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Head Injury Criterion

Assessing the Danger of Robot Impact

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Applications of robots are broadening from the traditional industrial setting, where safety fences and other measures exclude people from the robots' workspace, to new settings where people interact with robots and are often within reach of a powered device. Efforts to maintain safety in such settings include designing lightweight robots and implementing control systems that reduce robots speed in the presence of humans. The excellent track record for safety in industrial robotics over the past three decades has been maintained by almost always operating them in a controlled environment, obeying a set of safety standards that enforce the exclusion of workspaces between robots and people. It is important to maintain this level of safety as new technologies and applications come into use, including robots that have direct interaction with people. Standards for the operation of these next-generation robots such as International Standards Organization (ISO) 10218 [21] are under review.

In the design of robotic systems that safely interact with people, it is useful to have validated criteria for measuring injury risks. To this end, some researchers have advocated the use of metrics developed for assessing automotive safety, with the head injury criterion (HIC) receiving particular attention. The aims of this commentary are to clarify the proper use of the HIC, to briefly discuss its relationship to the risk of injury, and to give a closed-form formula for the HIC value produced by a simple mass–spring model of impact. We emphasize that there are many other factors besides HIC to consider before a robot system can be considered safe to interact with humans.

The HIC has been discussed in the context of robot safety in [1]–[11]. In [3], a formula for approximating the HIC from a mass–spring–mass model was put forward as part of a design method intended to reduce the risk of injury through the use of variable stiffness actuators, see also [4], [10]. Similarly, the HIC was used to motivate actuation approaches [1], [2], [6] that reduce the dynamic forces generated during impact by introducing compliance between actuators and robot links using either a dual-actuator strategy or series-elastic actuation. Among these, Edsinger [6] directly uses Bicchi's formula [3], while [1] and [2] use an unspecified mass–spring model. In comparison to these, the finite element models of [5] and the experimental evidence procured with crash test dummies in [7] both indicated much lower HIC values under similar

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conditions. The most recent reports [8]–[10] also support low values of HIC. This situation implies that other criteria for assessing injury risks, such as those discussed in [7], [11], [13], and [14], may be more relevant for robot design.

The disparity between early estimates of HIC based on the mass–spring–mass model and the later works has never been adequately discussed in the literature. In the following, we present an exact formula for the HIC predicted by a mass–spring–mass model that resolves the discrepancy in favor of lower estimates of HIC.

Definition of HIC

The HIC is defined as [16]–[18]

$$\mathrm{HIC}(\Delta t_{\max}) = \max_{t_1, t_2}\left[\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \hat{a}\, dt\right)^{2.5}(t_2 - t_1)\right],$$
$$\text{subject to } t_2 - t_1 \le \Delta t_{\max}, \tag{1}$$

where $\hat{a}$ is the head acceleration measured in g's (acceleration of gravity, $g \approx 9.8\,\mathrm{m/s^2}$) and time is measured in seconds. (In [3], it is stated that in the definition of Gadd severity index (GSI), a predecessor to HIC, head acceleration is measured in grams. Apparently, this error was introduced in the publication process in a misunderstanding of the statement given in the manuscript that said acceleration should be measured in g's.) The result is called HIC_{15}, if $\Delta t_{\max} = 15$ ms, and HIC_{36}, if $\Delta t_{\max} = 36$ ms. It is important to note that measured in g's means that $\hat{a} = a/g$, where a is the head acceleration and g is the acceleration of gravity in any compatible units. We will refer to $\hat{a}$ as the normalized head acceleration. Since the normalized head acceleration is unitless, it is clear that HIC has the units of seconds.

HIC and Injury Risk

An injury index, also known as an injury assessment value, is calculated from measurements such as forces or accelerations taken on human subjects or crash test dummies. Experiments must be performed to validate and calibrate the relationship between an injury index and the risk of an injury of a specified severity under certain test conditions. The severity of an injury can be rated on the abbreviated injury scale (AIS), which ranges from AIS 0, meaning no injury, to AIS 6, meaning virtually unsurvivable injury.

The HIC has been validated as a predictor for skull fracture and brain injury of certain severities. The validation was conducted in a testing context using blunt force trauma to an unconstrained head. Further discussion of HIC can be found in [16]–[18].

The following facts from the biomechanical literature on HIC are relevant to its use in the robotics context.

- References to both HIC_{15} and HIC_{36} appear in the literature. However, research indicates that only HIC intervals of 15 ms or less are relevant to cerebral concussion [19].
- HIC is an injury index that correlates to the risk of AIS ≥ 2 skull fracture and AIS ≥ 4 brain injury [15]. The conversion from HIC to a risk estimate can be done by reference to the Prasad/Mertz curves in [15] that are based on experiments that recorded the presence or absence of skull fracture and brain hemorrhage. It is unclear what data have been used to justify the expanded Prasad/Mertz curves, published in [20] and used in [7], so the conversion of HIC to a risk of minor injury (AIS = 1) or virtually unsurvivable injury (AIS = 6) may lack experimental verification.
- Because of the uncertainties involved, it is standard practice in automotive safety assessment to round HIC to the nearest integer.

HIC for a Mass–Spring–Mass Model

Suppose, as in [3], that a robot of total effective inertia m_1 moving at velocity v_1 impacts an unconstrained head of mass m_2 at rest. Further, suppose that the stiffness of the contact interface is k, so that if the positions of the robot and the head are x_1 and x_2, respectively, then the contact force is $k(x_1 - x_2)$ so long as $x_1 > x_2$. (Assume both positions are measured relative to their locations at the moment of first impact.) Since the head is unconstrained, it eventually loses contact with the robot (i.e., $x_2 > x_1$) and moves away at constant velocity. From these assumptions, one has that during impact the normalized head acceleration is

$$\hat{a} = A \sin \omega t, \qquad 0 \le t \le \pi/\omega, \tag{2}$$

where

$$\omega = \left[\frac{(m_1 + m_2)k}{m_1 m_2}\right]^{1/2} \quad \text{and} \quad A = \frac{m_1 v_1 \omega}{(m_1 + m_2)g}. \tag{3}$$

Given (2), one may calculate an exact formula for the HIC of the mass–spring–mass system. To do so, one must evaluate the integral in (1) and perform the indicated maximization. Because of the symmetry of $\sin x$ about $x = \pi/2$, it is clear that the t_1 and t_2 that maximize HIC are symmetric about $\pi/(2\omega)$. To find the maximum, it is convenient to introduce a variable α and write $t_2 = (\pi/2 + \alpha)/\omega$ and $t_1 = (\pi/2 - \alpha)/\omega$. With this change of variables, it is a straightforward exercise in calculus to find that the exact value of HIC for the mass–spring–mass system is

$$\mathrm{HIC}(\Delta t_{\max}) = 2A^{5/2}\omega^{-1}\alpha^{-3/2}(\sin\alpha)^{5/2}, \tag{4}$$

where

$$\alpha = \min(\alpha^*, \omega\Delta t_{\max}/2), \tag{5}$$

and α^* is the solution in $[0, \pi/2]$ of

$$3\sin\alpha - 5\alpha\cos\alpha = 0. \tag{6}$$

Since (6) does not depend on the parameters of the model, one may solve it numerically once and for all to get the approximate value $\alpha^* = 1.0528$.

Equation (5) indicates that a switch from the unconstrained maximizer of the HIC formula to the time-limited HIC occurs when $\alpha^* = \omega\Delta t_{\max}/2$. Let $T = \pi/\omega$ denote the full-impact interval. Using the numerical value of α^* and recommended HIC interval of 15 ms, one has that the switch occurs at $T = 22.38$ ms. For short impact times, $\alpha = \alpha^*$ applies; that is, a fixed central proportion of the impact interval is used in calculating HIC. For

long-impact times (characterized by a low-frequency ω), only the central $\Delta t_{\max}$ portion of the impact interval is used.

For short-impact times, $T \leq 22.38$ ms, HIC_{15} can be rewritten as

$$\begin{aligned}\mathrm{HIC}_{15} &= 1.303 A^{5/2}/\omega \\ &= 1.303\left(\frac{k}{m_2}\right)^{3/4}\left(\frac{m_1}{m_1+m_2}\right)^{7/4}\left(\frac{v_1}{g}\right)^{5/2}. \end{aligned} \quad (7)$$

This may be specialized to SI units with the substitution $g = 9.8$ m/s to get

$$\mathrm{HIC}_{15} = 0.00433\left(\frac{k}{m_2}\right)^{3/4}\left(\frac{m_1}{m_1+m_2}\right)^{7/4} v_1^{5/2}. \quad (8)$$

For long-impact times, α depends on the model parameters, and the appearance of $\sin\alpha$ in (4) prevents easy simplification of the expression. For very long-impact times, however, α becomes small, and one may use the approximation $\sin\alpha \approx \alpha$ to get

$$\mathrm{HIC}(\Delta t_{\max}) \approx A^{5/2}\Delta t_{\max}, \quad \text{for} \quad T \gg 1.5\Delta t_{\max}.$$

This can then be written out in terms of the model parameters in a similar fashion to (7) and (8), but since short-impact times are more characteristic in robotics, we do not write these expressions here.

Comparison to the Existing Formula

In [3], the authors considered the same mass–spring–mass system as earlier and published the following formula for HIC, which we will denote as $\mathrm{HIC}_{\mathrm{pub}}$.

$$\begin{aligned}\mathrm{HIC}_{\mathrm{pub}} &= 2\left(\frac{2}{\pi}\right)^{3/2}\left(\frac{k}{m_2}\right)^{3/4}\left(\frac{m_1}{m_1+m_2}\right)^{7/4} v_1^{5/2} \\ &\approx 1.016\left(\frac{k}{m_2}\right)^{3/4}\left(\frac{m_1}{m_1+m_2}\right)^{7/4} v_1^{5/2}. \end{aligned} \quad (9)$$

It can be seen that, with the following two changes, (4) becomes (9):

- the use of the full impact interval, i.e., $\alpha = \pi/2$, instead of (5), and
- the omission of g, i.e., the acceleration is not normalized.

The $\mathrm{HIC}_{\mathrm{pub}}$ does not involve a time limit, $\Delta t_{\max}$, so it is applicable only to short-impact times. For short-impact times, using $\alpha = \pi/2 \approx 1.5708$ instead of the maximizer $\alpha = \alpha^* = 1.0528$ reduces the HIC value by 22%. On the other hand, the omission of g increases HIC by a factor of

$$(9.8\,\mathrm{m/s^2})^{2.5} \approx 300\,\mathrm{m}^{5/2}\mathrm{s}^{-5}.$$

Thus, in SI units, the units of $\mathrm{HIC}_{\mathrm{pub}}$ are changed to $\mathrm{m}^{5/2}\mathrm{s}^{-4}$, and the numerical value increases compared with the normalized HIC.

If $\mathrm{HIC}_{\mathrm{pub}}$ is used only for short-impact times and only as a relative measure, for example, to compare to actuator designs as in [4], the change in multiplicative factors relative to the normalized HIC is inconsequential. However, $\mathrm{HIC}_{\mathrm{pub}}$ is incompatible with the Prasad/Mertz curves [15] or any of the published safety assessments based on the normalized HIC. This incompatibility caused an overestimation of danger in those publications that used $\mathrm{HIC}_{\mathrm{pub}}$ without normalization to estimate risk of injuries.

Example: PUMA 560

Edsinger [6] used the following values to estimate HIC for a programmable universal machine for assembly (PUMA) 560 robot: $m_1 = 25$ kg, $m_2 = 4$ kg, $k = 25{,}000$ N/m, and $v_1 = 1$ m/s. The impact time evaluates to $T = 36.9 > 22.4$ ms, so the time constraint for HIC_{15} is active. The foregoing formulas give $\mathrm{HIC}_{15} = 2$ s and $\mathrm{HIC}_{\mathrm{pub}} = 551\,\mathrm{m}^{5/2}\mathrm{s}^{-4}$, the latter numerical value comparable to the values published in [1], [2], [6]. The value $\mathrm{HIC}_{15} = 2$ s is too small to accurately assess a risk of injury on the Prasad/Mertz curves.

Conclusions

In [15], it is estimated that an unconstrained blunt impact to the head with $\mathrm{HIC}_{15} = 50$ s presents a 0.15% risk of AIS ≥ 2 skull fracture and a 0.06% chance of AIS ≥ 4 brain injury. Finite element computations from [5], experimental evidence from [7], and our calculations based on a mass–spring–mass model all agree that the HIC values generated by blunt impact with robots moving at less than 2 m/s are substantially lower than 50 s. Previously published estimates of HIC that indicated a more substantial danger of blunt impact head injury were calculated without properly normalizing head acceleration by the acceleration of gravity.

The reason that HIC is much more important in the context of automotive safety than in robotics is mainly attributable to the higher velocities involved. For example, in their New Car Assessment Program (NCAP), the National Highway Traffic Safety Administration's (NHTSA), a branch of the United States Department of Transportation, conducts tests of frontal crash into a rigid barrier at 56 km/h. Given all other factors equal, an increase in speed from 1 m/s (3.6 km/h) to 50 km/h implies an increase in HIC by a factor of $(50/3.6)^{2.5} = 720$. Of course, to counteract this effect in automotive crashes, occupant restraints (e.g., seat belts and airbags), vehicle padding, and structural crush characteristics are all designed to manage impact energy and better couple the occupant to the vehicle deceleration pulse, thereby lengthening the time the head decelerates and reducing the magnitude of the deceleration.

One should not conclude that low HIC values indicate that a robot is safe. HIC is only relevant to impact to the head with large enough contact area so as not to penetrate or puncture through the skull. The HIC is not applicable to crush situations where the human is trapped between the robot and a wall or other rigid constraint. (See [13] for work on constrained impact.) Moreover, HIC is only relevant to head injuries. In [7], experimental tests were conducted to also rate the danger of neck and chest injuries, again under conditions of blunt impact. Different metrics are needed to assess the risk of other mechanisms of injuries such as crushing, pinch points, and contact with sharp objects [11], [12], [14]. In addition to head injuries, minor soft tissue injuries resulting in contusions, cuts, punctures, sprains, and the like are of concern. The HIC has not been validated as a predictor for any of these. In both industrial and home settings, if humans are within the workspace

of active robots, it is paramount that the people are not only safe from injury but that they can feel comfortable. This might entail a higher standard beyond one of low risk of injury to one of low risk of pain or even some standard of psychological comfort. The development of such standards and the associated assessment metrics is an area open for research.

Finally, it is important to note that the overall risk of injury over time is influenced by whatever measures are in place to minimize the frequency of collisions. In conventional industrial robot applications, barriers and sensor systems at human entry points provide this function. As these barriers are eliminated to allow human–robot interaction, new types of sensors and the robot intelligence to interpret the sensor data can play a strong role in safety.

No matter what the design of the robot itself, there may be danger inherent in the tasks it is asked to perform. A robot that is lightweight with padded surfaces free from protrusions or sharp edges may nonetheless become dangerous as soon as it picks up a sharp object. For example, pencils in the office or knives in the kitchen present challenges for the safe deployment of a personal-assist service robot. One strategy might be to cover all sharp edges during transport, but this seems difficult to accomplish in an unstructured environment. Just as parents teach their children how to safely handle such objects, especially near other people, roboticists will need to equip their creations with the necessary intelligence to avoid dangerous maneuvers or else the robots' operating environments must be restricted.

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Keywords

Head injury criterion, HIC, robot impact, robot safety.

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