FORCES RESULTING FROM BAT IMPACT ON THE CHEST OF ADULT HUMAN HYBRID DO NOT DEPEND ON THE TORSO INERTIA

Ismail El Maach, Cathie Kessler, François-Xavier Jetté and Jean-Philippe Dionne
Med-Eng Systems, Ottawa, Ontario, Canada

The effect of inertia was investigated by impacting a Hybrid II mannequin in constrained and unconstrained configurations with a baseball bat swung at an angular velocity representative of a typical blow. The forces induced by the blow from a bat to the chest of the mannequin were found to be equivalent for both configurations. An analytical model of blunt impact used to validate the findings and provide insight into the physical phenomenon, suggests that the effect of inertia only becomes prevalent when the mass of the impactor is substantial as compared to that of the mannequin.

KEY WORDS: blunt impact, chest inertia, antrhopomorphic hybrid chest.

INTRODUCTION: To test chest protectors against baseball impacts, Viano et al. (1978) employed a customized biomechanical surrogate attached to a free-moving sled. In experiments aimed at evaluating chest protectors intended for crowd management operations, El Maach et al. (2003) used an isolated, constrained anthropomorphic Hybrid chest. Constraining the test device allowed simplifying of the experimental setup and ensured the repeatability of the experiment. However, there are concerns regarding the biofidelity of the test device and the validity of the results obtained with such a constrained torso.
The cause for such concerns is that the resistance of the thorax and abdomen during an impact is primarily developed by their inertial and viscous elements (Cavanaugh et al., 1993). Lobdell (1973) developed a complete analytical model of the torso. Viano (1978) identified the voigt material as the most influential element of this model. In Lobdell's model, inertial elements are represented by a mass, which is connected to the spine, while the viscous elements are represented by a dashpot and a spring that link the spine to the sternum. The inertial elements of the body will provide greater resistance the greater the impact velocity and this will be reflected by a greater rate of change of velocity at the spine, referred to as the Average Spine Acceleration (ASA). The ASA can be directly related to injury (e.g. the greater ASA, the greater the potential of injury). According to this model, the velocity at which the chest is impacted has to reach a certain level before the effect of inertia becomes significant. This impact velocity threshold level may be attributed to the viscous component of the chest, which is dependent of the rate of loading. Low velocity impacts will cause the chest to resist with low stiffness, lowering the rate of energy or momentum transfer to the spine. As the impact velocity increases, increasing the stiffness of the chest, the amount of momentum transferred to the spine increases and the chest inertia becomes an important factor in providing resistance to movement (or acceleration), which results in greater chest compression and, possibly, greater acceleration. Inertia is thus known to have an effect on the compression and/or motion of the chest when impacted. In this study, it was of interest to determine whether chest inertia also had an effect on the peak force transmitted to the sternum by a high-speed impact such as a blow from a bat.

METHODS: A cylindrical aluminum bat (mass 2 kg) consisting of a full cylindrical handle (L: 46.5 cm, Dia: 2.54 cm) and a hollow cylindrical barrel (thickness:0.5 cm, L: 35 cm, DIA: 6 cm) was swung using a blunt impact simulator (Dionne et al., 2002). An accelerometer (PCB Piezotronic 350A03) was installed on the bat, 54 cm away from the rotation axis on the opposite side from the percussion area of the bat. Data was acquired a rate of 10 kHz and filtered using a 4-pole Butterworth filter.
A Hybrid II (HII) mannequin representing the 50th percentile North-American male was suspended from a crane by a yoke between the shoulder blades connected to a quick-release mechanism, consisting of several relays and a solenoid-operated pneumatic cylinder (Figure 1) (Kessler et al., 2003). The impacts were carried out in two setup configurations:

Configuration 1 - Constrained: (Figure-2a). The mannequin remains suspended with its back constrained against a flat steel panel throughout the impact.

Configuration 2 - Unconstrained: (Figure-2b). The mannequin is initially suspended to the crane without the steel panel constraining its back. The mannequin is released from the crane shortly before impact.

The HII chest was positioned in such way to ensure that the percussion point of the bat, coincided with the center of the sternum at the moment of impact. The bat swing occurred horizontally, spanning an angle of 150 before striking the chest of HII. Eleven impacts per configuration were delivered at 28.8 rad/s, corresponding to a tangential impact velocity of 16.8 m/s. An optical sensor detected the bat approaching the chest, triggering the data acquisition and, in the case of the unconstrained mannequin, the release mechanism. The transmitted force was calculated using Newton's second law of inertia (F=meff..a), where the acceleration is given by the accelerometer placed on the bat and meff corresponds to the effective mass as obtained by Kessler et al. (2003).

Figure 1: Aluminum bat hits the mannequin on the chest.

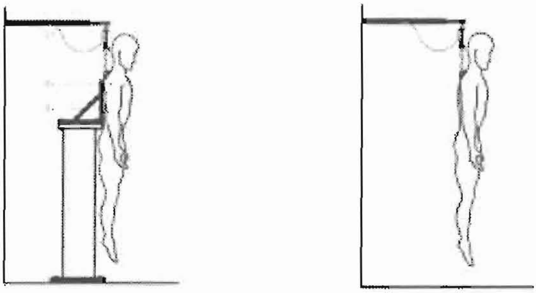

Figure 2: Restraining modes of HII: (a) Constrained: mannequin maintained suspended throughout the impact with its back blocked by a rigid column (b) unconstrained: mannequin in free fall during impact.

RESULTS AND DISCUSSION: The mean impact forces for the unconstrained and constrained configurations were 839 N and 768 N, respectively. A t-test (=5%) showed no significant differences in the forces obtained for the two configurations, suggesting that the induced force is independent of the restraining mode of the mannequin.

In an attempt to understand the underlying physical principles that govern the effect of inertia in impact testing, and to validate the experimental findings, a simple analytical model was developed. In this model, it is assumed that the situation is one-dimensional, along the direction of the impact, that the bat is perfectly rigid, and that the force induced at the interface between the mannequin's sternum and the bat is linearly related to the deflection of the mannequin's torso. This implies that an elastic response is assumed for the torso, and that viscous damping effects are neglected. Finally, it is assumed that the bat and mannequin sternum remain in contact throughout the impact. This implies that the model is limited to cases for which the bat is lighter than the mannequin. Otherwise the principles of conservation of momentum and conservation of energy would be violated.

A detailed description of the model is shown in the Appendix. This simplified model allows for a parametric study aimed at determining the influence of various factors on the maximum force transmitted to the mannequin. In particular, the effect of constraining the mannequin was considered by selecting the mass of the mannequin to be effectively infinite for the constrained case, while using the actual value of 70 kg for the unconstrained case. Force-time histories are illustrated in Figure 3 for four different mannequin masses and for a 2 kg bat mass. The curves indicate that the mass of the mannequin does not have a significant influence on the peak force in this case. This observation is in agreement with the experimental results obtained in this study, which indicated that constraining the mannequin (which is equivalent to increasing its effective mass) had no significant effect on peak force.

In Figure 4, the normalized peak force is plotted against mannequin mass for four different hypothetical bat masses. From this figure, it is found that the effect of inertia, which consists of comparing the actual mannequin mass with an infinite mass, is negligible for impactor masses of 0.5 to 2 kg. However, for the larger impactor mass of 15 kg, it is found that a more significant difference in peak-transmitted force would be obtained between the constrained and unconstrained configurations (of the order of more than 10%). In other words, it seems that the effect of inertia becomes important only in cases where the impactor mass is substantial as compared to the mannequin mass.

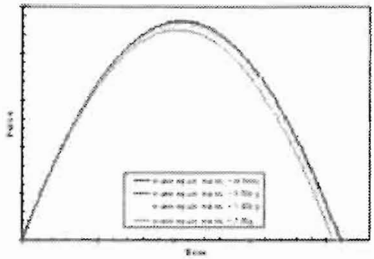

Figure 3: Force-time histories for various mannequin masses

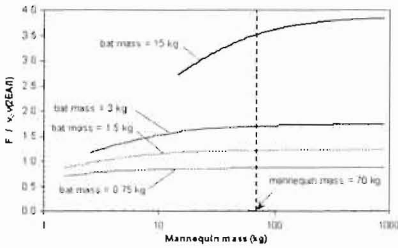

Figure 4: Peak normalized force values as a function of mannequin and bat masses.

The findings from this analytical model can be extrapolated to sport scenarios. For instance, it could be inferred that the peak force suffered by a hockey player who receives a puck on the chest while against boards would be similar to the force suffered if the player were not constrained, since the mass of the puck is much lower than that of the player. On the other hand, in the case of a collision between two hockey players, it is likely that the effect of inertia will be more important, since the two masses involved are of the same order. In other words, in a collision of two players against the boards, the impact force would be higher than if the two players collide with each other in the middle of the ice. The above analytical model has not been validated experimentally. Experiments with heavier bats should be performed to validate the findings. Finally, the current study investigated the effect of inertia on peak-transmitted force only. Since injuries do not depend solely on the peak force, tests should also be conducted to study the effect of inertia on maximum chest compression and/or predicted injuries.

CONCLUSION: Experiments involving a Hybrid II mannequin impacted with a bat at a typical angular velocity have demonstrated that the effect of constraining the mannequin was not significant; with peak transmitted forces being similar in both constrained and unconstrained configurations. A simplified analytical model, which provides more insight into the physical phenomenon, validates these findings. The model, which has not been validated experimentally, also suggests that the effect of inertia will be more prevalent when the masses of the two impacting objects are of similar order, such as in the collision of two players in a sport scenario.

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APPENDIX - ANALYTICAL MODEL OF BLUNT IMPACT: As shown in Figure 5, the bat (mass: m1, thickness: d), which is moving at an initial velocity vo, impacts the mannequin (mass: m2, initial thickness: l) and the force at the interface between the two materials is determined from the stress induced into the mannequin sternum through , and , where A is the estimated area of contact between the bat and the sternum, and are the stress and the strain of the mannequin torso, respectively, and E is the modulus of elasticity. For this particular case, the strain and force can be expressed as:

$$\varepsilon = \frac{d + l - 2(y - x)}{l}$$

and

$$F = AE\varepsilon = \frac{EA}{l}(d + l - 2(y - x))$$

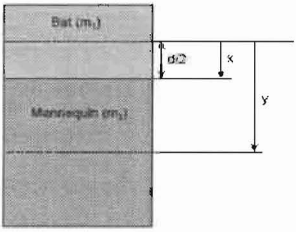

Figure 5: Schematic of the analytical model of blunt impact interaction. Variables x and y are defined as the location of the centre of mass of the bat and mannequin respectively, relative to a stationary reference frame.

Newton's "action-reaction" law yields the following two formulas:

$$-F = m_1 \frac{d^2 x}{dt^2} \qquad F = m_2 \frac{d^2 y}{dt^2}$$

where x and y are, respectively, the positions of the centers of mass of the bat and mannequin, relative to a stationary reference frame. The negative sign in the first equation accounts for the fact that the force acting on the bat is in the direction opposite to the motion of the bat. These two equations constitute two coupled second-order ordinary differential equations with the following initial conditions:

$$y\big|_{t=0} = \frac{d+l}{2} \qquad \left.\frac{dy}{dt}\right|_{t=0} = 0 \qquad \text{and} \qquad y\big|_{t=0} = \frac{d+l}{2} \qquad \left.\frac{dy}{dt}\right|_{t=0} = 0$$

The first condition states that the initial velocity of the bat is v_o , while the second condition states that just prior to impact, the mannequin's torso has not deflected yet. The solution to the ordinary differential equation for the transmitted force can then be obtained:

$$F = \frac{v_o \sqrt{\frac{2EA}{l}}}{\sqrt{\left(\frac{1}{m_2} + \frac{1}{m_1}\right)}} \sin\left(\sqrt{\frac{2EA}{l}\left(\frac{1}{m_2} + \frac{1}{m_1}\right)}\, t\right)$$