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Development and validation of a physical model to investigate the biomechanics of infant head impact

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ABSTRACT

Head injury in childhood is the single most common cause of death or permanent disability from injury. However, despite its frequency and significance, there is little understanding of the response of a child's head to injurious loading. This is a significant limitation when making early diagnoses, informing clinical and/or forensic management or injury prevention strategies. With respect to impact vulnerability, current understanding is predominantly based on a few post-mortem-human-surrogate (PMHS) experiments. Researchers, out of experimental necessity, typically derive acceleration data, currently an established measure for head impact vulnerability, by calculation. Impact force is divided by the head mass, to produce a "global approximation", a single-generalised head response acceleration value. A need exists for a new experimental methodology, which can provide specific regional or localised response data. A surrogate infant head, was created from high resolution computer tomography scans with properties closely matched to tissue response data and validated against PMHS head impact acceleration data. The skull was 3D-printed from co-polymer materials. The brain, represented as a lumped mass, comprised of an injected gelatin/water mix. High-Speed Digital-Image-Correlation optically measured linear and angular velocities and accelerations, strains and strain rates. The "global approximation" was challenged by comparison with regional and local acceleration data. During impacts, perpendicular (at 90°) to a surface, regional and local accelerations were up to three times greater than the concomitant "global" accelerations. Differential acceleration patterns were very sensitive to impact location. Suture and fontanelle regions demonstrated ten times more strain (103%/s) than bone, resulting in skull deformations similar in magnitude to those observed during child birth, but at much higher rates. Surprisingly, perpendicular impacts produced significantly greater rotational velocities and accelerations, which are closer to current published injury thresholds than expected, seemingly as a result of deformational changes to the complex skull geometry. The methodology has proven a significant new step in characterising and understanding infant head injury mechanics.

1. Introduction

Head injury in childhood is the single most common cause of death and permanent disability from injury. Approximately 35,000 children are admitted to hospital in England each year with head injuries, of which 19% are younger than a year of age [1]. Many more children will attend the ED with a head injury, accounting for 9% of all childhood attendances [2].

Paediatric head injury cause and effect is poorly understood, which is a significant limitation when making early diagnoses and informing clinical and/or forensic management. Of the many infant head trauma (HT) cases, clinicians are faced with the difficult task of trying to determine the cases that are a result of abusive head trauma (AHT). This determines whether they inform law enforcement and child protection agencies and provide evidence to support any subsequent legal process. A significant limitation is the paucity of response and injury threshold data available for this type of determination, predominantly due to the rare access to child PMHSs.

Few PMHS studies exist [3–5] and only Prange et al. [5], produced quantitative data. Thus, the majority of current infant

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head impact understanding is based on the Prange study [5], which investigated three infant postmortem human surrogate (PMHS) heads (1, 3 and 11 days old), impacted from two fall heights (0.15 m and 0.30 m), at five different impact locations (occipital bone, vertex, frontal bone, right and left parietal bones), at an angle perpendicular to a single (steel force plate) surface.

Prange [5], out of experimental necessity, had to derive the current key correlate for head impact injury, acceleration by calculation, by dividing the impact force at the impact surface by the head mass. This limited "global approximation" provides only a single generalised head impact response curve, rather than specific regional or localised responses. Thus, current injury prediction strategies are incapable of considering the significant complexities associated with infant head impacts. Overriding limitations in deriving this information include the rarity of access to child PMHSs and the technical complexities of measuring localised head responses. Faced with these restrictions, clinicians and researchers have often looked to models to help inform their opinions. Physical and computational modelling are an attempt to combine known anthropometry and material properties, with justified approximations for aspects which are not known. With respect to physical modelling, often the limits of suitable materials and manufacturing technologies mean that compromises have to be made. Anthropomorphic test devices (ATDs) are often used to act as surrogates for post mortem human surrogate (PMHS) testing when assessing the possibility of an injury being a result of a given incident. Infant and child head ATDs are, however, based on scaling animal and adult response data and since the paediatric head response is poorly characterised, their specific validity is ambiguous. None of the commercially available ATDs [6,7] represent the separate bone structures or the flexible nature of the infant skull, so there is no appropriate test device that properly represents the infant head impact response.

In addition to the commercially available ATDs, researchers have developed physical models for the investigation of dynamic scenarios [8–11]. Specific to short falls in young children, Prange et al. [10], developed a 1.5-month-old dummy. A limitation of the study, however, was that the head of the dummy was represented by a simplified 2.25 mm thick homogenous plastic shell. No account was given to the anatomical complexity of the infant skull plates, sutures and fontanelles, such that it would likely have produced a stiffer response and concomitantly higher output values than an actual infant head.

However, Prange et al. [10] out of experimental necessity, measured the head impact as if it were a 'rigid body', such that the impact force was measured at the point of impact. The impact acceleration values, a correlate for head injury risk, were calculated from the head impact force, measured at the force plate, by dividing the force by the head mass. Since the impact force is measured at one point on the impact surface, this approach is incapable of providing localised area-specific details with respect to head response.

Coats and Margulies [11] developed a more responsive infant head constructed from copolymer plates, connected by silicon rubber, overlayed by latex to represent the bone, suture and scalp characteristics, respectively. Again localised response measurement was not possible, since the focus was on the global translational and rotational head response, measured by a nine accelerometer array and angular velocity transducer placed at the centre of the surrogate head. Head response values were derived from a rigid body assumption.

In response, this present study investigates the development and validation of a 3D printed multi-material physical model, to study the biomechanics of infant head injury, with the capability to measure localised area specific metrics, allowing potential correlation with head injury. Such a physical model is also highly significant for deriving a "real world" correlation with the PMHS experimental response values for informing the design, validation and future development of computational models for investigating both accidental and non-accidental infant head trauma. The material and methods for the development of the physical model and the drop test methodology are provided in Section 2. The results obtained from the drop tests and the physical model's validation are provided in Section 3, the discussion of the results is in Section 4 and the salient points are specified in the conclusions in Section 5.

2. Materials and methods

2.1. Design and manufacture of the physical head model

2.1.1. Segmentation of the skull model

To take advantage of improved 3D technology, high resolution skull and brain post mortem imaging was performed on a 10-day old infant for whom no cause of death was found. Parental consent was obtained for pre-autopsy imaging as part of an ethically approved study, with institutional research ethics approval. Post mortem computer tomography (PMCT) imaging was performed with a 64-slice multidetector system (Siemens SOMATOM Definition; Siemens Healthcare, Erlangen, Germany). Volumetric brain PMCT imaging was performed at 120 kV with variable mAs, a pitch of 1, and 0.625 mm collimation. Images were reconstructed with bone algorithms to provide 1.25 mm slices. These images provide the highest resolution acquisition currently obtainable using conventional clinical scanners, although the dose may have been higher than currently in clinical use. Post mortem imaging clearly does not encounter the movement artefacts caused by patient movement, cardiac or respiratory variation and can be conducted until the scans are optimised.

The scans were processed using Mimics Software (Materialise; Leuven, Belgium) to separate the individual bones of the infant head. Separation was achieved by careful use of greyscale 'thresholding' and Mimics tools, together with some manual editing in irregular, geometrically-complex areas. Having separated the parietal (left and right) and occipital bones, the base of the skull and frontal bones were treated as a group, referred to as 'frontal bones' hereafter. Having separated the bones, each one was minimally smoothed to improve its definition as a 3D model, and to reduce its complexity to assist with further computational operations. The occipital bone was significantly recessed in the scan, a movement that occurs during head moulding at birth and typically reverses during the first few weeks of life. In an effort to make the skull more 'generic', that is, representing an infant shortly after birth and to create an easily definable position, the occipital bone was moved outwards slightly to line up with the edges of the parietal bones on each side. Many different 3-Matic tools were required to separate the sutures from the bones and other soft tissues, since their pixel greyscale values in the CT scans were so close to that of the surrounding tissues. Fig. 1 shows the final result of the segregation and occipital movement, with a 3D representation of major tissues within the head including cranial bones, skull base, sutures and fontanelles.

2.1.2. Bidirectional properties of infant bone

McPherson and Kriewall [12] determined that infant skull bone is approximately four times stiffer in line with its radial trabeculae, identified as having a fibrous appearance, compared with the perpendicular orientation. To improve the biofidelity of the model bones during impact, an attempt was made to mimic their anisotropic properties. This anisotropic nature could not be directly replicated by the printed materials, however, a solution to this problem was instigated during the development of the 3D