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Design Development of a Repeatable Helmet Test System for Public Order Threat Recreations

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Abstract. The prevalence of violence and blunt weaponry that Public Order (PO) officers are exposed to, place them at high risk of traumatic brain injury (TBI). Recreating these injurious occurrences, to assess protective equipment performance, can be problematic due to issues of repeatability when experimentally recreating PO threats. This led to the design of a bespoke helmet impact system. Following review of current test methods, the chosen design was a low-friction drop tower, compatible with anthropometric headforms as cradled, rigidly mounted, or affixed with a surrogate neck. Finite Element and torque calculations were used to optimise load bearing components, whilst maintaining low mass and safety requirements. The final system permits impact conditions in range for PO threat recreations, as well as meeting the standard test criteria of all non-vehicular sports, public sector and construction application standard drop tests.

Keywords: Impact Test: Helmet Design: Injury Prevention: Brain Injury.

1 Introduction

Public Order (PO) officers, referred to as ‘Riot Police’, are an occupation at high risk of Traumatic Brain Injury (TBI), due to the typical violent nature and prevalence of blunt weaponry they are exposed to in operations. UK PO officers are issued a helmet conforming to BSI product approval specification ‘PAS017’, set by the Home Office standard for protective headwear, PSDB 21/04 [1]. This dictates a minimum threshold for helmet effectiveness when dissipating impact energy. Anthropometric Test Device (ATD) headforms, affixed with PO helmet, are dropped with a low-friction guided carriage onto rigid anvils. A tri-axial accelerometer at headform centre of mass records peak translational accelerations, with pass criteria less than 250 and 150 g ($g = 9.81\ ms^{-2}$) for impact energies at 120 and 60 J.

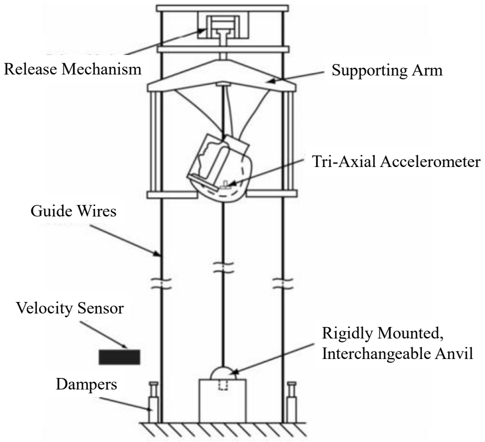

Fig. 1. Schematic for the PSDB 21/04 standard helmet impact attenuation test system [1].

1.1 Laboratory Recreation of Situational Threats

Thrown projectiles are a common cause of head injury in PO operations, due to their public accessibility, useability and weight. This is represented in PSDB 21/04 by a sharp 'corner of a small brick' impact anvil. Initial methods exploring the force transfer of brick-helmet impacts showed a lack of repeatability, attributable to the free-fall drop system used. This had a vacuum release with maximum 2 m drop height (6.3 ms^{-1}), that necessitated impacting the helmet with bricks, rather than dropping the helmet as per traditional standards. High-speed video of trials showed inconsistent brick orientations at impact, which was believed to be the primary factor in observed variation. Observed rotational behaviour of the bricks in freefall, was attributed to an inhomogeneous mass distribution within the brick and minor frictional affects in the vacuum release mechanism. A system capable of maintaining repeatable impact conditions would improve study of PO threats. The improvement of biomechanical and in-field representative constraints could advise test methodology that leads to more effective headgear.

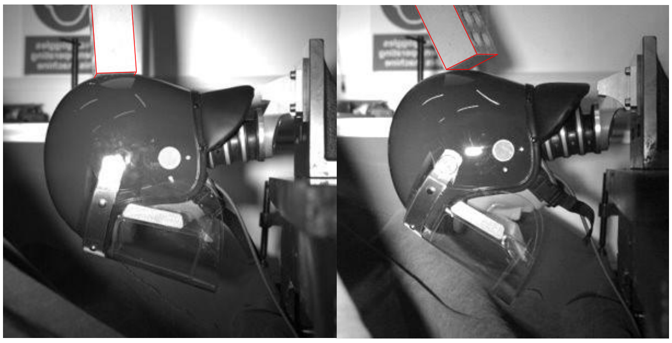

Fig. 2. High-speed frames showing the differing brick (highlighted) orientations at contact for 2m drops to the back of the helmet, believed as the primary cause of variation in initial findings.

1.2 Current Systems for Repeatable Helmet Impact Testing

Table 1. Example helmet test standards with individual maximum impact velocity criteria and required test systems [2-5].

Application	Procedure	Peak Velocity (ms^{-1})	Standard
Public Order (UK)	Drop	6.61	*PSDB 21/04*
Public Order (US)	Drop	6.60	*NIJ0104.02*
Mountain Bicycle	Drop	6.20	*ASTM F1952-15*
Equestrian	Drop	6.00	*ASTM F1163-15*
American Football	Drop & Pneumatic Ram	6.00	*(ND)002-17m21*

Table 2. Comparative review of prevalent systems for repeatable helmet impact testing procedures.

Impact Method	Key Features	Advantages (+)/ Disadvantages (-)
Guided Drop [6]	• Large structural tower. • Steel rail/cable guides. • Drop carriage. • Interchangeable impact anvils.	+ High control of impact energies. + Ease of use. + Low relative cost. + Small footprint area. + Can drop a helmet or an impactor. - Requires a large drop height. - No kinetic energy transfer in collisions.
Pneumatic Ram [7]	• Pressurised accumulator. • Steel impactor rod. • Padded impact surface. • Headform linear slider.	+ Impact velocities up to $15ms^{-1}$. + Changeable impactor surface. + Permits inelastic kinetic energy transfer. - Large footprint area. - Specialist maintenance and servicing. - Large relative cost. - Little control of impact energies.
Pendulum [8]	• Large pendulum arm. • Padded impact surface. • Headform linear slider. • Representative impact hammer	+ Changeable impactor surface. + Low relative cost. + Permits inelastic kinetic energy transfer. - Low range of impact velocities. - Very large footprint area. - Little control of impact energies. - Non-representative impactor mass.

2 Design Methodology

2.1 Design Definition

Initial concepts took inspiration from aforementioned impact systems, whilst considering PO situational representativity and the versatility for further applications of the design. Advantages of guided drop methods provide a greater flexibility in the range of situations that could be recreated, in comparison to a pendulum or pneumatic ram. The maximum achievable drop height (4.3 m), where the test apparatus was to be installed, permitted the recreation of all impact conditions associated with non-vehicular helmet standards procedures. System requirements and desirable capabilities were documented in a product design specification (PDS). A safety factor (SF) of 3 for all load-bearing components was applied.

Table 3. Design decisions for a guided drop helmet impact system.

Design Decision	Rationale
Floor-to-ceiling construction	Achieves maximum possible impact velocities.
Multi-railed drop guidance	Strengthens the system against a wider range of loading conditions.
Lightweight drop assembly	Broadens range of permissible impact energies while reducing system wear.
Option to cradle or affix headforms/helmets	Permits recreation of standard methods from broader helmet applications.
Controlled deceleration of dropper after impact	Reduces system wear and likelihood of failure.
Remote arming procedure with mechanical release	Improves the safety and useability of the system.

The drop carriage assembly had a maximum target design mass of 15 kg (including ATD headform, neck, and carriage bearings). This permits low-end impact energies without reducing velocity below in-field fidelity, while remaining in-line with other drop systems [6]. A linear rail system had been chosen due to the anticipated torsional loading at impact of the carriage, in preference to a steel cable guided drop system. The guide rails were to be mounted upon aluminium profile struts.

2.2 Bearing Selection

Linear bearings were identified that would sufficiently withstand impact loads, with a reduced preload to facilitate a low friction rolling action [9]. Four evenly distributed bearings fixed to an aluminium plate was determined as reasonable for load distribution and to limit torsional movement. Bearing strength requirements depended on both vertical (V) and horizontal (D) separation and was inversely proportional to plate size. Static equilibrium torque calculations were used to advise bearing selection, while optimising their separation for reducing drop mass. The effective reaction force (P_e) on individual bearings was calculated as the sum of its axial (P_a) and radial (P_r) components, for 0.01 m increments of V and D between 0.1 and 0.7 m. Loading conditions were of an assumed ‘worst case’, with a 25.5 kN impact force, derived from a 15 kg drop mass and 5 ms contact time. The lengths of the applied force (L = 0.4 m) , cantilever centre of mass (H = 0.28 m) and deviation from longitudinal section (K = 0.08 m) arms were extremes, advised from the properties of an assumed affixed headform and neck.

$$P_{\mathrm{a}1}:P_{\mathrm{a}4} = \frac{F\cdot L}{2V} - \frac{W\cdot H}{2V} \tag{1}$$

$$P_{r1} = P_{r3} = \frac{F}{4} - \frac{W}{4} - \frac{F\cdot K}{2D} \tag{2}$$

$$P_{r2} = P_{r4} = \frac{F}{4} - \frac{W}{4} + \frac{F\cdot K}{2D} \tag{3}$$

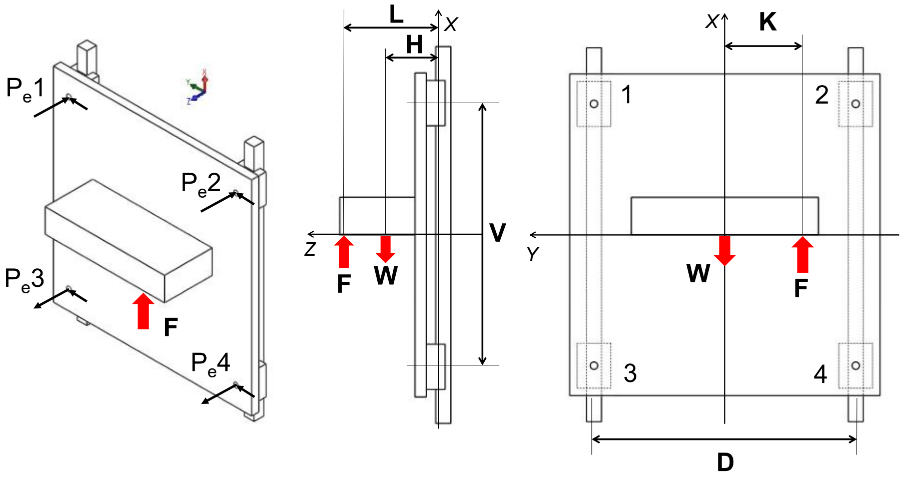

Fig. 3. Considered forces and moments used to calculate bearing reaction forces for iterated vertical (V) and horizontal (D) separations.

D variations effected the load distribution between the left- and right-side bearings, rather than overall load. V had greater influence on bearing strength requirements, with an inverse exponential relationship to P_a. Optimal V was between 0.35 and 0.45 m, where any further increase would add mass for minor strength benefit. The resultant bearing selection was a ‘super heavy load ball square type’ with an individual static load rating of 69 kN, stated frictional coefficient of 0.004 and mass of 0.69 kg [9].

2.3 Drop Plate Refinement

Any bending of the aluminium carriage plate would be exacerbated with increasing velocity. Finite element (FE) analysis was used to validate whether bending would exceed the yield stress of aluminium (280 MPa). This was done using Ansys Explicit Dynamics, with a halved symmetrical geometry to reduce computational effort. 8.5 ms^{-1} impact was simulated with a flat, rigid impact anvil of infinite density, positioned perpendicular to the plate, 2 mm from the ATD forehead. Bearing holes were constrained to permit only vertical motion. Mesh method was hexahedral preferred with 0.2 mm refinement at curvature, minimum 3 divisions along straight edges and 8 divisions along the depth of the plate. A minimum plate cell count of 7560 was optimal for mesh independence. Final mesh had 10,720 cells within the plate, and a total mesh of 85,811 cells (including ATD head and neck model) . Peak deflection was determined within the elastic range at 0.14 mm (44 MPa). The simulation was iterated while removing mass to improve plate strength to weight ratio. The final optimised design was 2.47 kg with external dimensions 0.19 x 0.44 x 0.016 m. Resultant peak deflection was 0.17 mm (91 MPa).

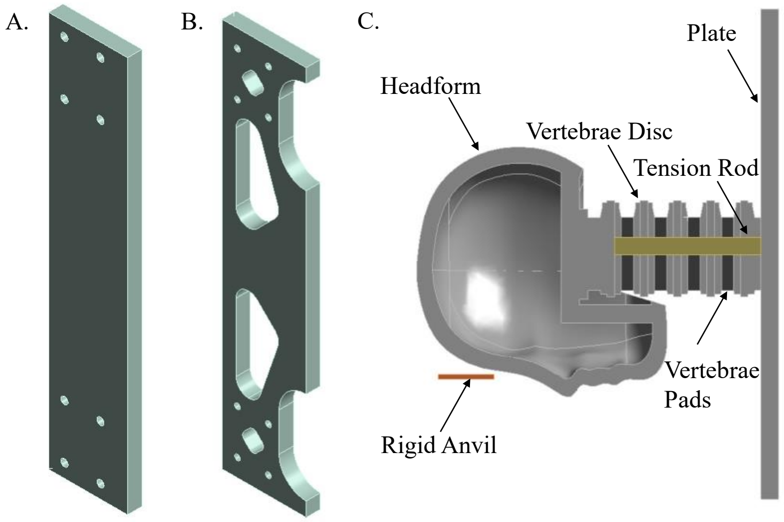

Fig. 4. FE modelled half-geometry for validating drop plate bending strength. Initial plate (A), refined plate (B), symmetry plane view of full simulated geometry (C).

Table 4. Material density and young's moduli allocations for FE simulated components.

Assigned Material	Component	Density (kg·m^{-3})	Young's Modulus (MPa)
Aluminium Alloy	Plate	2770	7.1×10^4
	Headform		
	Vertebrae Discs		
Neoprene Elastomer	Vertebrae Pads	1150	2.75
Steel Rope	Tension Rod	7850	1.9×10^5

3 Final Design

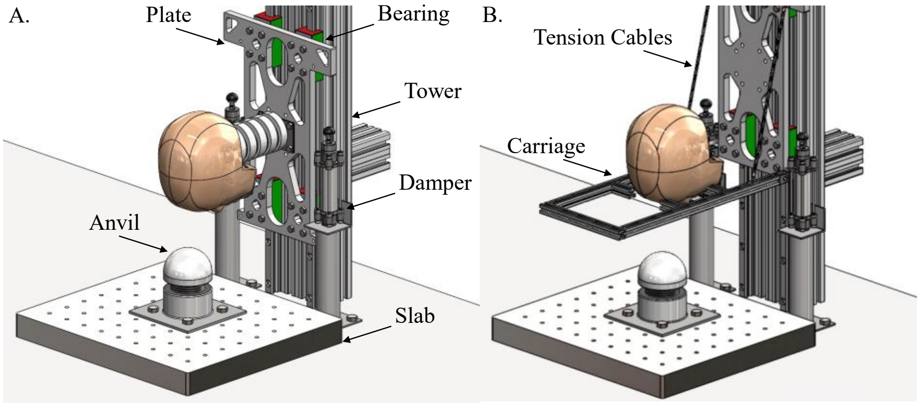

Fig. 5. 3D CAD model of the finalised drop tower system in configurations for affixing headforms with surrogate neck (A) and cradling without further support (B).

A single, floor to ceiling, 0.16 x 0.08 m profile aluminium strut ‘tower’ was sufficient for supporting the drop assembly, with a rail separation of 0.12 m. The configurations of the drop carriage permit the Hybrid III headform as cradled, rigidly mounted or affixed with surrogate neck, with potential for impacting anywhere on the headform/helmet. The final dropper mass is 6.82 kg, 12.6 kg with headform and neck. Impact anvils are interchangeable to represent in-field conditions, with a rigid 0.5 x 0.5 x 0.05 m steel slab base. Slab design includes a 0.05 m spaced grid of M12 tapped holes for compatible fixing. Two 32 mm diameter cylinder, 60 mm stroke length, shock absorbing pneumatic dampers are included to control the deceleration of the drop assembly, following impact [10]. The drop assembly is rearmed using a mechanical winch and release pin that permit operation away from the impact zone and do not risk accidental drop due to electrical failures. The final cost, as of Summer 2022, was £3200. This is similar to that expected for a pendulum system, while considerably cheaper than a pneumatic ram.

4 Discussion

The final design offers a method for producing repeatable impacts with a maximum 3.6 m drop height. This is less than the aforementioned permissible height due to the inclusion of a release mechanism and impact anvil. This, and its versatility with helmet constraining methods, means the system conforms to all non-vehicular standard helmet drop test methods. The inclusion of the ATD headform and neck improve the biomechanical representativity of the system. The system is capable of recreating PO conditions that may lead to the development of more effective headgear.

The necessity of the drop tower to have one of the colliding components fixed prohibits any potential inelastic energy transfer, that may occur in-field. Pendulum and pneumatic ram systems have overcome this by allowing the ATD assembly to travel with the impactor [7:8]. This could be achieved with a drop tower if the ATD assembly was suspended and released at impact, though release would need constraining so that resultant acceleration is due to the collision and not gravitational effects. The available ceiling height prohibits further increase in velocity. Further acceleration of the drop assembly is possible with a spring or pneumatic actuator, though likely to hinder velocity repeatability. Assumptions based on worst-case conditions throughout the design process proved reliable for guaranteeing strength, while allowing for an appropriate SF. Bearing selection could also have been advised from FE simulation, though it was believed unnecessary, as prior torque calculations simulated a worst-case condition.

Further work is required to validate the repeatability of impact velocities. This includes quantifying any frictional elements of the drop assembly, for masses between only the plate and the included headform and neck assembly. If necessary, protocol may then be documented to improve the repeatability and predictability of velocities. Brick impact characteristics will be explored with more repeatable conditions and representative velocities than the previous equipment allowed. The comparisons between brick corner and face impacts for initial trials were seemingly disparate and may now be explored with a method capable of producing significant results.

5 Conclusion

The designed system permits method for producing repeatable PO impact conditions, with a wide range of geometries, velocities and biomechanical constraints. The versatility of the system means it conforms with criteria for all non-vehicular helmet drop test standards. PO threats leading to TBI will be recreated using the repeatable test system, with aim of further comprehending in-field loading conditions and advising the design of more effective headgear.

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