The University of British Columbia
School of Biomedical Engineering

BMEG 330 Project Final Report

Effect of Helmet Positioning on Head Kinematics and Injury Risk During Impact Events

Group 3
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Table of Contents:

0.0 Summary

This report looks at the impact of helmet positioning on head kinematics and injury risk during simulated motorcycle impacts. The team conducted six drop tests using a helmeted anthropomorphic test device (ATD), testing different helmet fit conditions: proper fit, right/left offsets, and upward/downward misalignments. Using nine accelerometer sensors and high-speed video tracking, the study analyzed linear and rotational accelerations and calculated the corresponding force transmission to the ATD. The original hypothesis posited that improperly positioned helmets would increase both force transmission and rotational acceleration, leading to higher injury risk.

Surprisingly, properly fitted helmets exhibited some of the highest force and acceleration readings, while some misaligned configurations resulted in lower values, disproving the original hypothesis. These unexpected outcomes suggest that helmet geometry, impact angles, and other mechanical interactions may have played a larger role than just helmet fit and foam compression. Despite these findings, the study found that misaligned helmets can cause inconsistent and unpredictable impact responses, which may still pose safety concerns.

1.0 Introduction

1.1 Background Information

Motorcycle crashes frequently result in severe head and neck trauma, making helmets the single most important safety device for riders. Standard motorcycle helmets are engineered with a hard outer shell, a compressible foam liner to decrease impact forces, and comfort padding to ensure a snug fit. Upon impact, the rigid outer shell spreads and dissipates the force over a broader area and prevents object penetration, while the energy-absorbing liner crushes to lengthen the impact duration and reduce the peak acceleration transmitted to the head [1]. However, traditional helmet designs primarily address linear impact energy and provide little explicit mitigation of rotational forces. The inner foam typically fills the entire shell and is fixed in place, so during an oblique impact the helmet tends to rotate with the head, transmitting angular forces to the brain [2].

Real-world motorcycle impacts are often oblique rather than purely head-on, meaning they induce both linear and angular accelerations to the head. These two components of motion influence injury risk in different ways. Linear acceleration is strongly associated with focal injuries like skull fractures, contusions, and acute subdural hematomas when the force exceeds tissue tolerance [2]. In contrast, rotational acceleration induces shear strains in the brain because the brain can lag behind the skull's motion during sudden rotation [2]. When rotational forces are high, they can cause diffuse brain injuries such as concussion, diffuse axonal injury (DAI), and subdural hematoma [2]. These injuries result from the impulse loading of the brain and are often severe or fatal. Analyses of motorcycle fatalities indicate that rotational forces are a leading cause of deadly head injuries as the primary injury mechanism in over 60% of fatal head trauma cases (versus 31% for purely linear impacts) [2].

However, this only works if the helmet stays correctly positioned upon impact. If a helmet is tilted out of position or not securely strapped, the rider's head might hit the interior of the helmet improperly or the helmet might not remain in place, resulting in much higher impact forces being transmitted to the skull. In many regions, a large fraction of riders fail to secure their helmets properly. Studies in Asia have found that roughly one-third of motorcyclists wear a helmet improperly, often leaving the chin strap unfastened or loosely fastened to comply with helmet laws [3] [4].

Correct fit and positioning also affect how well a helmet decreases rotational acceleration of the head. Rotational forces are a major cause of brain injuries like diffuse axonal injury [5]. Research has shown that head rotation is strongly linked to brain injury risk [5].

Motorcyclists face a much higher risk of serious injury or death per mile traveled compared to occupants of cars. According to the U.S. National Highway Traffic Safety Administration (NHTSA), a motorcyclist's risk of a fatal crash is on the order of 30 times greater than that of a passenger car occupant, per vehicle-mile traveled [2]. In 2020 more than 5,500 motorcyclists lost their lives on U.S. roads, and over 180,000 were treated in emergency departments for crash-related injuries [6]. Globally, 340,000 motorcyclist fatalities occur worldwide each year, about 28% of all road traffic deaths [2]. Head injuries are the leading cause of death in these crashes, given the vulnerability of the unprotected head.

In a COST report, Three-quarters (75%) of fatal motorcycle injuries involve trauma to the head or brain [2]. According to the CDC, motorcycle helmets are 37–41% effective in preventing fatal injuries to riders and reduce the risk of head injury by 69% [6]. Despite these benefits, a helmet's protection depends on its design, condition, and the nature of the crash impact.

1.2 Objective

The objective of this study is to look at how improper helmet positioning affects head and neck kinematics during motorcycle impact and how variations in helmet fit, such as tilting forward, backward, or sideways, impact linear and rotational acceleration experienced by the head and cervical spine. Since motorcycle helmets are designed to provide optimal protection when worn correctly, when worn incorrectly, it may compromise their ability to absorb and distribute impact forces. To simulate misuse scenarios, a series of controlled drop tests will be performed using an anthropomorphic test device (ATD). Measurements of linear acceleration across 9 different accelerometers, video analysis, and force directionality will be collected and compared across helmet fit conditions to assess the impact of improper helmet usage on injury risk.

1.3 Hypothesis

We aim to test the hypothesis that improper helmet positioning will result in increased force transmission to the head and neck, along with higher peak linear and rotational accelerations, compared to correctly positioned helmets due to misalignment between the helmet and the skull, which may reduce the helmet's ability to properly absorb and distribute impact forces.

2.0 Materials and Methods

2.1 Equipment and Materials

Drop Tower Setup

- Anthropomorphic Test Device (ATD): Hybrid III 50th percentile male dummy headform embedded with 9 accelerometer units
- Motion Capture: Hamera system with tracking markers to capture kinematic data
- Impact Surface: Adjustable anvil to simulate various collision angles and surfaces
- Surface Material: 80-grit sandpaper fixed to the anvil to replicate the texture of concrete

Helmet Samples

- Sample: One "like new," uncrashed motorcycle helmet acquired from Facebook Marketplace, conforming to relevant safety standards for street legal use.

Data Storage and Processing

- Storage Device: USB flash drive for storing accelerometer data
- Analysis Tools: MATLAB or Python for data processing, including conversion of motion data to acceleration values

2.2 Method

To look at how variations in helmet positioning affect head and neck kinematics during motorcycle impacts, we will conduct controlled drop tests using a drop tower equipped with an anthropomorphic test device (ATD) containing 9 accelerometer units. The primary focus of the study is to simulate helmet misalignment scenarios, forward tilt, backward tilt, left twist, and right twist to study their effects on force transmission and acceleration patterns during impact events.

Each test will involve dropping the helmeted ATD from a predetermined height onto an impact anvil. Linear and rotational accelerations of the head will be captured using the embedded accelerometer units and a high-speed video system with motion tracking markers will be used to record helmet displacement and validate motion trajectories during impact.

All sensor and video data will be stored on a 32+ GB USB device and processed using MATLAB or RStudio. Motion capture data will be converted into acceleration values, and will be used to find peak linear acceleration, peak rotational acceleration, and force transmission. These results will be analyzed and compared across helmet fit conditions to determine how improper positioning alters protective performance and increases injury risk.

2.3 Experiment Setup

A drop tower system was used to replicate motorcycle impact conditions. The components of the experimental setup include the drop tower frame, helmet mounting rig, impact anvil, and surface conditioning material, as shown below in figure [1].

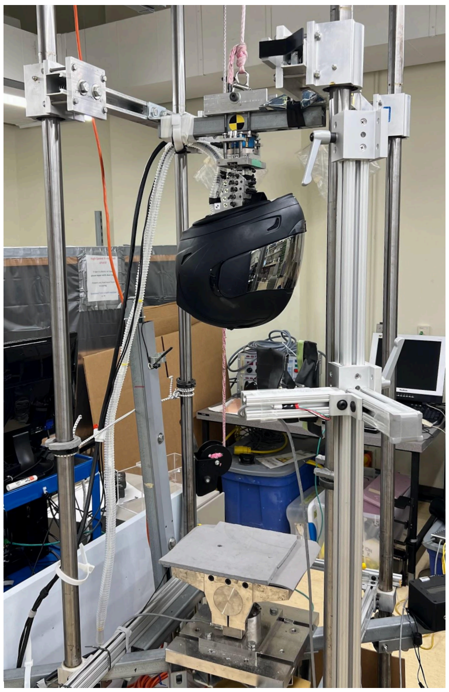

Figure 1: Drop tower setup

Figure 2: motion tracking markers

The drop tower, shown in figure 1, consists of a vertical steel guide rail assembly, allowing for a controlled vertical drop of the helmeted ATD headform. The height of which the ATD is raised and released from was limited to prevent damage to the IMU load sensors and accelerometers located within the ATD.

The impact anvil remained fixed at its initial position but foam padding was placed on top of the impact anvil to protect the accelerometer units by serving as a mechanical buffer to prevent sensor overload.

Prior to testing, motion tracking markers were attached to the helmet (shown in figure 2) to make video analysis easier. Below were the 5 different positioning configurations of the helmet onto the ATD headform.

Figure 3: helmet proper fit on ATD

Figure 4: Location of nose relative to helmet in reference

Figure 5: right offset helmet fit on ATD

Figure 6: 2in offset from nose to centreline of helmet

Figure 7: left offset helmet fit on ATD

Figure 8: 2 in offset from nose to centreline of helmet

Figure 9: upwards offset helmet fit on ATD relative to the ATD head

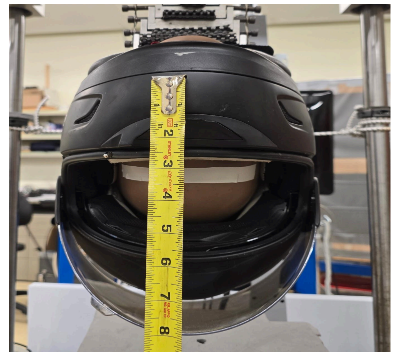

Figure 10: 2.5in offset from tip of nose to reference point.

Figure 11: downward offset helmet fit on ATD relative to the ATD head

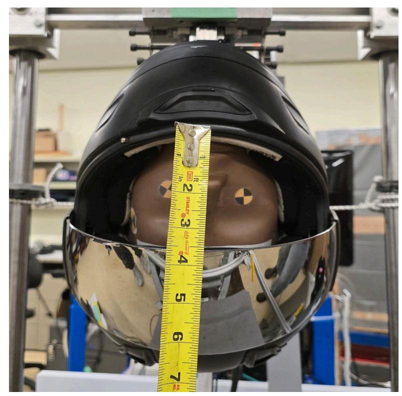

Figure 12: 2in offset from tip of nose to reference point.

2.3 Procedure

The motorcycle helmet was installed on the ATD under five fit conditions across 6 total tests:

Trial 1: proper fit (figures 3 & 4)

Trial 2: proper fit (figures 3 & 4)

Trial 3: right offset (figures 5 & 6)

Trial 4: left offset (figures 7 & 8)

Trial 5: upward offset (figures 9 & 10)

Trial 6: downward offset (figures 11 & 12).

Each configuration was measured and verified using a ruler between each trial. The impact anvil was set at 0 degrees relative to the horizontal, and was not adjusted throughout the duration of the experiments.

For each trial, the helmeted ATD was raised to a height of 27 inches (2.25 feet) and released to fall freely onto the impact anvil. Data collection began 0.5 seconds before impact and continued for 0.5 seconds afterward, for a total duration of one second per trial. Accelerometer data were sampled at a frequency of 10,000 Hz while video footage was recorded simultaneously with a smartphone.

2.4 Data Processing and Analysis

The primary software used for processing and analyzing the impact kinematics was MATLAB. Each excel file contained metadata followed by time-series data from nine accelerometer channels located at key anatomical regions of the helmeted ATD (Anthropomorphic Test Device), including the center of gravity (COG), anterior, lateral, and superior position, shown below in table 1.

Channel Name	Sensor	Direction
COGX (CH31-1)	COG	X (forward/back)
COGY (CH31-2)	COG	Y (left/right)
COGZ (CH31-3)	COG	Z (up/down)
ANTY (CH32-1)	Anterior	Y (sideward)
ANTZ (CH32-2)	Anterior	Z (vertical)
LATX (CH32-3)	Lateral	X (longitudinal)
SUPX (CH39-2)	Superior	X (longitudinal)
SUPY (CH39-3)	Superior	Y (lateral)

Table 1: accelerometer channel names, their corresponding sensor placements on the helmeted ATD, and the directional axis each sensor measures

After importing the raw data, the acceleration signals, the signals were converted from units of g to m/s^2 using a scalar conversion factor (1 g = 9.81 m/s^2). To reduce high-frequency noise without introducing phase shifts or distortion, a zero-phase 4th-order Butterworth low-pass filter was applied with a 50 Hz cutoff frequency. Each of the nine filtered channels was then grouped and plotted according to its anatomical location.

Peak linear acceleration and rotational acceleration were calculated to determine the severity of impact forces experienced by the ATD. Linear acceleration was assessed along the X, Y, and Z axes by identifying the maximum absolute values across relevant sensor channels, with the highest peak indicating the direction of greatest force transmission. Rotational acceleration was estimated using the differences in acceleration between spatially separated sensors divided by their estimated distances apart. This provided an approximation of angular acceleration about each XYZ axis.

As for the video analysis, MATLAB was also the primary software utilized. Each of the six trials were filmed using an iPhone 13 Pro at 60 fps. Using the Apple native “Photos” app, each clip was trimmed to roughly 2 seconds long, with the helmet stationary and the drop commencing at the beginning of the clip, and the helmet making first contact with the drop surface at 1 min 48 sec, with the “neck” of the drop tower device settling at the 2 minute mark. These videos were then imported into MATLAB, where an Impact Analysis script was developed using the help of ChatGPT to produce displacement, velocity, acceleration, and force vs time plots.

On the helmet's left side is a yellow, rectangular sticker with measurements in centimeters, however, as there was a bit of excess sticker on both sides of the helmet we took this as 15 cm for a correlation between pixel and length. As there are many other items in the frame with similar colours, we developed the code to prompt the user for the identification of the sticker ruler, with a similar identification prompt of the tracked marker. The length of this sticker ruler was calculated using a colour mask algorithm, and correlated with the measured real world distance to get a proper conversion. Next, a marker placed near the temple of the helmet is tracked, taking two derivatives of the displacement to get velocity and acceleration (along with some data smoothing to process noise introduced during derivation). Finally, each plot is visualized, and a maximum distance, force, and duration is outputted.

3.0 Results

3.1 Results: Accelerometer Sensors

This section presents the results from trials 1-6, using data from the 9 accelerometer sensors to determine linear acceleration, rotational acceleration, and force transmission. Figures 13 to 18 below graph out the acceleration vs time by sensor location to visualize acceleration across different axes.

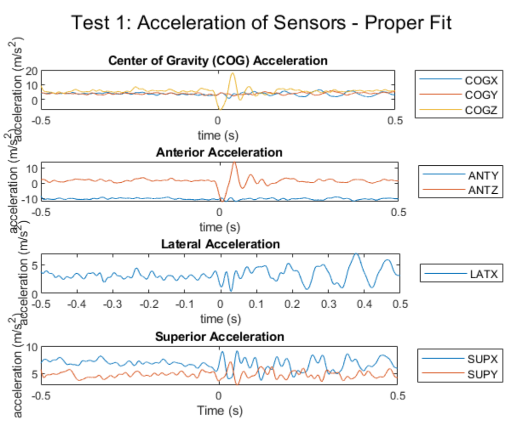

Figure 13: Acceleration of sensors grouped by sensor location during test 1 with the helmet on the ATD with proper fit.

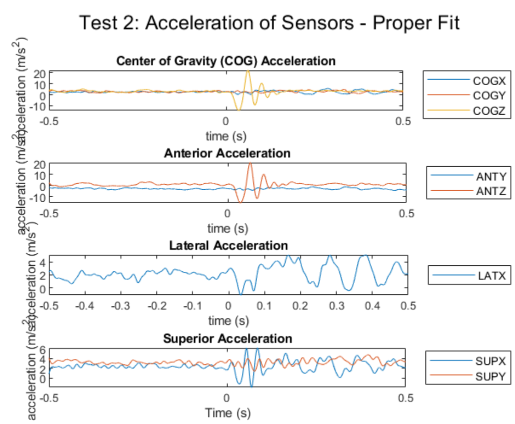

Figure 14: Acceleration of sensors grouped by sensor location during test 2 with the helmet on the ATD with proper fit

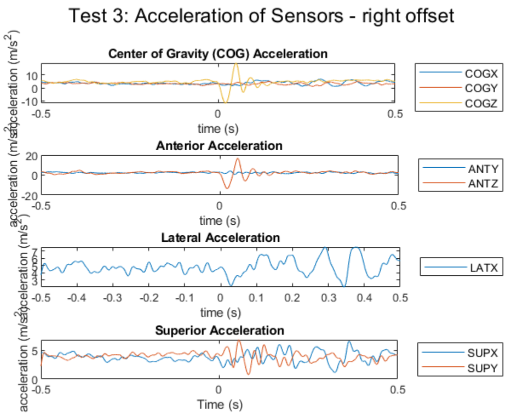

Figure 15: Acceleration of sensors grouped by sensor location during test 3 with the helmet on the ATD with right offset

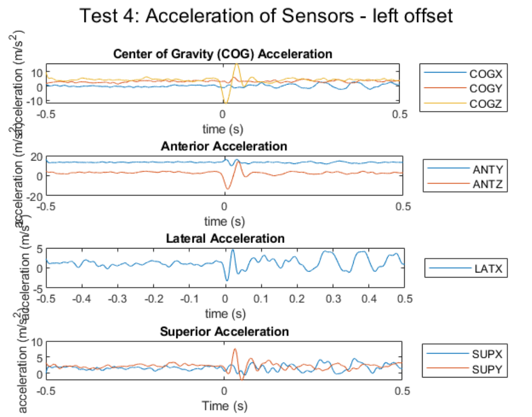

Figure 16: Acceleration of sensors grouped by sensor location during test 4 with the helmet on the ATD with left offset

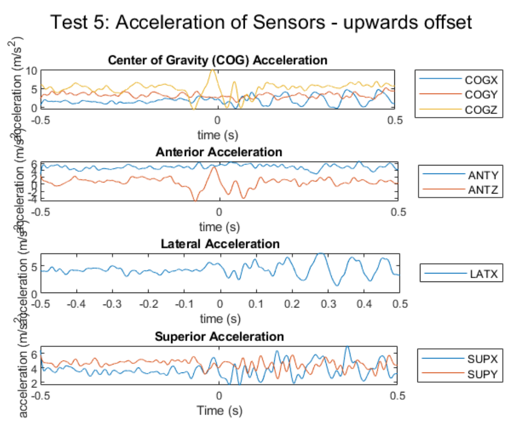

Figure 17: Acceleration of sensors grouped by sensor location during test 5 with the helmet on the ATD with upwards offset

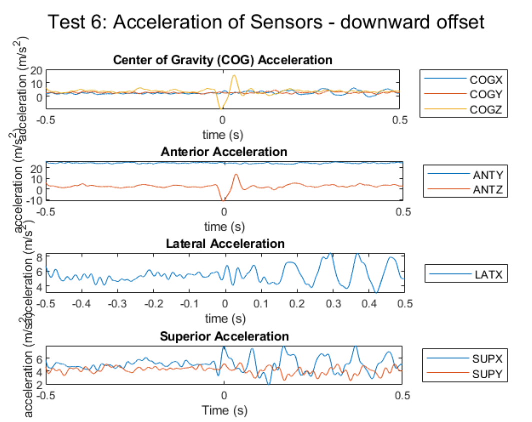

Figure 18: Acceleration of sensors grouped by sensor location during test 6 with the helmet on the ATD with downward offset

Force transmission over time was calculated by multiplying the filtered linear acceleration vector at the center of gravity (COG) by the mass of the average male of 80kg [7]. Rotational acceleration over time about the true axis of rotation was determined by first finding the 3D rotational acceleration vector at each time point using acceleration differences between sensor pairs. This vector was then projected onto the direction of maximum rotational acceleration, allowing us to isolate and analyze the rotational component of the primary axis of rotation.

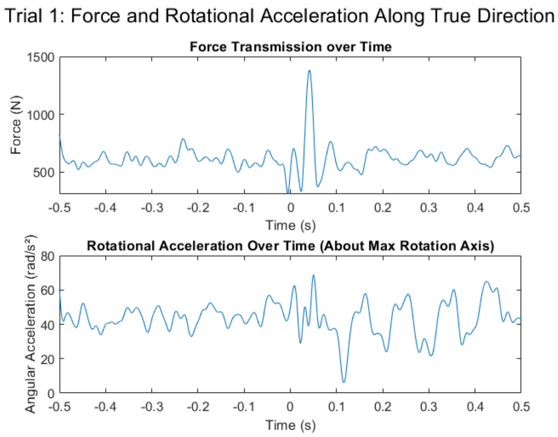

Figure 19: force and rotational acceleration along true direction for trial 1

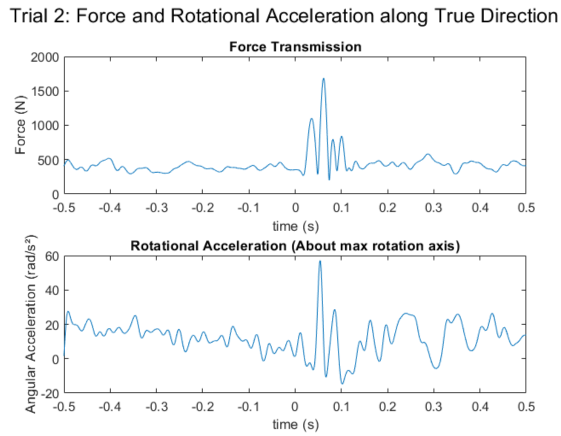

Figure 20: force and rotational acceleration along true direction for trial 2

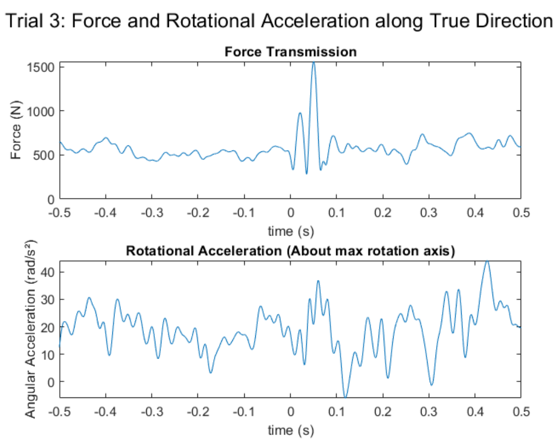

Figure 21: force and rotational acceleration along true direction for trial 3

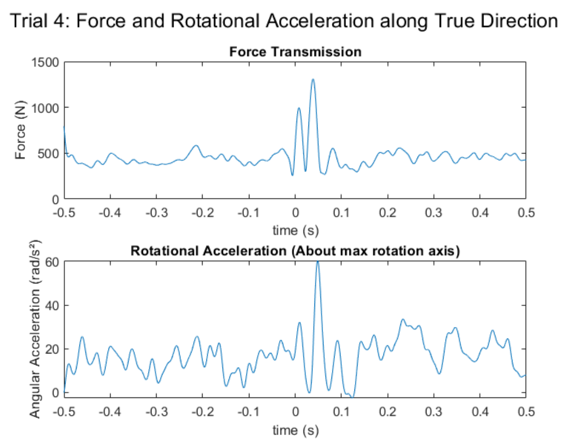

Figure 22: force and rotational acceleration along true direction for trial 4

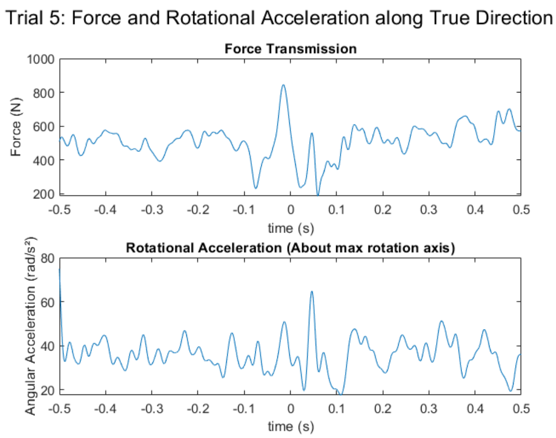

Figure 23: force and rotational acceleration along true direction for trial 5

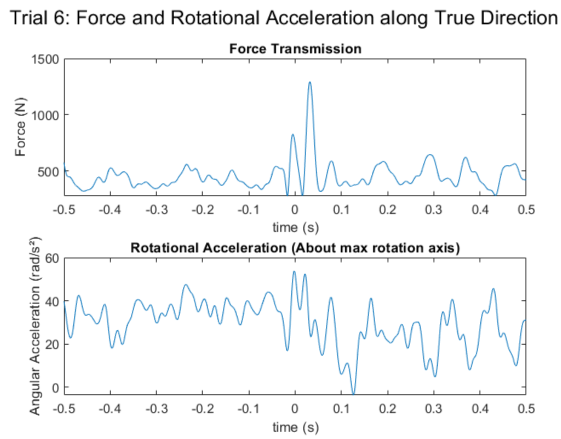

Figure 24: force and rotational acceleration along true direction for trial 6

The peak values were found and presented in table 2 after filtering the acceleration data collected from sensors mounted on the ATD headform during impact tests and graphing their plots.

Maximum linear acceleration along the X, Y, and Z axes was determined by identifying the highest peak acceleration values from the center of gravity (COG), anterior, lateral, and superior sensors.

Rotational acceleration about the X, Y, and Z axes was found using the differences in linear acceleration between sensor pairs positioned at known distances from the COG.

Trial #	Max Linear Acceleration along XYZ axis (m/s^2)	Max Linear Acceleration (m/s^2)	Max Rotational Acceleration About XYZ Axis (rad/s^2)	Max Rotational Acceleration (rad/s^2)	Max Force Transmission (N)
1	X: 9.10 Y: 11.91 Z: 17.93	18.42	X: 34.00 Y: 58.63 Z: 54.25	68.80	1473.23
2	X: 6.13 Y: 4.84 Z: 22.27	22.46	X: 26.55 Y: 43.78 Z: 36.16	57.10	1797.10
3	X: 7.55 Y: 6.84 Z: 18.99	19.53	X: 30.16 Y: 42.10 Z: 27.01	44.12	1562.55

4	X: 4.63 Y: 16.40 Z: 15.71	16.37	X: 52.97 Y: 41.50 Z: 34.95	60.36	1309.68
5	X: 7.25 Y: 6.55 Z: 9.97	10.57	X: 35.08 Y: 49.85 Z: 59.57	74.97	845.34
6	X: 8.44 Y: 26.09 Z: 15.72	16.19	X: 29.87 Y: 26.09 Z: 46.48	53.72	1295.03

Table 2: maximum linear acceleration components along the X, Y, and Z axes, the peak net linear acceleration magnitude, the maximum rotational acceleration about each axis, the overall peak rotational acceleration magnitude, and the maximum force transmission calculated from the COG acceleration from each trial.

To determine the overall maximum linear acceleration, the magnitude of the vector sum of the COG acceleration was graphed (refer to figures 13-18), and the peak value was found, which was the highest translational acceleration experienced by the headform. The maximum rotational acceleration was calculated as the peak magnitude of the combined rotational acceleration vectors.

Finally, force transmission over time was found by multiplying the COG linear acceleration vectors by the average mass of the 50th percentile ATD (80 kg) [7]. The magnitude of this force vector was tracked over time, and the highest value was found as the maximum force transmission.

3.2 Results: Video Analysis

This section presents the results from trials 1-6, using data from the video recording analysis to determine linear position, velocity, acceleration, and force transmission. Figures 25 to 30 below graph out each parameter vs. time.

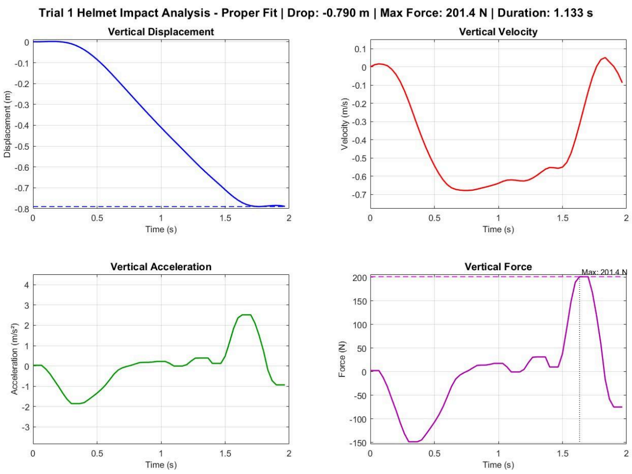

Figure 25: displacement, velocity, acceleration, and force vs time for Trial 1

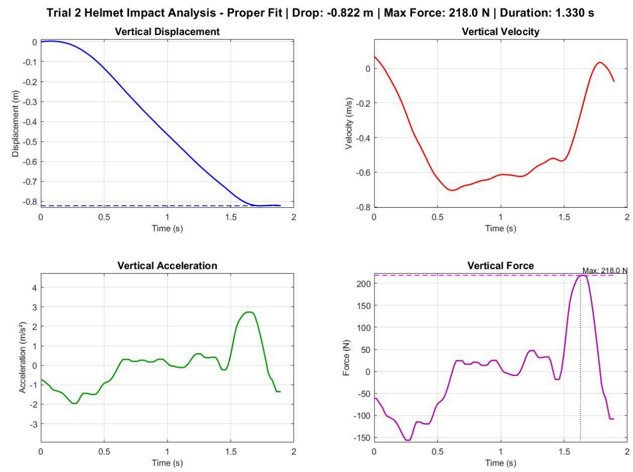

Figure 26: displacement, velocity, acceleration, and force vs time for Trial 2

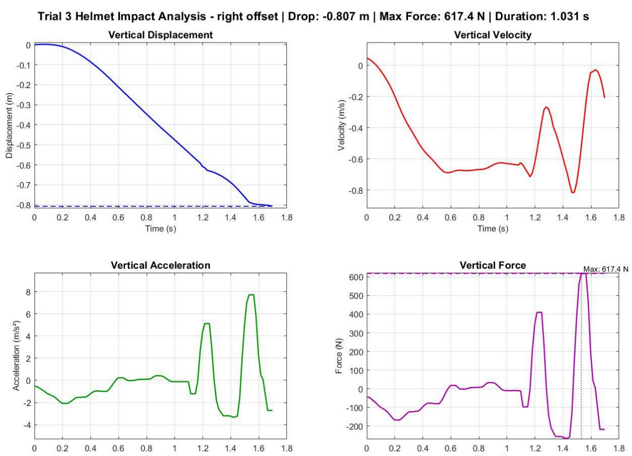

Figure 27: displacement, velocity, acceleration, and force vs time for Trial 3

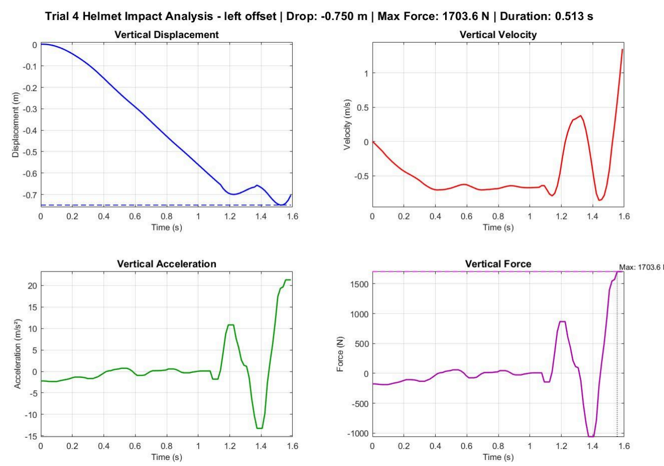

Figure 28: displacement, velocity, acceleration, and force vs time for Trial 4

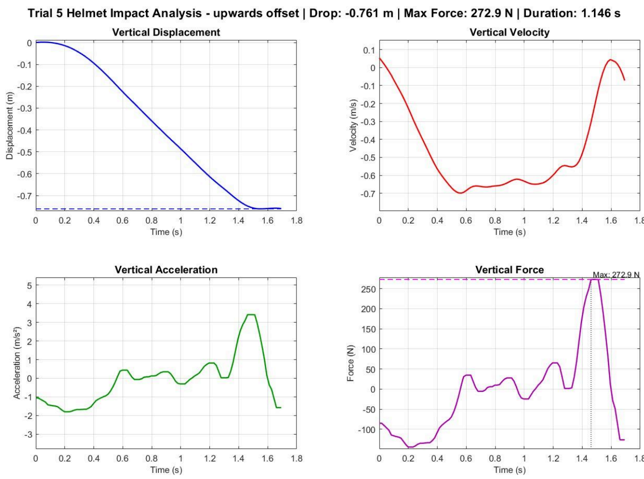

Figure 29: displacement, velocity, acceleration, and force vs time for Trial 5

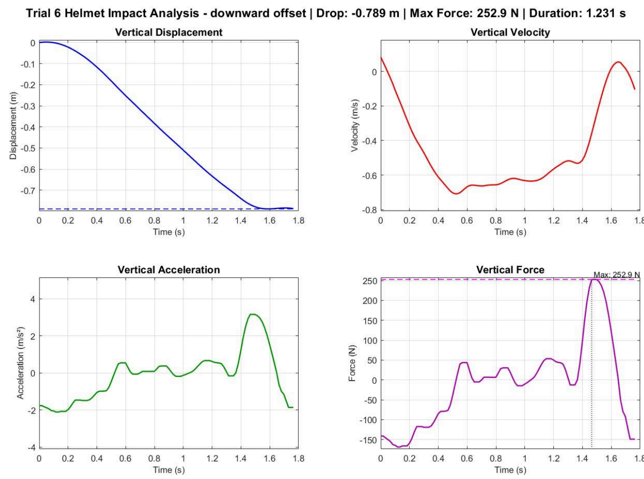

Figure 30: displacement, velocity, acceleration, and force vs time for Trial 6

A summary of the video analysis results can be found in Table 3 below:

Trial #	Analyzed Drop Height (m)	Max Force Along Z Axis (N)	Impact Duration (s)
1	0.790	201.4	1.133
2	0.822	218.0	1.330
3	0.807	617.4	1.031
4	0.750	1703.6	0.513
5	0.761	272.9	1.146
6	0.789	252.9	1.231

Table 3: drop height, maximum force along the Z axis, and impact duration calculated from the temporal helmet marker from each trial.

4.0 Discussion

4.1 Interpretation of Results: Accelerometer Sensors Analysis

Most surprisingly, trials 1 and 2, where the helmet had a proper fit, showed relatively high peak force transmission values, 1473.23 N and 1797.10 N respectively. Trial 2 recorded the highest max linear acceleration of 22.46 m/s² and the highest Z-axis linear acceleration at 22.27 m/s², which contributed to the increased force measured. This might suggest that a properly fitted helmet allows more direct force transmission to the ATD, which may reflect better energy absorption through the helmet shell and padding rather than rotational displacement of the helmet itself.

We expected trial 3 and trial 4 to produce similar results. Trial 3 (right offset) demonstrated a relatively high linear acceleration (19.53 m/s^2) and moderate force (1562.55 N) but had the lowest Z-axis rotational acceleration (27.01 rad/s^2). Trial 4, with a left offset, produced a relatively moderate max linear acceleration (16.37 m/s^2) and rotational acceleration (60.36 rad/s^2), but recorded a lower force transmission of 1309.68 N. Interestingly, its Y-axis linear acceleration was very high at 16.40 m/s^2, more than triple that of trial 2 (4.84 m/s^2), which suggests that the asymmetric force is due to the helmet misalignment.

The lowest force transmission occurred in trial 5 (845.34 N), where the helmet had an upward offset. While its max linear acceleration was relatively low (10.57 m/s^2), it produced the highest max rotational acceleration of all trials at 74.97 rad/s^2, with especially high values on the Z-axis (59.57 rad/s^2). This is probably due to the gap between the helmet and ATD, allowing time for the helmet to decelerate through friction before the impact event.

Trial 6 (downward offset) showed the highest Y-axis linear acceleration of 26.09 m/s^2, which corresponds to lateral helmet motion. However, its rotational acceleration (53.72 rad/s^2) and force transmission (1295.03 N) were moderate, possibly due to the direction of the helmet offset affecting how energy was transferred.

4.2 Interpretation of Results: Video Analysis

According to the video analysis results, Trials 1 and 2 had the lowest force transmission along the Z axis, which helps to support our hypothesis. The correct alignment of the helmet did not result in any excess displacement or motion of the helmet during the drop, which enabled the most efficient force absorption by the helmet and its structure and materials.

Trials 3 and 4 had the highest force transmission out of all of the tests, with Trial 4 specifically peaking at over 1,700 N. In comparison to the other trials, it is likely that there was an error of some kind during the marker tracking process, and thus Trial 4 from the video analysis may be labelled as an outlier. As Trial 4 was the left offset, with the markers being placed on the left side of the helmet, the marker detection and tracking algorithm may have had issues, leading to the extreme difference in force transmission between video analysis trials. The same reasoning may also apply to Trial 3 with its force being 2-3x higher than the other trials. It is worth noting that the 1703.6 N of Trial 4 is the only trial from the video analysis that yielded a result in the same force transmission range as the accelerometer sensor analysis.

Trials 5 and 6 had higher force transmission than Trials 1 and 2, which was expected, however was not remarkably high as was the case with Trials 3 and 4. The upward and downward offset of the helmet meant that there were likely areas in the helmet not properly contacting the ATD head, so with the drop test the force likely first transmitted to the points with proper contact, then rotated the helmet to make contact with the rest of the ATD head, resulting in a higher peak force than Trials 1 and 2.

4.3 Relation to Hypothesis

Contrary to our original hypothesis, the results did not consistently show that improper helmet positioning leads to increased force transmission or higher rotational accelerations. In fact, the trials with properly fitted helmets (Trials 1 and 2) showed some of the highest force transmission values, with Trial 2 recording the highest peak linear acceleration overall. Meanwhile, some of the misaligned helmet configurations, like the upward and downward offsets, actually produced lower force and acceleration values in certain directions. While we did observe some variation in acceleration patterns depending on helmet position, the data didn't clearly support the idea that improper fit always leads to greater risk.

4.4 Errors and Limitations

This study had several limitations that impacted the reliability of our findings. One major constraint was the limited number of trials where we were only able to perform one trial per helmet positioning condition (except for the proper fit, which was repeated twice). With such a small sample size, it's difficult to draw strong conclusions or account for variability between tests and therefore, we're unable to identify potential outliers.

Another major limitation was that the impact forces used in the drop tests may not have been high enough for the helmet's energy-absorbing foam to compress. Instead of compressing and deforming plastically as it would under more severe conditions, the foam likely only deformed elastically and behaved more like a spring, exaggerating acceleration measurements due to bounce-back rather than damping. This could mean that much of the observed acceleration differences were driven by helmet geometry and positioning rather than the inner foam lining.

The video analysis, while helpful, was limited to the sagittal plane, making it hard to capture lateral or rotational movements accurately. Including a second camera from the frontal plane could have provided more complete motion tracking. Our marker tracking software occasionally struggled with consistency, likely due to the placement of stickers and visual clutter in the frame. The algorithm may have jumped between points, especially in the left-offset trials, introducing error into our force and motion calculations.

5.0 Conclusion

This study set out to look at whether improper helmet positioning increases the risk of head and neck injury by analyzing linear and rotational accelerations during simulated impact events. While we initially hypothesized that misaligned helmets would lead to higher force transmission and more severe kinematics, our results did not consistently support this. Surprisingly, the properly fitted helmet trials showed higher peak force and acceleration values than some of the misaligned configurations under the accelerometer sensor analysis. Despite the inconclusive results, this study shows that even if misalignment doesn't always result in higher forces, it can cause inconsistent or unpredictable force distributions, which could still increase injury risk in real-world crashes.

For future research, we recommend increasing the number of trials per condition to account for variability, using higher-impact forces to maximize the use of the foams intended impact strength. Additionally, capturing video data from multiple angles, and implementing machine learning to boost the reliability of marker tracking would facilitate a more complete kinematic analysis.

6.0 References

Code developed with the help of ChatGPT

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7.0 Appendix

[A1] - Contributions

Jackie Chen	83382721	Objective, Method, Data Processing (Video Analysis), Results (Video Analysis), Discussion (interpretation of results for Video Analysis), Errors and Limitations, Conclusion
Jung Kyu Yoon	61298212	Background information, Objective, Hypothesis, Equipment and Materials, Method, Experiment Setup, Procedure, Data Processing (Accelerometer Sensor Analysis), Results (Accelerometer Sensor Analysis), Discussion (interpretation of results for Accelerometer Sensor Analysis), Relation to hypothesis, Summary, Conclusion

[A1] - MATLAB Code for Accelerometer Sensor Analysis

```
clear;
clc;
filename = 'BMEG_330_April_2_OOP_4_FILTERED.csv';
headerLines = 24;
g_to_mps2 = 9.81;
sampleRate = 10000;
dt = 1 / sampleRate;
%% Filter
cutoffFreq = 50;
filterOrder = 4;
[b, a] = butter(filterOrder, cutoffFreq/(sampleRate/2), 'low');
%% Load data
opts = detectImportOptions(filename, 'NumHeaderLines', headerLines);
data = readtable(filename, opts);
time = data{:,1};
acc_raw = data{:,2:10};
acc_mps2 = acc_raw * g_to_mps2;
%% Filter
acc_filtered = filtfilt(b, a, acc_mps2);
% Centre of Gravity: COGX, COGY, COGZ
COG = acc_filtered(:, 1:3);
% Anterior: ANTY, ANTZ
ANT = [acc_filtered(:,4), acc_filtered(:,5)];
% Lateral: LATX
```

```
LAT = acc_filtered(:,6);
% Superior: SUPX, SUPY
SUP = [acc_filtered(:,8), acc_filtered(:,9)];
%% Plot
figure;
subplot(4,1,1)
plot(time, COG)
title('Center of Gravity (COG) Acceleration')
xlabel('time (s)'); ylabel('acceleration (m/s^2)')
legend({'COGX','COGY','COGZ'}, 'Location','eastoutside')
subplot(4,1,2)
plot(time, ANT)
title('Anterior Acceleration')
xlabel('time (s)'); ylabel('acceleration (m/s^2)')
legend({'ANTY','ANTZ'}, 'Location','eastoutside')
subplot(4,1,3)
plot(time, LAT)
title('Lateral Acceleration')
xlabel('time (s)'); ylabel('acceleration (m/s^2)')
legend({'LATX'}, 'Location','eastoutside')
subplot(4,1,4)
plot(time, SUP)
title('Superior Acceleration')
xlabel('Time (s)'); ylabel('acceleration (m/s^2)')
legend({'SUPX','SUPY'}, 'Location','eastoutside')
sgtitle('Test 6: Acceleration of Sensors - downward offset')
%% find peak linear acceleration
peakLinearX = max(abs([COG(:,1); LAT; SUP(:,1)]));
peakLinearY = max(abs([COG(:,2); ANT(:,1); SUP(:,2)]));
peakLinearZ = max(abs([COG(:,3); ANT(:,2)]));
fprintf('\nPeak Linear Acceleration\n');
fprintf('X-direction: %.2f m/s²\n', peakLinearX);
fprintf('Y-direction: %.2f m/s²\n', peakLinearY);
fprintf('Z-direction: %.2f m/s²\n', peakLinearZ);
%% find rotational acceleration along the axis
% estimating distances (m) of sensors from COG
r_sup_cog = 0.10;
r_ant_cog = 0.12;
```

```
% a_x ( difference in Z accel between SUP and COG)
a_x = (SUP(:,2) - COG(:,2)) / r_sup_cog;
% a_y ( difference in Z accel between ANT and COG)
a_y = (ANT(:,2) - COG(:,3)) / r_ant_cog;
% a_z ( difference in Y accel between SUP and COG)
a_z = (SUP(:,1) - COG(:,1)) / r_sup_cog;
peakaX = max(abs(a_x));
peakaY = max(abs(a_y));
peakaZ = max(abs(a_z));
fprintf('\nRotational Acceleration\n');
fprintf('About X-axis: %.2f rad/s²\n', peakaX);
fprintf('About Y-axis: %.2f rad/s²\n', peakaY);
fprintf('About Z-axis: %.2f rad/s²\n', peakaZ);
%% Max linear acceleration and its direction
% linear acceleration vectors from COG
accVecs = COG;
% magnitudes at each point
accMags = vecnorm(accVecs, 2, 2);
% location of maximum magnitude
[peakLinearMag, idxMaxAcc] = max(accMags);
% direction as unit vector
maxAccDir = accVecs(idxMaxAcc, :) / peakLinearMag;
fprintf('\nmaximum Linear Acceleration: %.2f m/s²\n', peakLinearMag);
fprintf('unit vector: [%.3f, %.3f, %.3f]\n', maxAccDir);
%% max rotational acceleration
rotVecs = [a_x, a_y, a_z];
rotMags = vecnorm(rotVecs, 2, 2);
[peakRotMag, idxMaxRot] = max(rotMags);
maxRotDir = rotVecs(idxMaxRot, :) / peakRotMag;
fprintf('\nMax rotational acceleration: %.2f rad/s²\n', peakRotMag);
fprintf('rotation axis (unit vector): [%.3f, %.3f, %.3f]\n', maxRotDir);
%% force tranmission plot and rotational acceleration plot
mass = 80;
forceVecs = mass * COG;
forceMags = vecnorm(forceVecs, 2, 2);
rotVecs = [a_x, a_y, a_z];
rotProj = rotVecs * maxRotDir';
figure;
```

```
subplot(2,1,1)
plot(time, forceMags)
title('Force Transmission')
xlabel('time (s)'); ylabel('Force (N)')
subplot(2,1,2)
plot(time, rotProj)
title('Rotational Acceleration (About max rotation axis)')
xlabel('time (s)'); ylabel('Angular Acceleration (rad/s²)')
sgtitle('Trial 6: Force and Rotational Acceleration along True Direction')
%% max force transmission
[maxForce, idxMaxForce] = max(forceMags);
fprintf('\nMaximum force transmission: %.2f N\n', maxForce);
```

[A2] - MATLAB Code for Video Acceleration Analysis

```
clc; clear; close all;
%% Load video
vid = VideoReader('filename.mp4');
frame = read(vid, 1);  % Use first frame
% Get video properties
frameRate = vid.FrameRate;
nFrames = floor(vid.Duration * frameRate);
vid.CurrentTime = 0;  % Reset to beginning
%% Yellow strip detection and measurement
imshow(frame);
title('Click near the yellow strip on the helmet');
[x0, y0] = ginput(1);  % Initial position guess
% Define ROI around clicked point
roiSize = 500;  % Adjust as needed
x1 = max(round(x0 - roiSize/2), 1);
y1 = max(round(y0 - roiSize/2), 1);
x2 = min(round(x0 + roiSize/2), size(frame,2));
y2 = min(round(y0 + roiSize/2), size(frame,1));
roi = frame(y1:y2, x1:x2, :);
% Detect yellow using HSV
hsvROI = rgb2hsv(roi);
yellowMask = (hsvROI(:,:,1) >= 0.12 & hsvROI(:,:,1) <= 0.18) & ...
             (hsvROI(:,:,2) >= 0.4) & ...
             (hsvROI(:,:,3) >= 0.4);
```

```
% Process mask
yellowMask = bwareafilt(yellowMask, 1);
yellowMask = imfill(yellowMask, 'holes');
% Get length more efficiently
stats = regionprops(yellowMask, 'MajorAxisLength', 'Orientation', 'Centroid');
if ~isempty(stats)
   stripLength_px = stats.MajorAxisLength;
   fprintf('Yellow strip length: %.2f pixels\n', stripLength_px);

   % Visualize with corrected rectangle drawing
   imshow(roi);
   hold on;

   % Calculate rectangle parameters
   theta = stats.Orientation;
   halfLength = stripLength_px/2;
   halfWidth = 5; % Width of the yellow strip (adjust as needed)
   centroid = stats.Centroid;

   % Calculate rectangle vertices
   x = [-halfLength -halfLength halfLength halfLength];
   y = [-halfWidth halfWidth halfWidth -halfWidth];

   % Rotate vertices
   R = [cosd(theta) -sind(theta); sind(theta) cosd(theta)];
   rotatedVertices = [x; y]' * R;

   % Translate to centroid
   xv = rotatedVertices(:,1) + centroid(1);
   yv = rotatedVertices(:,2) + centroid(2);

   % Draw the rotated rectangle
   plot([xv; xv(1)], [yv; yv(1)], 'r-', 'LineWidth', 2);
   title('Detected Yellow Strip with Length Measurement');
else
   error('Yellow strip not detected in ROI.');
end
%% Get real-world length for calibration
```

```
realLength = 0.15; % meters
pixelToMeter = realLength / stripLength_px;
fprintf('Calibration factor: %.6f meters/pixel\n', pixelToMeter);
%% Marker tracking initialization
figure; imshow(frame);
title('Click on the helmet marker to track');
[x0, y0] = ginput(1);
% Create template from initial position
templateSize = 50;
x1 = max(round(x0 - templateSize/2), 1);
y1 = max(round(y0 - templateSize/2), 1);
x2 = min(round(x0 + templateSize/2), size(frame,2));
y2 = min(round(y0 + templateSize/2), size(frame,1));
template = rgb2gray(frame(y1:y2, x1:x2, :));
% Preallocate positions
helmetPos = zeros(nFrames, 2);
helmetPos(1,:) = [x0, y0];
%% Template matching tracking
h = waitbar(0, 'Tracking marker...');
for k = 2:nFrames
   currentFrame = readFrame(vid);
   grayFrame = rgb2gray(currentFrame);

   % Perform template matching
   corrMap = normxcorr2(template, grayFrame);

   % Find peak correlation
   [ypeak, xpeak] = find(corrMap == max(corrMap(:)));
   yoff = ypeak - size(template,1);
   xoff = xpeak - size(template,2);

   % Update position
   helmetPos(k,:) = [xoff + size(template,2)/2, yoff + size(template,1)/2];

   waitbar(k/nFrames, h);
end
close(h);
%% Final Kinematics Calculation and Output
```

```matlab
% Convert positions to meters and adjust coordinate system
helmetPos_m = helmetPos * pixelToMeter;
helmetPos_m(:,2) = max(helmetPos_m(:,2)) - helmetPos_m(:,2);  % Flip vertical axis
helmetPos_m = helmetPos_m - helmetPos_m(1,:);  % Set initial position to (0,0)
% Time vector
dt = 1/frameRate;
t = (0:nFrames-1)' * dt;
% 1. Smooth position data with adaptive window size
windowSize = min(25, floor(nFrames/5)); % Start with larger window
windowSize = windowSize + mod(windowSize+1,2); % Ensure odd number
helmetPos_m(:,2) = sgolayfilt(helmetPos_m(:,2), 3, windowSize);
% 2. Calculate velocity with central difference
vel = zeros(size(helmetPos_m));
vel(2:end-1,2) = (helmetPos_m(3:end,2) - helmetPos_m(1:end-2,2)) / (2*dt);
vel([1 end],2) = vel([2 end-1],2); % Handle edges
% 3. Smooth velocity before acceleration calculation
velWindow = min(15, floor(nFrames/10));
velWindow = velWindow + mod(velWindow+1,2); % Ensure odd
vel(:,2) = sgolayfilt(vel(:,2), 2, velWindow);
% 4. Calculate acceleration with central difference
accel = zeros(size(vel));
accel(2:end-1,2) = (vel(3:end,2) - vel(1:end-2,2)) / (2*dt);
accel([1 end],2) = accel([2 end-1],2);
% 5. Final smoothing on acceleration
accel(:,2) = medfilt1(accel(:,2), 5); % Median filter to remove spikes
% Calculate force
Mass = 80;  % kg, includes helmet and average male mass
force = Mass * accel(:,2);
%% Calculate and display key metrics
% Find maximum drop distance (positive displacement)
minDropDistance = min(helmetPos_m(:,2));
% Find maximum force (positive or negative)
[maxForce, maxForceIdx] = max(abs(force));
maxForceTime = t(maxForceIdx);
impactDuration = sum(abs(force) > 0.1*maxForce) * dt;
% Display results in command window
fprintf('\n=== IMPACT ANALYSIS RESULTS ===\n');
fprintf('Maximum drop distance: %.4f meters\n', minDropDistance);
```

```
fprintf('Maximum force transmission: %.2f N at %.3f seconds\n', maxForce,
maxForceTime);
fprintf('Impact duration: %.3f seconds\n', impactDuration);
fprintf('Average force during impact: %.2f N\n\n', mean(abs(force(abs(force) >
0.1*maxForce))));
%% Create professional 2x2 plot arrangement
figure('Position', [100 100 1200 800], 'Color', 'w');
% Displacement plot
subplot(2,2,1);
plot(t, helmetPos_m(:,2), 'b', 'LineWidth', 1.5);
hold on;
plot([t(1) t(end)], [minDropDistance minDropDistance], 'b--', 'LineWidth', 1);
text(t(end), abs(minDropDistance), sprintf(' Max: %.4f m',
abs(minDropDistance)), ...
   'VerticalAlignment', 'bottom', 'HorizontalAlignment', 'right', 'FontSize',
9);
xlabel('Time (s)', 'FontSize', 10);
ylabel('Displacement (m)', 'FontSize', 10);
title('Vertical Displacement', 'FontSize', 12);
grid on;
ylim([min(helmetPos_m(:,2))-0.01, max(helmetPos_m(:,2))+0.01]);
% Velocity plot
subplot(2,2,2);
plot(t, vel(:,2), 'r', 'LineWidth', 1.5);
xlabel('Time (s)', 'FontSize', 10);
ylabel('Velocity (m/s)', 'FontSize', 10);
title('Vertical Velocity', 'FontSize', 12);
grid on;
ylim([min(vel(:,2))-0.1, max(vel(:,2))+0.1]);
% Acceleration plot
subplot(2,2,3);
plot(t, accel(:,2), 'Color', [0 0.6 0], 'LineWidth', 1.5);
xlabel('Time (s)', 'FontSize', 10);
ylabel('Acceleration (m/s²)', 'FontSize', 10);
title('Vertical Acceleration', 'FontSize', 12);
grid on;
ylim([min(accel(:,2))-2, max(accel(:,2))+2]);
% Force plot
subplot(2,2,4);
plot(t, force, 'Color', [0.7 0 0.7], 'LineWidth', 1.5);
```

```
hold on;
plot([t(1) t(end)], [maxForce maxForce], 'm--', 'LineWidth', 1);
plot([t(1) t(end)], [-maxForce -maxForce], 'm--', 'LineWidth', 1);
plot([maxForceTime maxForceTime], [min(force) max(force)], 'k:', 'LineWidth',
1);
text(maxForceTime, maxForce, sprintf(' Max: %.1f N', maxForce), ...
   'VerticalAlignment', 'bottom', 'FontSize', 9);
xlabel('Time (s)', 'FontSize', 10);
ylabel('Force (N)', 'FontSize', 10);
title('Vertical Force', 'FontSize', 12);
grid on;
ylim([min(force)-5, max(force)+5]);
% Add overall title with key metrics
sgtitle(sprintf('Trial 1 Helmet Impact Analysis - Proper Fit | Drop: %.3f m |
Max Force: %.1f N | Duration: %.3f s', ...
   minDropDistance, maxForce, impactDuration), ...
   'FontSize', 14, 'FontWeight', 'bold');
%% Save comprehensive results
analysisResults = struct(...
   'time', t, ...
   'displacement', helmetPos_m(:,2), ...
   'velocity', vel(:,2), ...
   'acceleration', accel(:,2), ...
   'force', force, ...
   'maxDropDistance', minDropDistance, ...
   'maxForce', maxForce, ...
   'maxForceTime', maxForceTime, ...
   'impactDuration', impactDuration, ...
   'calibrationFactor', pixelToMeter, ...
   'frameRate', frameRate);
disp('Analysis complete! Results saved in ''analysisResults'' structure.');
```