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Biomechanical Model to Assess Injury Reduction During Impact

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Abstract—**This paper implements a biomechanical model and actual tipover trajectory data to assess the risk of head and neck injuries in standup forklift accidents. Seven accident scenarios were analyzed for right tipover, left tipover and off-dock accidents both with and without a door on the operator compartment. Each model had specific data including human anthropometry and trajectory input into the modeling and analysis software packages, Visual-Safe MAD and MADYMO. For all three accident scenarios, each of the seven biomechanical models was analyzed for Injury Assessment Reference Values (IARVs) including angular velocity (omega, ω), angular acceleration (alpha, α), Head Injury Criterion (HIC), Neck Injury Criterion – shear, tension and bending (NIC) and the biomechanical Neck Injury Predictor (N_{ij}). The study concluded that, in general, the addition of a door to the standup forklift operator compartment leads to a reduction in injury during tipover and off-dock accidents. The ability to brace for impact is not included in these MADYMO models. Bracing is far more effective with an enclosed compartment provided by a latching rear door.**

I. Introduction

Standup forklifts and pallet jacks are frequently used in industry for transporting materials from one location to another. Both provide a platform on which the operator is in a standing (upright) position. A study on the safety of forklifts by the Occupational Health and Safety Administration (OSHA) found that forklift accidents cause approximately 85 fatalities and 34,900 serious injuries yearly [1]. The review by OSHA also concluded that the greatest number of forklift accidents involve vehicle tipover or overturn. "Forklift overturn" was the accident type in 24 percent of the 170 fatal reported forklift accidents. OSHA's Office of Data Analysis examined 53 fatal forklift accidents that occurred between 1980 and 1986 and found that 22 (42 percent) involved the operator being crushed by a tipping vehicle, which often happens in off-dock accidents [1]. The National Institute for Occupational Safety and Health (NIOSH) also determined that overturns were the leading cause of fatalities involving forklifts. According to NIOSH, forklift overturns represent approximately 25 percent of all forklift related fatalities [2]. Forklift tipover and overturn accidents fall under the category of stability accidents.

Berry found that the most significant injury mode in stability accidents is the risk of being crushed between the ground and forklift. Berry also concluded that the average injury to a standup forklift operator from a stability accident is greater when the operator is ejected or jumps from their compartment than when they remain in the operator compartment [3].

One issue that limits operators' ability to remain in their compartment is the postural instability experienced with mild changes in acceleration. Braking postures the operator in a single limb stance position as the forklift decelerates. Our group previously determined that postural balance is easily lost on a standup forklift with acceleration levels from 0.06 g to 0.12 g [4, 5].

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II. Methods

A. MADYMO Model Construction

Visual-Safe MAD 4.5 (ESI Group) and MADYMO 6.2 (TASS Americas) were used to create and analyze output dynamics of seven forklift and operator models and their interactions. MADYMO (**MA**thematical **DY**namic **MO**dels) is a 3-D modeling software that combines rigid body dynamics and finite element modeling simulations. Its applications include automotive, aerospace and military industries as well as accident reconstruction and biomechanical research. While MADYMO performs the explicit analysis, the pre- and post-processing of the models are carried out in Visual-Safe. Visual-Safe links with MADYMO and uses its database of dummy and human body models as well as airbags and seat belts. These models can be scaled to fit specific cases (Figure 1). Parameters such as velocities, gravity, simulation time, impulses, surrounding space, dummy/surroundings interaction, desired outputs, etc. are defined in Visual-Safe. MADYMO performs the analysis and creates the output files. Visual-Safe's post-processor, Visual-Viewer, is used to plot the outputs and view the simulation animations.

Figure 1. Scaled, positioned, standing Hybrid III dummy from MADYMO.

Forklift models were based on measurements from physical inspections and photogrammetry of seven actual cases. For each of the seven cases, gender-matched Hybrid III dummies were scaled to match the height and weight of the vehicle's operator (Table 1). The ability to brace for impact is not included in these models.

Table 1. Hybrid III scaling data for the seven models.

	1	2	3	4	5	6	7
Gender	M	F	M	F	M	M	M
Height (inches)	67	67	69	67	70	68	72
Weight (lbs)	208	125	200	230	235	167	160

B. Impact Parameters

Left and right tipover accidents were modeled for each of the seven cases (Figure 2). Forklift trajectory was input based on physically tested tipover trajectories. Off-dock accidents were also modeled for each of the seven cases with trajectory input based on physically tested off-dock, forks trailing trajectories. One example of a modeled case where the operator attempted to jump to safety is shown in Figure 3. The simulated operator egress confirms an unsuccessful attempt to clear the forklift structure during an off-dock, forks trailing accident.

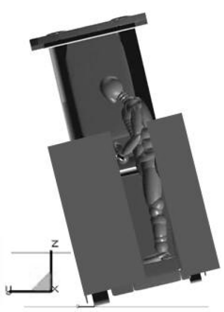


Figure 2. Model of left tipover forklift accident.

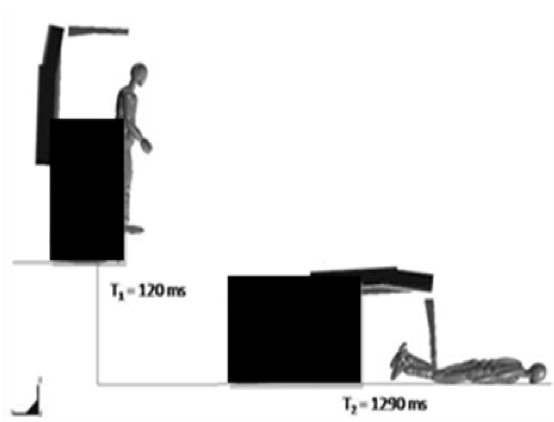


Figure 3. MADYMO simulation of a standup forklift operator attempting to jump to safety during an off-dock, forks trailing accident. Jump trajectory is from physiologic data.

C. Output Parameters

The Injury Assessment Reference Values (IARVs) examined include the maximum Head Injury Criterion (HIC), angular velocity of the head (omega, ω), angular acceleration of the head (alpha, α), Neck Injury Criterion (NIC) in tension, shear and bending as well as the biomechanical Neck Injury Predictor (N_{ij}) for compression-extension (CE), compression-flexion (CF), tension-extension (TE) and tension-flexion (TF). The four N_{ij} values are calculated by the equation:

$$N_{ij} = \frac{F_z}{F_{zc}} + \frac{M_y}{M_{yc}} \quad (1)$$

Where F_{zc} and M_{yc} are constants that depend on the dummy and neck loading conditions [6]. HIC is defined by:

$$HIC = \max_{T0 \le t_1 \le t_2 \le TE} \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} R(t)dt \right]^{2.5} (t_2 - t_1) \quad (2)$$

Where T_0 is the starting time, T_E is the end time, R(t) is the resultant head acceleration in g's (measured at the head's center of gravity) over the time interval $T_0 \le t \le T_E$, t_1 and t_2 are the initial and final times (in s) of the interval during which the HIC attains a maximum value [6]. HIC_{15} and HIC_{36}, where the 15 and 36 represent the respective integration time interval in Equation 2 (in ms), are commonly reported. Omega and alpha are the first and second derivatives, respectively, of the angular position data through the time steps of the model and output by MADYMO.

D. Analysis

The threshold for NIC-bending is 57 Nm. The thresholds for NIC-tension and NIC-shear are based on exposure duration as follows: tension should not exceed 3.3 kN at time 0 ms, 2.9 kN at time 35 ms and 1.1 kN at time 60 ms and greater; axial force should not exceed 3.1 kN at time 0 ms, 1.5 kN at time 25-35 ms and 1.1 kN at time 45 ms and greater. The sum of the four N_{ij} values has a threshold of 1 [6]. The HIC_{36} threshold is 1000 and the conservative thresholds for ω and α are:

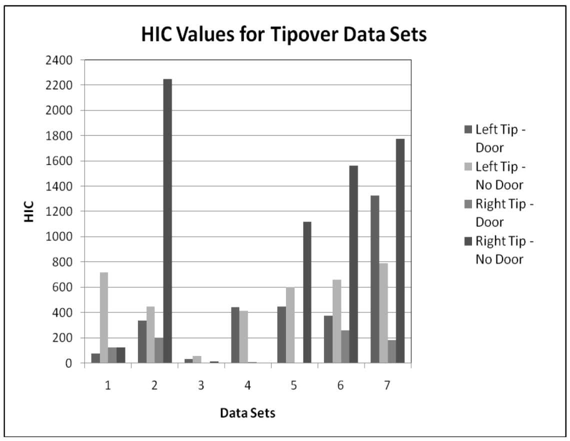
$\omega \ge 30 \,^{radians}/_{sec}$, $\alpha \ge 1800 \,^{radians}/_{sec^2}$
$\omega \le 30 \,^{radians}/_{sec}$, $\alpha \ge 4500 \,^{radians}/_{sec^2}$

In other words, an angular velocity value about 30 radians/sec has an angular acceleration threshold of 1800 radians/sec^2, whereas an angular velocity below 30 radians/sec has a much higher angular acceleration threshold of 4500 radians/sec^2.

III. RESULTS

In general, the addition of a door to the tipover model decreased HIC, NIC shear and NIC bending values. In some cases, the difference between the HIC value with a door and with no door was injury threshold (Figure 4). Most cases had an injurious α level, which was usually greater with no door.

The greatest danger in an off-dock forklift accident is of being crushed by the truck after falling or jumping from the operator compartment (Figure 3). The results of the MADYMO models also show a general increase in HIC values with no door compared to having a door. All of the off-dock cases modeled had HIC values above the threshold. These increased by as much as fivefold when there was no operator compartment door on the forklift (Figure 5).



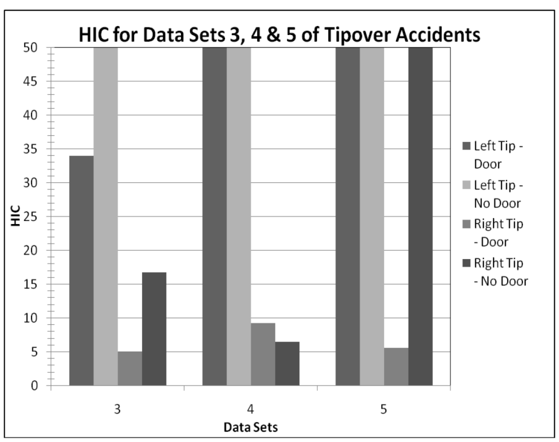


Figure 4. Peak HIC_{36} values of four scenarios for each of the seven modeled right and left tipover cases with and without a door (top). Bottom graph is zoomed in portion of the top graph showing the HIC_{36} values for sets 3-5, which were too small to be seen on the full-scale graph.

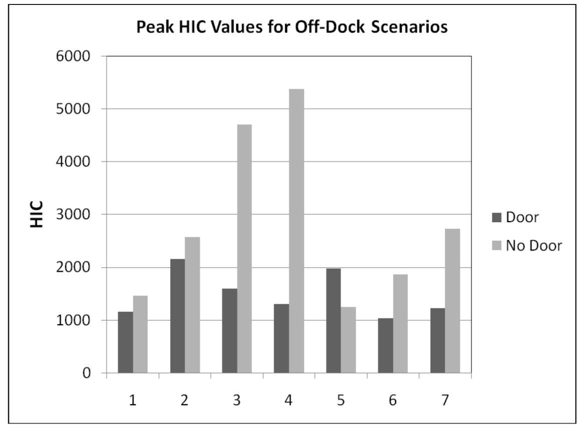


Figure 5. Peak HIC_{36} values for the seven off-dock cases modeled with and without doors.

IV. DISCUSSION

Stability and collision accidents are a major safety concern with standup forklifts and pallet jacks. They are involved in a relatively high number of accidents leading to serious injuries and fatalities. The postural instability caused to an operator compounds the dangers of forklift accidents. Risk of sustaining serious or fatal injuries can be mitigated through the use of additional guarding. Vertical posts extending to the overhead guard and extended backrests can prevent injuries associated with intrusion collisions. Operator enclosures or doors reduce injuries associated with collision, tipover and off-dock accidents [1]. Enclosures or doors arrest the loss of balance, falling and injury in standup forklift operation [4,5]. Zoghi-Moghadam et al have suggested that use of an operator enclosure or door would be detrimental to head and neck loading based on analysis of testing and simulation, which is in contradiction to our results [1]. Zoghi-Moghadam et al also used a computer model to look at HIC in left tip, right tip and off dock accidents. They modeled an accident with zero initial velocity, which was unlike the real-world accident cases modeled here. In concurrence with our findings, they concluded that a head injury is more likely to occur in a right tipover accident than in a left tipover. However, their model did not produce HIC values above the injury threshold level [7]. Four of the seven tipover cases modeled for this work show peak HIC_{36} values above the threshold of 1000. In a comparison of right tipover no door and left tipover no door, the right tipover in four of seven cases results in a higher HIC_{36}. Interactions between the Hybrid III, rear posts, compartment interior and console are included in these analyses. The left tipover represents a forward operator motion, while the right tipover represents rearward operator motion. These factors contribute to the differences seen in the two tipover directions. This work shows that standup forklift operators generally incur more serious injuries when their operator compartment is open rather than when there is an enclosure or door. Since forklift operators suffer more serious injuries when they are ejected or jump from the compartment, extended walls and backrests and the addition of doors or enclosures could reduce injury severity in forklift accidents. This is supported by previous work by our group and work by Berry [3-5].

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