Performance Score (HPS).

Impact Location	5.5 m/s	7.4 m/s	9.3 m/s
Side Upper (SU)	2.93e-2	1.82e-2	2.33e-2
Oblique Front (OF)	9.49e-3	6.01e-3	7.82e-3
Oblique Rear (D)	5.83e-3	3.71e-3	4.72e-3
Side (C)	9.96e-3	6.24e-3	8.13e-3
Facemask Side (FMS)	3.92e-3	2.58e-3	3.58e-3
Facemask Central Oblique (FMCO)	6.87e-3	4.93e-3	6.87e-3

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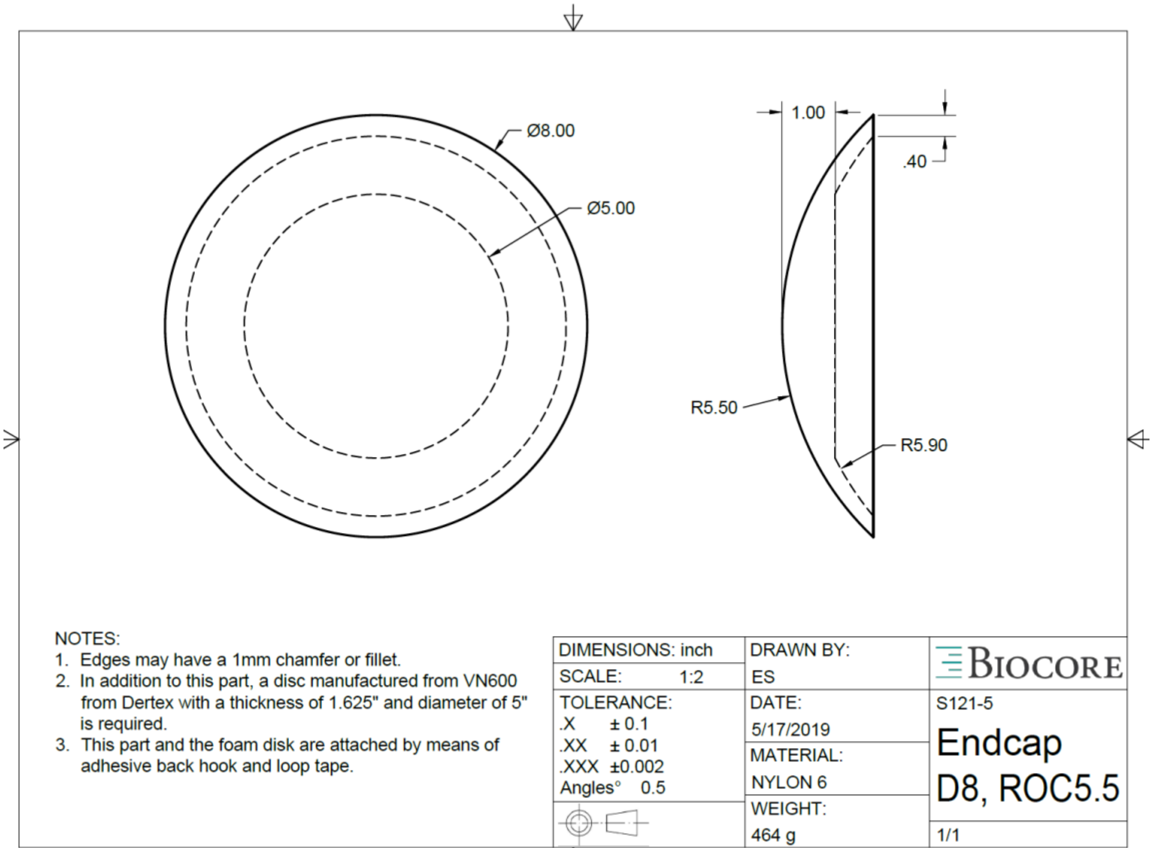
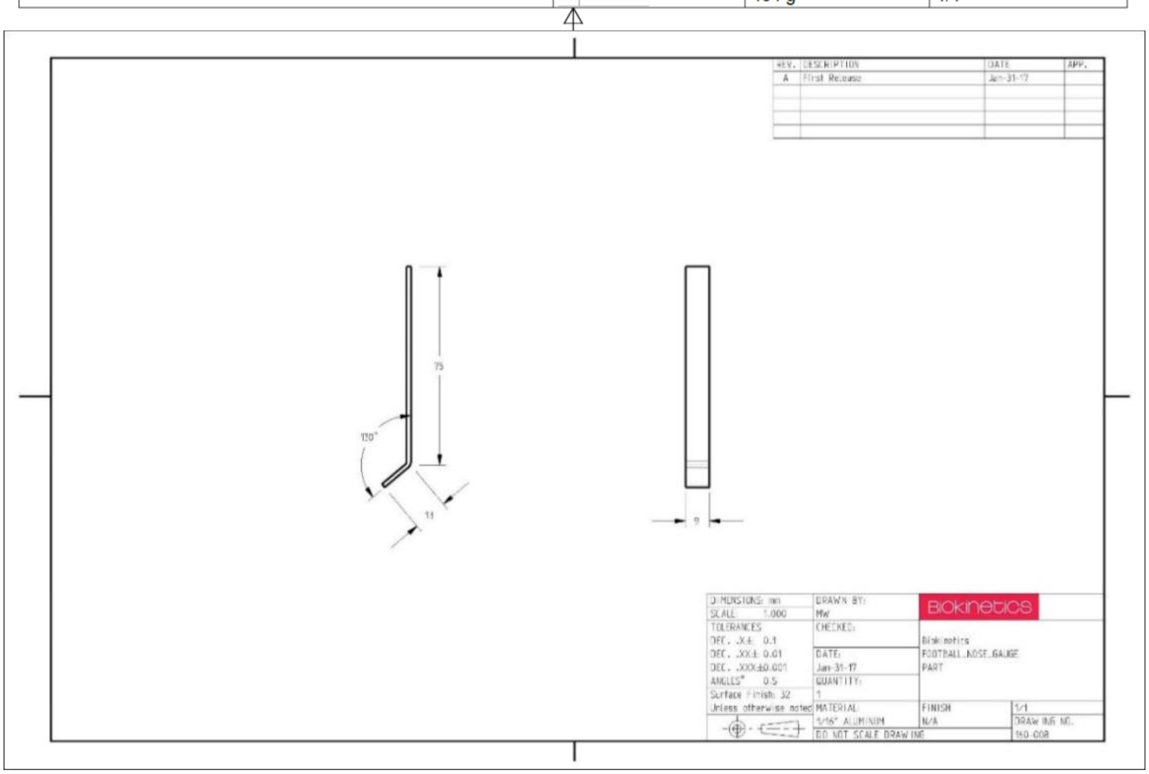
Appendix I – Drawings for the nylon end cap and the helmet positioning nose gauge.





Appendix II – Head position and orientation at each impact location

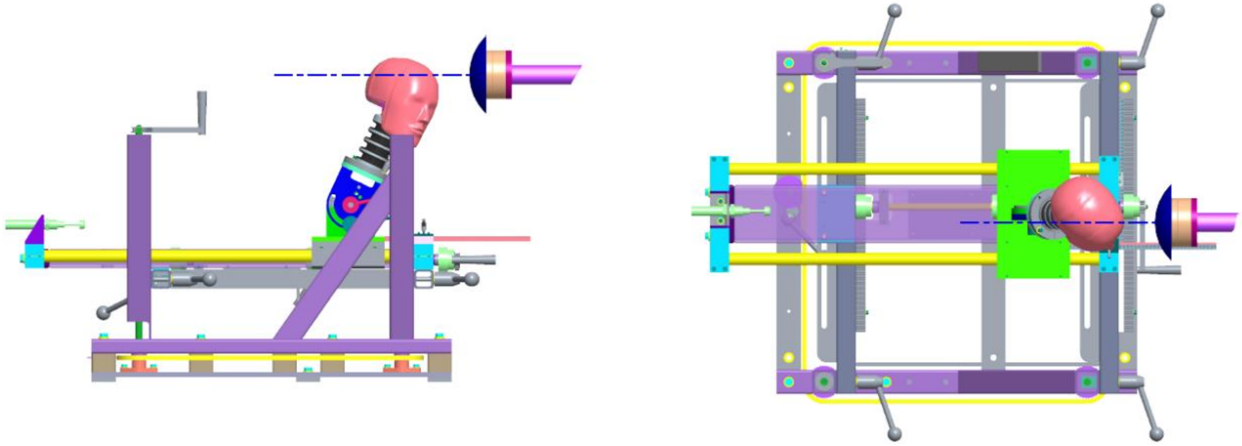


Figure A2.1 – Impact site Oblique *Front (OF)*.

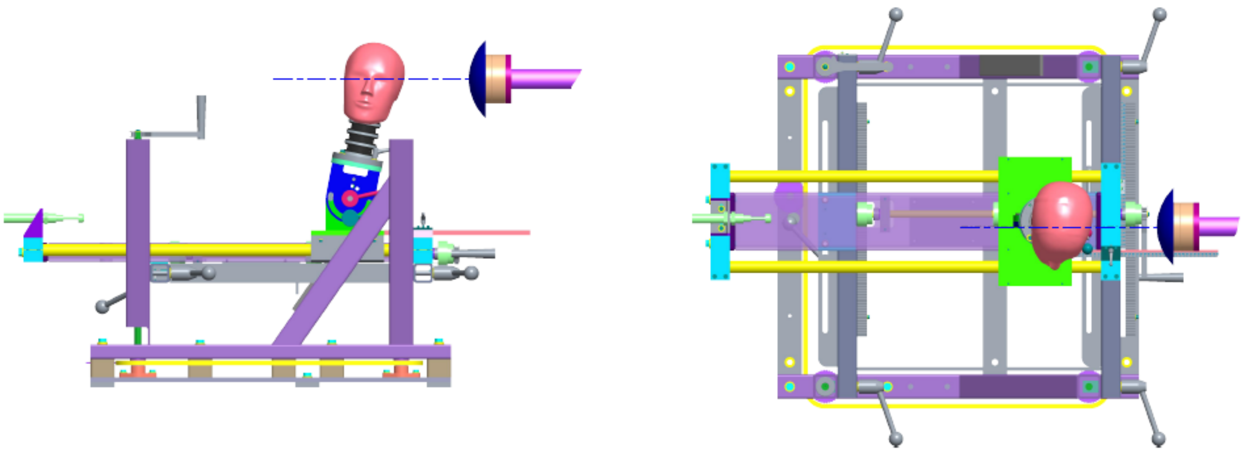


Figure A2.2 – Impact site *Side (C)*.

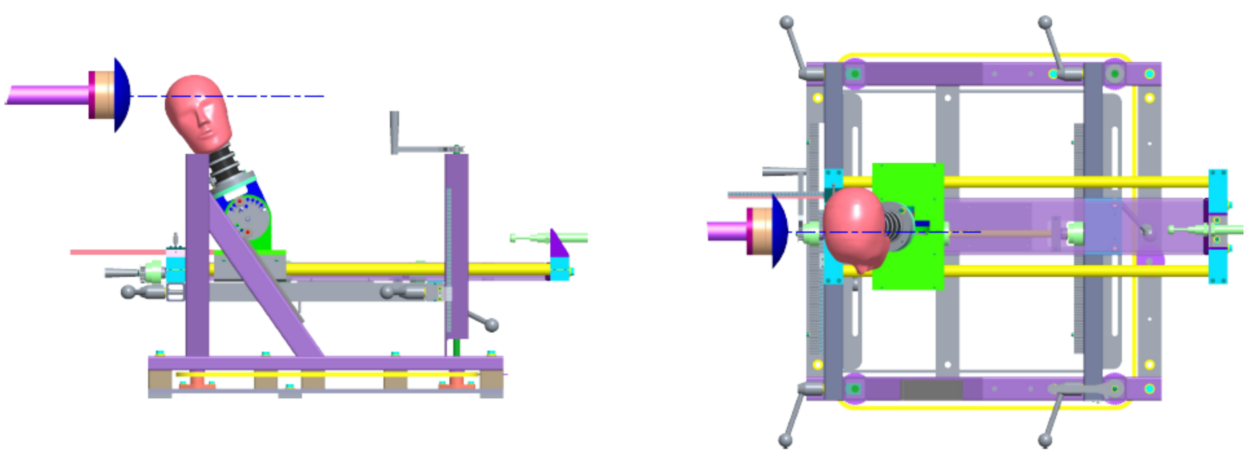


Figure A2.3 – Impact site *Side Upper (SU)*.

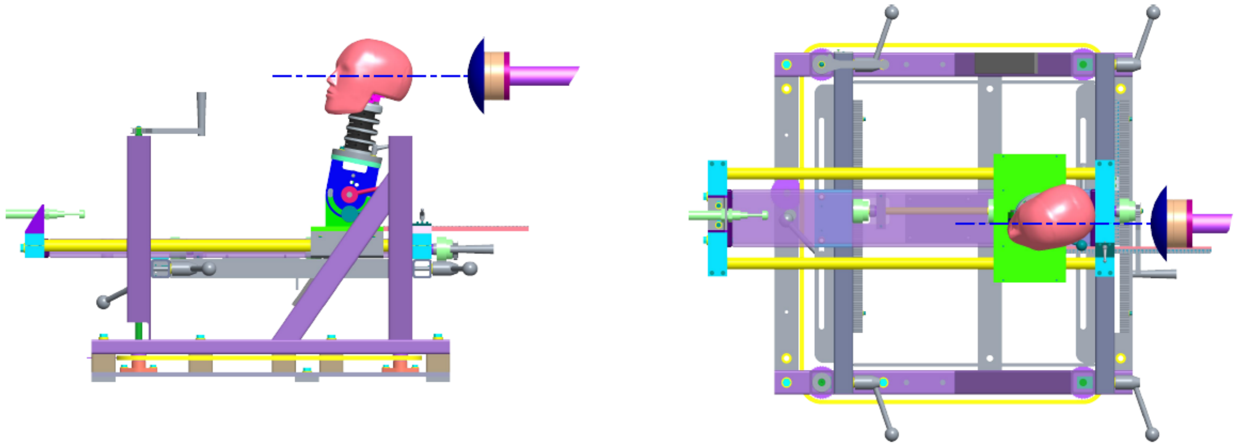


Figure A2.4 – Impact site *Oblique Rear (D)*.

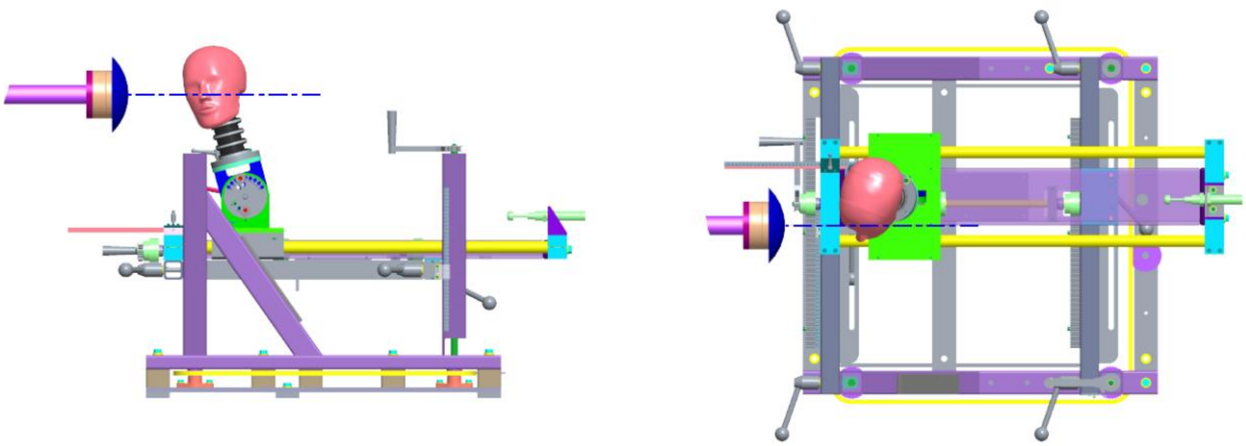


Figure A2.5 – Impact site *Facemask Side (FMS)*.

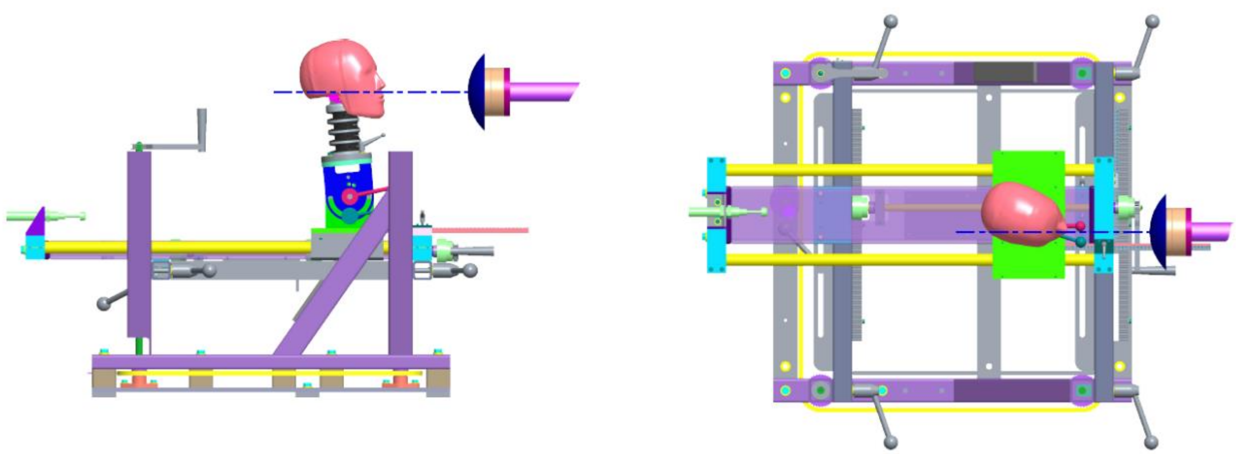


Figure A2.6 – Impact site *Facemask Central Oblique (FMCO)*.

Appendix III - List of terms and symbols

Term/Symbol	Definition
X	Horizontal lab coordinate axis in line with the axis of the impactor ram
Y	Horizontal lab coordinate axis perpendicular to the ram axis
Z	Vertical lab coordinate axis
x	Fore-aft axis of the SAE head coordinate system
y	Lateral axis of the SAE head coordinate system
z	Superior-inferior axis of the SAE head coordinate system
θ	Table adjustment for rotation about the vertical axis of the neck
β	Table adjustment for rotation about the lab Y axis
Z_{off}	Distance in the Z direction from the head CG to the pivot point on the Biokinetics slider assembly when the head is in the reference position
X_{off}	Distance in the X direction from the head CG to the pivot point on the Biokinetics slider assembly when the head is in the reference position
Y_{table}	Table displacement from the head reference position (Y coordinate axis)
Z_{table}	Table displacement from the head reference position (Z coordinate axis)
Y_{CG}	Y position of the head CG in the YZ plane relative to the ram axis
Z_{CG}	Z-axis position of the head CG in the YZ plane relative to the axis of impactor travel
Head Injury Criterion (HIC)	$\mathrm{HIC} = \max_{(t_1,t_2)}\left\{(t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \lvert a(t)\rvert dt\right]^{2.5}\right\}$
a(t)	Resultant translational head acceleration time history in units of g
t_1	Lower bound time point for calculation of HIC
t_2	Upper bound time point for calculation of HIC
DAMAGE	Diffuse Axonal Multi-Axis General Evaluation, $\mathrm{DAMAGE} = B \max_t\{\lvert\vec{\delta}(t)\rvert\}$ See Gabler et al. 2018.
$\vec{\delta}(t)$	Vector containing the displacement time histories of the coupled masses from the multibody model used to represent the brain. See Gabler et al. 2018.
B	Scale factor that relates the maximum multibody displacement to maximum brain strain from a finite element model. See Gabler et al. 2018.
HARM	Head Acceleration Response Metric, HARM = C_1HIC + C_2DAMAGE
C_1	Coefficient for HIC used to calculate HARM
C_2	Coefficient for DAMAGE used to calculate HARM
HPS	Helmet Performance Score, $\mathrm{HPS} = \sum_{i=1}^{18} M_i(\mathrm{HARM})_i$
M_i	Weighting factor of the i^{th} test condition, used to calculate HPS