

Accelerations relevant to blunt trauma: theory and data

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Abstract: Maximum acceleration and the Head Injury Criterion (HIC) are both used as indicators of likely head injury severity. A dataset has previously been published of impacts of an instrumented missile on four ground surfaces having a layer of between 0 and 16 cm of sand. The dataset is compared with recently-developed theory that predicts power-function dependence of maximum acceleration and HIC on drop height. That prediction was supported by the data. The surfaces differed in respect of the exponents estimated.

Key words: Fall accident, Playground equipment, Head injury, HIC, Maximum acceleration

Kato *et al.*¹⁾ conducted tests in which an instrumented missile was dropped on to playground surfaces and recorded the accelerations over the milliseconds of the impact. Maximum acceleration (G-max) and the Head Injury Criterion (HIC) were determined. Kato *et al.* did not use any theory to help interpret their results. The present paper will do so, attempting to fit functions to G-max and HIC in terms of drop height *h*. Kato *et al.* showed lines of proportionality for all of their datasets. In the present interpretation, that is a good approximation only for some of the data.

Impacts on to bare ground and on to 16 cm of sand are considered first. These are the extremes of the ground conditions considered by Kato *et al.* Impacts on to 6 cm or 10 cm of sand may be regarded as intermediate between the extremes. The following description refers to results using the ASTM F1292 procedure.

- Bare ground. For G-max, the line of proportionality appears satisfactory. For HIC, a line fitted to the data points would have negative HIC at $h=0$ (if it were a straight line), or would be concave upwards (if it were a

curve going through the origin).

- 16 cm sand. For HIC, the line of proportionality appears satisfactory. For G-max, a line fitted to the data points would have positive G-max at $h = 0$ (if it were a straight line), or would be concave downwards (if it were a curve going through the origin).

This theory²⁾ connects a hypothesised law describing how force changes from moment to moment with the consequences in regards to how G-max and HIC depend on impact speed.

Suppose the following differential equation relates acceleration (and force) to instantaneous deformation (distance) and instantaneous velocity:

$$m \cdot x'' - k \cdot x^n \cdot [1 + (b/v) \cdot x'] = 0 \quad (1)$$

Here x is instantaneous deformation of the surface, with differentials x' (instantaneous speed) and x'' (instantaneous acceleration), v is impact speed, m is headform mass (and $m \cdot x''$ is force), and k , b , and n are constants. Then G-max is proportional to $v^{2 \cdot n / (n+1)}$ and HIC is proportional to $v^{(4 \cdot n + 1) / (n+1)}$.

The undamped linear spring is represented by setting $n=1$ and $b=0$. Equation (1) is two steps of generality beyond this: dependence on x may be nonlinear (i.e., n need not be 1), and there is a form of damping (i.e., there is a

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term in x^2).

As v^2 is proportional to drop height h , G-max is proportional to $h^{n/(n+1)}$ and HIC is proportional to $h^{(4.n+1)/(2.n+2)}$. With $\ln(\cdot)$ referring to natural logarithm, plotting $\ln(A)$ and $\ln(HIC)$ versus $\ln(h)$ will linearise the relationships: the slopes are predicted to be $n/(n+1)$ and $(4.n+1)/(2.n+2)$.

Kato *et al.* were interested in simplifying the ASTM F1292 procedure. They compared results using that method with results from a shortened procedure. In the course of that, they reported how G-max and HIC vary with drop height h . That was for four ground surfaces: bare ground, and loose fill surfaces having 6 cm, 10 cm, and 16 cm of sand. The data for the ASTM procedure will be used below.

Impacts on to bare ground and on to 16 cm of sand will be considered initially. In view of the descriptive summary given earlier, the features of the quantitative summary below are not surprising.

- Bare ground. (a) The dependence of $\ln(G\text{-max})$ on $\ln(h)$ is approximately a straight line, and the slope is estimated to be 0.78. As this is $n/(n+1)$, n is found to be about 3.5. (b) The dependence of $\ln(HIC)$ on $\ln(h)$ is approximately a straight line, and the slope is estimated to be 1.63. As this is $(4.n+1)/(2.n+2)$, n is found to be about 3.0.

- 16 cm sand. (a) The dependence of $\ln(G\text{-max})$ on $\ln(h)$ is approximately a straight line, and the slope is estimated to be 0.39. This implies n is about 0.6. (b) The dependence of $\ln(HIC)$ on $\ln(h)$ is approximately a straight line, and the slope is estimated to be 1.01. This implies n is about 0.5.

There are only five or six data points for each surface. Consequently, the slopes are estimated only imprecisely (that is, the standard errors are quite large). Despite this, the evidence of a difference between the n 's for bare ground and 16 cm of sand is reasonably strong. The estimates were quite different: 3.5 and 0.6 (if based on G-max), or 3.0 and 0.5 (if based on HIC). Furthermore, for bare ground n is unlikely to be less than 1.2, whereas for 16 cm of sand n is unlikely to be greater than 1.1. (More fully, for bare ground, if $n=1.2$, the exponents for both G-max and HIC would be at least two standard errors below their estimates, and for 16 cm of sand, if $n=1.1$, the

exponents for both G-max and HIC would be at least two standard errors above their estimates.)

As to the results for 6 cm of sand and for 10 cm of sand, these are consistent with the respective values of n being intermediate between the n 's for bare ground and for 16 cm of sand. But, as already noted, the standard errors are large.

Kato *et al.* did not present any theory, but did show lines of proportionality for both G-max and HIC in all of their datasets. In place of that, the present interpretation is as follows. (a) G-max and HIC each depend on drop height h via power functions. The exponents of the power functions are different for G-max and HIC. But they are not independent, as each is a function of the exponent n in the differential equation given earlier. (b) The exponents are different for different surfaces. (There is not any theory available for how n might depend on sand depth.) (c) The empirical results of Kato *et al.* have been interpreted here as suggesting a large n (appreciably greater than 1) for bare ground (zero sand depth) and a small n (appreciably less than 1) for 16 cm of sand.

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