Biomechanical Analysis of Head Gear Designed for Older Population Fall Protection

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Abstract *Falls* lead to increased morbidity and mortality, representing a significant public health concern in the older population. Head protection designed and sold to older adults does not require certification, resulting in a wide range of head protection designs, which in return creates a wide range of safety. Certified helmets, including hockey and cycling helmets, provided superior protection across all tested impact conditions. Two head protection prototypes for older adults were developed for this study using rotational technology. Two commercially available head protectors for older adults, two prototype head protectors, a certified hockey helmet and a certified cycling helmet were impact tested. Peak resultant linear and rotational acceleration values varied for the commercial head protectors and prototypes depending on the impact test conditions. Even with the incorporation of rotational technology, Prototype One resulted in inconsistent performance in reducing rotational acceleration. Prototype Two included two rotational technologies, resulting in decreased rotational acceleration for all conditions, with the highest reduction being 55% at 5.0 m/s front impact and 61% at 5.0 m/s rear impact. While the older adult head protection prototypes did reduce linear acceleration, on average, they did not perform as well as the two certified helmets. Even though the certified sports helmets were specifically designed and certified for other activities (hockey and cycling), on average, they performed better in all conditions when compared to the two prototype helmets. These findings support the value of employing a certification standard for older adult headgear. While the prototypes showed potential, the adoption of an older adult headgear standard would support head gear innovation and decrease head injuries among the older population.

Keywords: certification, injuries, headgear, head protection, older adults

I. INTRODUCTION

Falls among the older populations represent a significant public health concern, leading to considerable morbidity and mortality. Annually, the Centers for Disease Control and Prevention (CDC) reports 36 million falls by older adults, resulting in 3 million of these older adults being treated in emergency rooms for fall-related injuries [1]. One in 5 falls results in a head injury [1]. For adults 65 years of age and older, falls result in nearly half of the Traumatic Brain Injury-related (TBI-related) hospitalizations and account for the majority of TBI-related deaths [2]. While the data reflect significant health risks posed by falls among the older population, there have been limited interventions proposed to mitigate the risk of head injuries resulting from falls. Protective headgear is advertised as reducing the severity of head injuries resulting from falls in the older population. However, presently, head protection for older adults does not require certification to evaluate the level of impact protection. The absence of a required certification standard for protective headgear exposes older adults to increased risks for fall-related injuries. Certified and effective head protection devices, such as those used in ice hockey and cycling, offer a consistent level of protection. A head gear test protocol was developed to reflect real-world falls resulting in head impacts experienced by the older population. The test protocol representing real-world head impacts experienced by older adults was used to assess the head gear in this research. Hockey helmets are primarily designed to protect against falls and collisions between players, boards, or the ice. Ice hockey helmets are constructed with a hard outer shell and compliant foam padding to absorb and dissipate impact forces. Cycling helmets are designed primarily to protect against falls and impacts typically encountered in cycling accidents, including collisions with vehicles, pavement, or stationary objects. They consist of a thin, hard outer shell with extended coverage around the sides and back of the head to provide additional protection for fall events. Ice hockey and cycling involve similar head impacts, including collisions and falls, resulting in concussions and traumatic brain injuries similar to those reported in older adults. Comparing older adult headgear to certified helmets designed for different applications provides useful insights

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into the effectiveness of existing older adult head protectors. Understanding the performance of helmets designed for specific activities compared to traditional adult headgear provides a reference for potential improvements in older adult head protection design. A test protocol designed to reflect head impact events specific to older adults was used to compare older adult headgear with specialized sport helmets and design prototypes. The results from this study provide an evaluation of existing older adult head protectors and the potential for improvement.

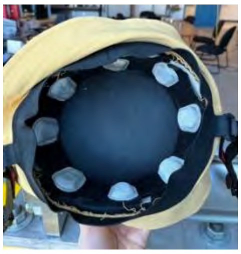
II. METHODS

Prototype One consisted of 2 layers of ½ inch-closed cell foam within a fabric-wrapped headband with a Velcro side closure and a slip rotational technology on the exterior edge of foam (limited head coverage). Prototype Two consisted of a bucket hat design with 11 mm microperforated compact foam panels and a chin strap with the addition of both fluid and slip rotational technology (full head coverage). These two prototypes presented an opportunity to include a rotational technology with limited disruption to the integrity of the comfort and design of the original headgear for older adults. The two prototypes, two commercially available older adult head gear and a cycling and hockey helmets were tested in this study (Table I).

A monorail drop rig (free drop) with a Hybrid III 50th percentile head form and no neck was used to create a free drop to represent head impacts during a fall. The Hybrid III head form was not attached to the drop rig and allowed to freely rotate upon impact. A horizontal (flat) Modular Elastomer Programmer (MEP) anvil was used to represent falls that resulted in head impacts to the floor. Impact velocities were obtained from the scientific literature for real-world head impacts representing older adults [3-4]. A velocity of 3.5 m/s was selected to represent the velocity of head impacts when there was interference, such as arms and shoulders, resulting in decreased head impact velocity [3-6]. A velocity of 5.0 m/s was chosen to reflect falls where no interference occurred during the head impact event. These impacts occur when older adults faint, slip or fall and their head impacts the floor directly [3-6]. TDAS Pro software was used to record linear and rotational acceleration (20,000 Hz). Impact locations were chosen based on the most commonly reported impact locations during falls in older adults and included the front, side, and rear locations [3], [4], [7]. Each helmet and headgear was placed and secured on the head form according to the manufacturer’s instructions. Based on the reference plane of the Hybrid III head, the location was specified for each headgear/helmet. The head form was marked to ensure the head gear and helmets aligned with intended impact locations. The placement of the head gear and head protector on the drop rig were marked and recorded for each headgear and impact for each condition. The impact location for the front anterior site was at the intersection of the median and horizontal planes, at a point 30 mm above the reference plane, with the head elevated 15° towards the impactor surface. The right-side impact location was at the intersection of the frontal and horizontal planes, 30 mm above the reference plane, with a -45° azimuth rotation in the horizontal plane. The impact vector was applied perpendicular (90°) to the head form surface, with the head elevated 15° towards the impactor surface. The rear impact location was at the intersection of the median and horizontal planes, 30 mm above the reference plane, with a -45° azimuth rotation in the horizontal plane. Each helmet was subjected to 3 impacts at each location (front, side, rear) at one velocity – with the same helmet (hockey, cycling, Prototype one, Protype two, on market head gear one, on market head gear two) being used for the three repeated impacts at each location and for one condition. Table II describes the testing parameters used in this study. Statistical analysis was conducted to evaluate the effectiveness of two helmet prototypes for peak linear and rotational accelerations under impact location and velocity conditions. A repeated measures ANOVA was used to compare the helmets across impact locations (front, side, rear) and velocities (3.5 m/s, 5.0 m/s). Post-hoc tests with Bonferroni correction were performed to identify differences between prototypes. Significance was determined at $P < 0.05$.

Table I

DESCRIPTION OF EACH HELMET TESTED

Headgear	Description	Impact Condition	Category	Image
Prototype One	Headband 2 Layers of ½ inch Closed Cell Foam Velcro Close Slip (Rotational Technology)	All Conditions	Limited coverage	
Prototype Two	Bucket hat 11 mm Microperforated - Compact Foam Panels Chin Strap Fluid (Rotational Technology) Slip (Rotational Technology)	All Conditions	Full Coverage	
Hockey	CMM FL 60 Liquid Filled Bladders Expanded Polypropylene (EPP) Comfort and Protective Foam Chin Strap Adjustable Sizing	All Conditions	Full Coverage	

Cycling	Fox Flux Drafter Varizorb multi-density Expanded Polystyrene (EPS) Foam Chin Strap 300-degree retention system	All Conditions	Full Coverage	
On Market Headgear One	Headband 2 Layers of ½ inch Closed Cell Foam Velcro Close	All Conditions	Limited Coverage	
On Market Headgear Two	Bucket hat 11 mm Microperforated - Compact Foam Panels Chin strap	All Conditions	Full Coverage	

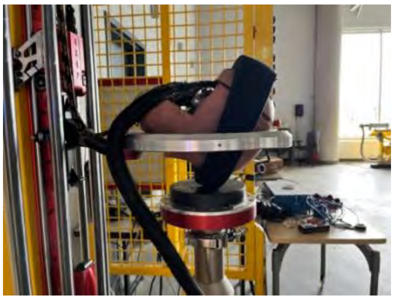
TABLE II

DESCRIPTION OF EACH TEST METHOD WITH VELOCITIES, LOCATIONS AND ANVIL

Test Method	Anvil	Inbound Velocity (m/s)	Location	Total Number of Impacts
Monorail Drop Test	Flat – MEP	3.5 – 5.0	Front – Side – Rear	108

TABLE III

TESTING LOCATIONS

Front	Rear	Side
		

Dependent Variables:

a) Resultant Linear Acceleration (g's)
b) Resultant Rotational Acceleration (rads/sec^2)

Independent Variables:

c) Helmet (6)
    a. Prototype One
    b. Prototype Two
    c. CCM FL-60 (Hockey Helmet)
    d. Fox Flux Drafter (Cycling Helmet)
    e. On Market Headgear One
    f. On Market Headgear Two
d) Velocity (2)
    a. 3.5 m/s
    b. 5.0 m/s
e) Impact Location (3)
    a. Front
    b. Side
    c. Rear

III. RESULTS

When the head gear were compared by velocities with locations collapsed, the two helmet prototypes had significantly reduced linear and rotational accelerations. Prototype Two significantly reduced linear acceleration at impact velocities of 3.5 m/s (P=0.006) and 5.0 m/s (P=0.005) when compared to O.M. HG Two. Prototype Two also significantly reduced rotational acceleration at 5.0 m/s (P=0.012) compared to O.M. HG Two, with a non-significant decrease at 3.5 m/s (P=0.056) (Table IV). When the head gear were compared for location Prototype Two significantly decreased rotational acceleration at the front location (P=0.005) when compared to O.M. HG Two (Table V). At the side location, Prototype One significantly reduced linear acceleration (P=0.0354) and rotational acceleration (P=0.0167), and Prototype Two showed significant reductions in both linear (P=0.0276) and rotational acceleration (P=0.004) when compared to O.M. HG Two (Table V). At the rear location, Prototype Two significantly reduced linear acceleration (P=0.489) and rotational acceleration (P=0.001) when compared to O.M. HG Two (Table V).

When the head gear were compared for location and velocity (Table VI) Prototype Two significantly reduced rotational acceleration at both 3.5 m/s (P=0.0293) and 5.0 m/s (P=0.0193) in the front location. At the side location, Prototype One significantly reduced linear acceleration at 3.5 m/s (P=0.0156). Prototype Two demonstrated significant reductions in linear acceleration at 3.5 m/s (P=0.00394) and 5.0 m/s (P=0.0476), as well as in rotational acceleration at 3.5 m/s (P=0.0036) and 5.0 m/s (P=0.0010). In the rear location, Prototype One significantly reduced linear acceleration at 3.5 m/s (P=0.0162). Prototype Two showed significant improvements in reducing linear acceleration at both 3.5 m/s (P=0.0392) and 5.0 m/s (P=0.0138) and in reducing rotational acceleration at both 3.5 m/s (P=0.015) and 5.0 m/s (P=0.0156). Overall, Prototype Two consistently outperformed Prototype One in reducing both linear and rotational accelerations across the impact locations and velocities, indicating the effectiveness of rotational technology in the head gear. For some impact conditions, the addition of rotational technology in Prototype One increased both rotational and linear acceleration of the head, demonstrating that modifications may be head gear specific.

When the head gear were compared by location and velocity Prototype Two significantly reduced rotational acceleration at both 3.5 m/s (P=0.0293) and 5.0 m/s (P=0.0193) in the front location when compared to O.M. HG Two (Table VI). At the side location, Prototype One significantly reduced linear acceleration at 3.5 m/s (P=0.0156). Prototype Two demonstrated significant reductions in linear acceleration at 3.5 m/s (P=0.00394) and 5.0 m/s (P=0.0476), as well as in rotational acceleration at 3.5 m/s (P=0.0036) and 5.0 m/s (P=0.0010) when compared to O.M. HG Two (Table VI). For the rear location, Prototype One significantly reduced linear acceleration at 3.5 m/s (P=0.0162) when compared to O.M. HG Two (Table VI). Prototype Two showed significant reductions for linear acceleration at both 3.5 m/s (P=0.0392) and 5.0 m/s (P=0.0138) and in reducing rotational acceleration at both 3.5 m/s (P=0.015) and 5.0 m/s (P=0.0156) when compared to O.M. HG Two. Overall, Prototype Two consistently outperformed Prototype One in reducing both linear and rotational accelerations across the impact locations and velocities, indicating the effectiveness of rotational technology in the head gear. A comparison for each head gear at 3.5 and 5.0 m/s impacts at the front impact location is provided in Fig. 1. A comparison of peak linear and rotational acceleration for each head gear at 3.5 and 5.0 m/s impacts at the side impact location is provided in Fig. 2. A comparison of peak linear and rotational acceleration for each head gear at 3.5 and 5.0 m/s impacts at the back impact location is provided in Fig. 3.

TABLE IV

MEAN COMPARISON OF DYNAMIC HEAD RESPONSE BETWEEN PROTOTYPE 1 AND PROTOTYPE 2, ON MARKET HEAD GEAR 1, ON MARKET HEAD GEAR 2, CCM FL 60 AND FOX FLUX DRAFTER, FOR 3.5 M/S AND 5.0 M/S IMPACTS WITH LOCATION COLLASPED. * SIGNIFIES THE HIGHEST VALUE, AND ** SIGNIFIES THE LOWEST VALUE **^** SIGNIFIES IF PROTOTYPE LOWERED VALUES.

Helmet Type	Resultant Linear Acceleration (g)		Resultant Rotational Acceleration (rads/s2)	
	3.5 m/s	5.0 m/s	3.5 m/s	5.0 m/s
Prototype One	115.1 (20.18)	223.1 (27.19)	3672.8 (1539.17)	10609.6 (4170.99)
Prototype Two	120.4^ (12.78)	222.2**^** (21.04)	7309.8**^** (3219.93)	10339.7**^** (4306.5)
O.M. HG One	90.6 (22.59)	185.9 (31.29)	3470.7** (1150.34)	7798.8 (5034.36)
O.M. HG Two	124.4* (14.50)	265.1* (55.96)	12313.5* (5516.91)	21238.9* (3175.29)
Hockey	84.2** (7.36)	153.8** (10.11)	3640.3 (621.22)	7362.3** (1904.12)
Cycling	95.1 (13.35)	154.2 (26.87)	6728.5 (1898.24)	9463.9 (5897.63)

TABLE V

MEAN COMPARISON OF DYNAMIC HEAD RESPONSE BETWEEN PROTOTYPE 1 AND PROTOTYPE 2, ON MARKET HEAD GEAR 1, ON MARKET HEAD GEAR 2, CCM FL 60 AND FOX FLUX DRAFTER, FOR 3.5 M/S AND 5.0 M/S IMPACTS WITH VELOCITIES COLLASPED. * SIGNIFIES THE HIGHEST VALUE, AND ** SIGNIFIES THE LOWEST VALUE ^ SIGNIFIES IF PROTOTYPE LOWERED VALUES.

Impact Location	Helmet Type	Resultant Linear Acceleration (g)	Resultant Rotational Acceleration (rads/s2)
Front	Prototype One	185.01* (65.25)	4001.9 (1377.84)
	Prototype Two	183.6 (57.63)	5803.2^ (2570.87)
	O.M. HG One	145.7 (75.66)	2952.9** (1023.82)
	O.M. HG Two	174.9 (71.34)	11244.7* (9522.34)
	Hockey	112.9 (46.32)	4965.4 (1598.06)
	Cycling	105.6** (33.51)	5826.3 (1951.61)
Side	Prototype One	157.4^ (59.14)	5817.9**^ (611.23)
	Prototype Two	149.1^ (49.17)	11986.8^ (4034.89)
	O.M. HG One	160.4* (67.88)	9205.8 (5945.28)
	O.M. HG Two	219.5 (154.99)	20900.0* (6637.33)
	Hockey	122.45** (60.32)	7169.1 (4079.29)
	Cycling	138.7 (62.22)	13320.0 (5976.75)
Rear	Prototype One	153.2 (59.84)	7654.2 (5914.76)
	Prototype Two	187.02^ (58.08)	8920.8^ (3713.24)
	O.M. HG One	108.8** (58.62)	4745.5 (2212.18)
	O.M. HG Two	189.9* (72.05)	18319.01* (3965.06)
	Hockey	121.7 (41.01)	4369.4** (2218.19)
	Cycling	129.7 (29.76)	5142.3 (2125.56)

TABLE VI
MEAN COMPARISON OF DYNAMIC HEAD RESPONSE BETWEEN PROTOTYPE 1 AND PROTOTYPE 2, ON MARKET HEAD GEAR 1, ON MARKET HEAD GEAR 2, CCM FL 60 AND FOX FLUX DRAFTER, FOR 3.5 M/S AND 5.0 M/S IMPACTS. * SIGNIFIES THE HIGHEST VALUE, AND ** SIGNIFIES THE LOWEST VALUE ^ SIGNIFIES IF PROTOTYPE LOWERED VALUES.

Impact Location	Helmet Type	Resultant Linear Acceleration (g)		Resultant Rotational Acceleration (rads/s2)	
		3.5 m/s	5.0 m/s	3.5 m/s	5.0 m/s
Front	Prototype One	136* (14.64)	250.4* (35.20)	2917.6 (349.72)	5447.7 (158.93)
	Prototype Two	130.9 (1.26)	236.2 (1.55)	3470.5^ (325.65)	8135.9^ (305.61)
	O.M. HG One	92.2 (9.45)	199.2 (10.27)	2229** (434.12)	3676.9** (467.8)
	O.M. HG Two	124.5 (2.07)	225.4 (7.75)	4511.4* (439.41)	17978.02* (366.37)
	Hockey	80.1** (2.93)	145.6 (10.18)	3835.4 (175.5)	6095.4 (913.7)
	Cycling	81.9 (11.5)	129.3** (11.41)	4446.3 (421.77)	7206.3 (467.8)
Side	Prototype One	103.5^ (3.11)	211.3 (2.90)	5817.9 (683.38)	13607.2 (536.16)
	Prototype Two	104.5^ (4.55)	193.7^ (7.03)	8308.1^ (274.08)	15665.4^ (170.91)
	O.M. HG One	112.4* (7.89)	208.4 (104.73)	5001.8* (892.50)	13409.7 (5784.57)
	O.M. HG Two	109.9 (9.11)	329.1* (5.07)	16206.7** (1369.31)	25593.3** (183.92)
	Hockey	79.8** (2.29)	165.1** (4.42)	10053.6 (540.20)	10053.6* (647.75)
	Cycling	94.7 (4.89)	182.7 (25.11)	9093.8 (2079.91)	17546.2 (2266.06)
Rear	Prototype One	98.8 (4.91)	207.7 (5.52)	2534.5^ (156.00)	12773.9 (2966.96)
	Prototype Two	125.7^ (6.46)	233.05^ (11.42)	10150.7^ (2362.16)	7998.4^ (4605.36)
	O.M. HG One	67.3** (9.42)	150.2** (11.91)	3181.2 (489.36)	6309.7 (879.10)
	O.M. HG Two	138.9* (5.55)	240.8* (6.94)	16222.39* (586.79)	20415.63* (6235.65)
	Hockey	92.7 (8.51)	150.7 (12.79)	2800.9** (582.52)	5937.9 (862.18)
	Cycling	108.6 (5.96)	150.7 (16.26)	6645.3 (861.36)	3639.3** (2399.44)

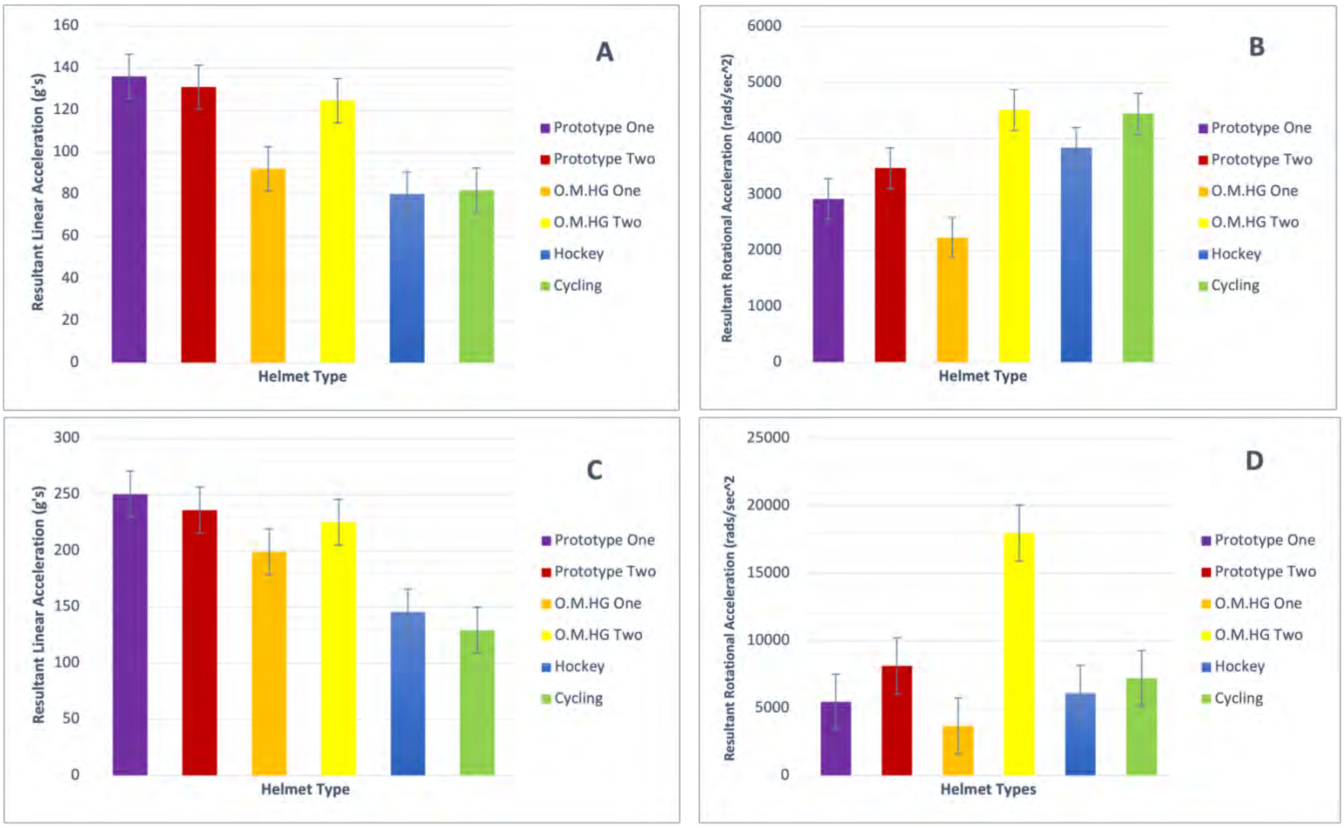


Fig. 1. Front Impact Location: The average resultant linear acceleration of each helmet using the flat MEP anvil. A. Front location at 3.5 m/s (Peak linear acc.). B. Front location at 3.5 m/s (peak rotational acc.) C. Front location at 5.0 m/s, D. Front location at 5.0 m/s. The average resultant rotational acceleration of each helmet using the flat MEP anvil.

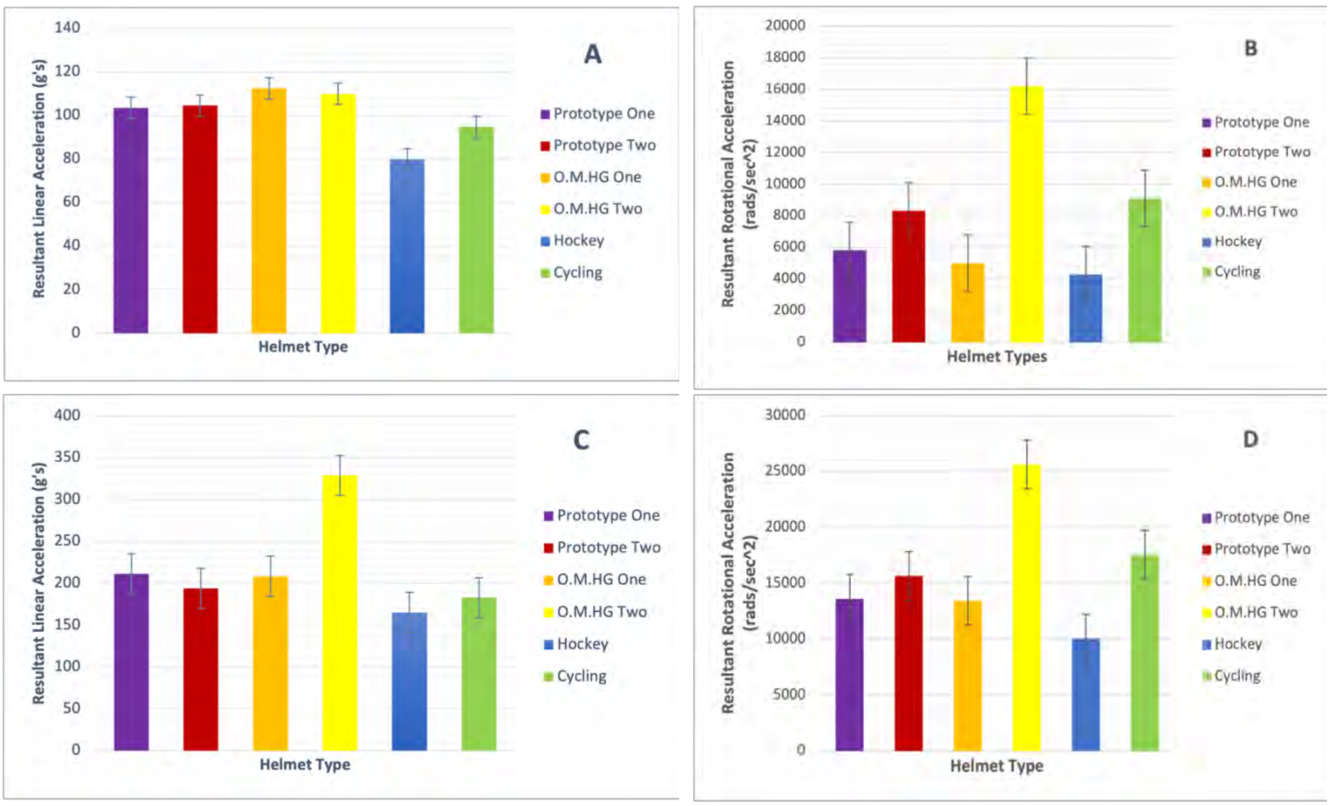


Fig. 2. Side Impact Location: The average resultant linear acceleration of each helmet using the flat MEP anvil. A. Side location at 3.5 m/s. B. Side location at 3.5 m/s. C. Side location at 5.0 m/s. D. Side location at 5.0 m/s. The average resultant rotational acceleration of each helmet using the flat MEP anvil.

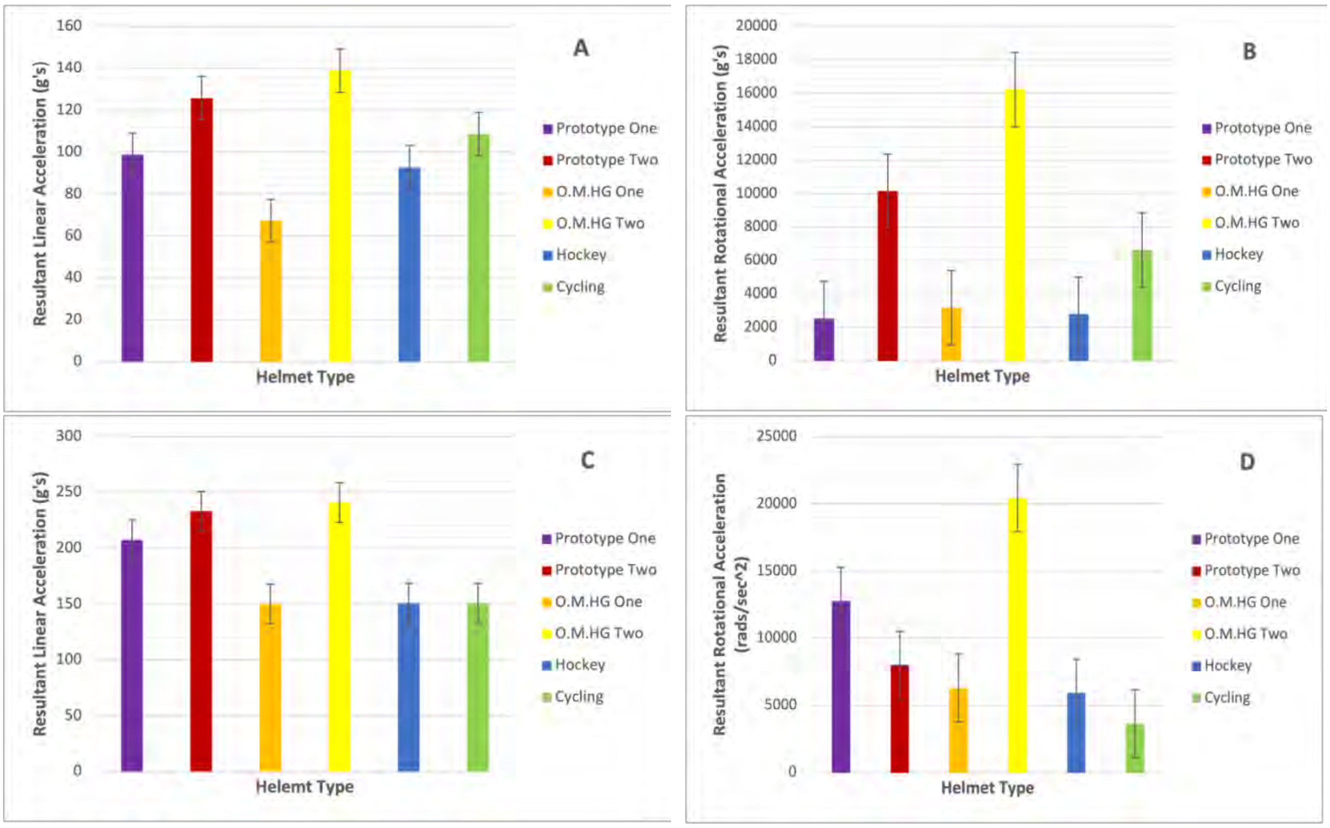


Fig. 3. Rear Impact Location: The average resultant linear acceleration of each helmet using the flat MEP anvil. A. Rear location at 3.5 m/s. C. Rear location at 5.0 m/s. The average resultant rotational acceleration of each helmet using the flat MEP anvil. B. Rear location at 3.5 m/s. D. Rear location at 5.0 m/s.

IV. DISCUSSION

This study investigated the effectiveness of head gear in mitigating head injury risk among the older population in simulated falls.

The certified sport helmets included in this study consistently provided significantly better head protection across all tested conditions. The two headgear prototypes developed for this research exhibited improved performance compared to the head protectors currently on the market. However, their effectiveness varied depending on the specific impact conditions tested. Prototype One and Prototype Two demonstrated promising results in decreasing rotational acceleration; more specifically, Prototype One resulted in a decreased mean rotational acceleration of 20% at 3.5m/s rear condition. Prototype Two resulted in decreased mean rotational acceleration for all impact conditions. The two prototype head gear performed better than the existing on market head gear but not as well as the two certified sport helmets.

Interestingly, Prototype One saw a decrease in performance with a 32% mean linear acceleration increase across all conditions with the except of one and an increase in mean rotational acceleration of 40% across all conditions again with the except of one. These results highlight the challenges in designing effective headgear for older adults, as in most trials (in the absence of a chin strap or securing feature), the headgear not only shifted but, in some trials, was dislodged from the head. It is expected that further innovation improvements, such as adding a chin strap, could improve head gear performance.

The findings support the potential advantage of using rotational technology to reduce the risk of injury from falls among older adults. By incorporating this technology, helmets provided better protection for a range of impact types. The findings in study revealed commercially available head gear for older adults provide limited and a wide range of protection. The prototype head gear tested in this study primarily involved the addition of rotational technology resulting in improvements in managing rotational accelerations. Finally, the two certified sports helmets (hockey and cycling) provided the best protection across the test conditions. The variability in performance observed among the two prototypes could be attributed to several factors, including design differences, material properties, and impact dynamics, suggesting further optimization and refinement of these prototypes are necessary to improve their effectiveness in head protection. The wide range of performance of the older adult head gear tested and significant differences when compared to certified sport head gear and rudimentary prototype supports the need for developing a certification test standard to guide the design of head gear for the older population.

V. CONCLUSION

The head gear tested in this research resulted in a wide range of peak linear and rotational acceleration results across the three impact sites and two impact velocities. The certified hockey and cycling helmets were clearly superior in managing peak linear and rotational accelerations while the commercially available older adult head protectors performing the least effective. The author developed two prototype head protectors by integrating rotational technology into a commercially available head gear. The performance results for the two prototypes resulted in were unique. Results were unique depending on the impact test conditions.

Notably, when collapsing velocity and focusing on effectiveness for each impact location, Prototype One at the side location had the lowest peak rotational acceleration of 5817.9 (rads/sec^2), with 19% and 53% lower rotational acceleration than the Hockey and Bicycle helmet respectively. Prototype Two decreased mean rotational acceleration in all conditions with an average of 44% decrease when compared to the original O.M HG

The findings from this research demonstrated the wide range of performance of existing commercially available head gear for older adults. It also demonstrated the superior performance of certified sport helmets when compared to older adult head protectors. The two prototypes that incorporated rotational technology showed inconsistent performance, highlighting the importance of continued research and the value of certification standards to improve head protection for the older population.

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