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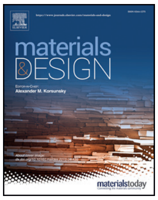

Adaptive head impact protection via a rate-activated helmet suspension

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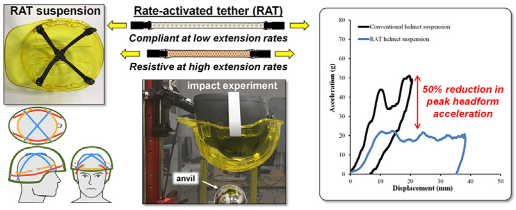
HIGHLIGHTS

- A helmet suspension containing shear thickening fluid is designed and tested under conditions representative of head impacts.
- The helmet suspension exhibits rate-sensitive behavior, increasing in resistance to extension as impact velocity increases.
- Impact accelerations for the rate-sensitive suspension are ~50% lower than observed for a conventional suspension.
- Model calculations reveal ideal suspension characteristics: a rate-sensitive force that is steady over large displacements.

GRAPHICAL ABSTRACT



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ABSTRACT

The design of an adaptive helmet suspension system that provides optimized head protection under variable impact conditions is reported. The adaptive response is achieved through the use of rate activated tethers (RATs), a flexible strap-like material that uses shear thickening fluids to generate speed-sensitive extensional resistance. The RATs are integrated into a helmet by replacing the webbing system of a traditional construction hardhat with a network of RATs, and performing impact attenuation testing over a range of velocities. Impacts to the crown region of the helmet demonstrate a 50% reduction in peak acceleration experienced by the headform for impact velocities between 1.5 and 3.5 m/s compared to the conventional webbing system, and comparable response to the conventional system at 4.5 m/s. Complementary RAT extensional testing and low velocity helmet compression tests confirm that the rate-sensitive response of the RATs contributes significantly to improved system performance. Additionally, calculations for suspension model systems show that the steady yield force exhibited by RATs over long strokes is a critical feature for minimizing head acceleration, and that the RAT suspension systems are achieving responses remarkably close to the ideal suspension response.

1. Introduction

Head protection is a vital requirement for military, sports, and industrial safety. Most helmets are primarily designed to avert fatality by preventing severe injuries such as intracranial bleeding and skull fracture [1,2]. Helmet test standards, such as NOCSAE performance standards [3], FMVSS 2218 [4], ASTM F1446-13 [5], and ANSI/ISEA Z89.1-2014 [6], were created to determine a helmet's ability to attenuate impact forces, where the acceptance criteria were derived from the observation of cranial fracture in cadaveric studies [2]. Generally, these standards require mounting the helmet to an instrumented headform,

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subjecting the head and helmet to an impact, measuring translational head response, and then comparing head response to injury limits. Most helmet test standards report translational acceleration metrics, both peak value and time-integrated, which correlate well with likelihood of skull fracture [1,7]. Due to the emphasis on averting fatal injuries, these tests evaluate helmets under relatively high impact energies where skull fracture is likely to occur for an unprotected head and seldom provide additional requirements for reducing head loads at lower impact energies. As a result, many helmets are designed with relatively stiff webbed or foam suspension systems that are optimized for high energy impact, but provide little compliance during lower energy events.

More recently, the medical community has recognized that concussion and repetitive brain trauma are also a serious health concern [8–10], leading to interest in designing helmets that also reduce the likelihood and severity of brain injuries [11]. Translational acceleration has been shown to correlate with concussion [12–15], although newer hypotheses propose that rotational loads more directly generate brain tissue strains that are believed to induce axonal damage associated with long term diffuse brain injury [16–19]. In the present study we focus on translational dynamics, consistent with most existing head protection performance requirements. Studies have also suggested that multiple impacts, even if each impact is at low energy, can cause cumulative effects that lead to serious injury [20–24]. Therefore, an emerging goal for head protection is to minimize head loads at all velocities, rather than designing helmets to meet only maximum thresholds at high energies.

To minimize translational head accelerations at all impact velocities, an energy absorber with uniquely tuned properties is required. First, the energy absorber must yield at a near constant force over the full stroke of the energy absorber [25–28]. A constant resistance force induces constant head deceleration, which minimizes peak and time-averaged acceleration metrics when the translational body is brought to rest at the point of maximum stroke. The stroke of the energy absorber is typically limited by a fundamental geometric constraint such as the shell-to-skull gap in a helmet, and there is no penalty associated with using that full stroke during the impact event. Second, the energy absorber should generate a resistance force that is proportional to impact energy, thereby minimizing acceleration by using the full stroke of the energy absorber under all impact conditions. This requirement is met by designing an energy absorber that is compliant under lower velocity impacts, but becomes increasingly resistive to displacement as impact velocity increases. This combination of properties – a velocity-sensitive yield force, which, upon yielding, displaces at a constant force – is rarely found in energy absorbers, including those used in current helmet technologies.

The three main components of a helmet are the shell, the suspension system, and the retention system. The suspension system maintains a standoff distance between the shell and the skull, and provides the primary means of absorbing energy during impact. The two most common suspension designs are a webbed suspension or compression pads. The main advantage of a webbed design is improved thermal comfort, made possible by the large air gap between the suspension and the helmet shell. Compression pads have proven to be more efficient for energy absorption and can provide a better helmet fit [29]. For these reasons, padded suspensions are currently used in most military and sports helmets. Compression pads include open cell and closed cell foams [30–32], pneumatic pads [33,34], and elastomeric trusses [35–38]. Closed cell polystyrene foams are commonly used in bicycle and motorcycle helmets, but are only designed to withstand a single impact event and are then discarded. For most sports and military applications, suspension energy absorbers (both webbed and pad systems) must retain their protective attributes over multiple impacts. Other suspension approaches include slip layers to reduce rotational loads, and hybrid systems that combine both webbing and compression pads into a single system.

In the present study, we evaluate a new helmet webbing suspension design, in which the web elements consist of "rate activated tethers" (RATs) [39,40]. RATs are flexible straps that exhibit a low force, elastic response at low velocities, but exhibit increasing resistance to extension as extension rates increase. RATs consist of an outer elastic tube, with two enclosed ribbons, immersed in a shear thickening fluid (STF) (Fig. 1). The STF imbues speed sensitivity to the device, and consists of colloidal particles stabilized at high volume fraction in a carrier fluid. At low shear rates, the STF exhibits a flowable low viscosity state, but at high shear rates the STF becomes solid-like [41–43]. These unique properties have been exploited for a range of energy absorbing applications, including protective textiles [44–48], shock absorbers [49,50], and foam pads [51–53]. For the RATs, the detailed mechanism of interaction between the STF and ribbons is uncertain, but it is likely that the transitioned STF transfers load between ribbons through a combination of viscous forces and particle-particle force chains [54–56]. Increasing RAT extension rates lead to high shear rates between the ribbons, resulting in the aforementioned STF transition which drives an increased resistance to RAT extension. For typical RATs, a 10–100× increase in extension forces are possible with an increase in extension rate of 10–100×. Factors such as RAT diameter, length, ribbon material, and STF composition can be selected to tune mechanical response to suit specific application needs.

The objective of this study is to compare the impact response of a helmet with a RAT-based suspension system to a conventional web-based suspension. First, details on the construction of the RATs, and their assembly into a helmet suspension, are provided. Then, mechanical and impact testing of RATs and RAT-based helmet suspensions are conducted and compared with a conventional helmet suspension system. A construction hard hat is used as a simple and low cost test platform, and testing follows the ANSI/ISEA Z89.1-2014 test standard. Impact results are then compared with analytical impact models to identify key features of system response, and quantify the behavior of the helmet suspensions relative to ideal performance.

2. Experimental methods

2.1. Materials

The RAT assemblies utilized two commercially available STFs, STF-PO-52 and STF-PO-50 (STF Technologies, New Castle, DE). These fluids consist of precipitated calcium carbonate (PCC) particles with a mean size of 600 nm, suspended at 52 vol% and 50 vol%, in a paraffinic oil carrier fluid. Fig. 2 shows viscosity (resistance to flow) as a function of shear rate and shear stress, measured by an AR2000 (TA Instruments, New Castle, DE) stress-controlled rheometer with 40 mm diameter parallel plates and a 1 mm gap. Both fluids exhibit steady shear thinning, a reduction in viscosity as shear stress increases, at low shear rates. For both fluids, the viscosity reaches a minimum value at a "critical shear rate", γ_c, as marked on Fig. 2a. The 0.52 volume fraction STF shows a sharp rise in viscosity, or shear thickening, at higher shear rates. Additionally, a similar viscosity rise would be expected at higher shear rates for the 0.50 volume fraction STF, but the rheometer is unable to operate at shear rates higher than 100 s^{-1}. The critical shear rate for each fluid occurs at a common critical shear stress value, τ_c, of 100 Pa as indicated in Fig. 2b. Two ascending and two descending shear rate sweeps were performed for each STF to confirm repeatability of the STF formulations. Critical shear stress values over these four sweeps exhibited a coefficient of variation of 10% for the 0.50 volume fraction STF, and 11% for the 0.52 volume fraction STF.

RATs were constructed using elastomeric tubing, a polymer spacer, steel ribbons, heat shrink tubing, and epoxy (Fig. 3a). Viton tubes (10 mm inner diameter and 12 mm outer diameter, cut to 127-mm lengths; McMaster Carr, Robbinsville, NJ, product number 5102K15) were pre-conditioned in an oven at 100 °C for 24 h to remove any moisture, and placed in a bag with desiccant for storage prior to RAT