PROCESSING AND PRODUCTS

Predicting hairline fractures in eggs of mature hens

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ABSTRACT Eggshell damage poses a serious problem for the consumption egg industry. Increasing the maximum age of laying hens will increase eggshell damage due to loss of shell strength. This poses a serious problem for automatic collection, packing, and transport. We performed a model based study focused on hairline fractures in eggs of 88-week-old hens, and simulated side collisions on 1,235 eggs using a specially designed pendulum. The kinetic energy at the moment of impact was related to the accelerations measured by an electronic egg going through the transport chain. Further, several egg mechanical properties were measured.

For collisions with a realistic impact, fracture occurrence correlated negatively with dynamic stiffness (14%), mass (15%), shape index (9%), and damping ratio (12%). We manipulated the data set to investigate the influence of improving egg properties. Removing the least favorable 50% of the eggs based on stiffness and mass resulted in a moderate reduction of fracture occurrence, from 7.7% down to 4.4%.

The peak acceleration of an egg running through the transport chain lies typically in the range of 15 to 45 *g*. Our model predicts that a moderate decrease from 30 *g* down to 20 *g* will result in a drastic reduction of fracture occurrence from 7.7% down to 0.3 to 1% (95% confidence region), whereas an increase to 40 *g* will increase fracture occurrence to 42 to 55%.

The model predicts that severe collisions pose a relatively high risk for eggshell damage, which suggests that a reduction of collision severity is of first priority when increasing the age of laying hens.

Key words: consumption eggs, fracture, model, risk

2017 Poultry Science 96:1956–1962
http://dx.doi.org/10.3382/ps/pew411

INTRODUCTION

Eggshell damage is a serious problem in the consumption egg industry. Even tiny hairline fractures, i.e., a broken shell but with the membranes still intact, devalues the selling price. For caging systems, 2 to 7% of the eggshells were damaged within the transport chain, amounting to a cost of $240 million per year in the United States in 1998 (Singh et al., 2007). For non-caging systems in Europe, this number is typically 2 to 6%, according to the Vencomatic company (Eersel, The Netherlands). Eggs with detected fractures are worth approximately one euro cent less than intact eggs. This means an economic loss of €16 000 for a complete production round of 100,000 hens (from 18 to 90 wk of age, with 400 eggs per hen, and an average fracture rate of 4%). Moreover, hairline fracture occurrence increases the risk of bacterial contamination, thereby negatively influencing food safety (Mertens et al., 2006). Research on automated monitoring methods (Sloan et al., 2000; Ketelaere et al., 2002; De Ketelaere et al., 2003; Mertens, 2009) focuses on eggshell properties, such as dynamic stiffness, egg specific gravity, shell color, egg mass, shell thickness, non-destructive deformation, and mechanical egg properties such as shell breaking strength by impact fraction force, puncture force, and quasi-static compression (Hamilton, 1982; Roberts, 2004; Nedomová et al., 2009). Eggshell quality can be increased via genetic selection (Ketelaere et al., 2002), or adjusting the feed composition (Grizzle et al., 1992). Alternatively, the risk of collisions that cause fractures may be decreased by identifying locations and transitions within the transport chain corresponding to the most severe collisions. These can be identified via an electronic device that has the mass and shape representative of an egg, that follows the same collection, packing, and transport procedures as real eggs, while measuring shocks in the form of accelerations (Singh et al., 2007). Our own observations (from 7,000 measurements in non-cage systems) show peak accelerations typically in the range of 15 to 45 *g,* corresponding to a 1 to 6 % breaking percentage. There is no gold standard for an accepted maximal breaking percentage. Typically, however, for first-quality eggs

Received May 4, 2016.
Accepted October 16, 2016.
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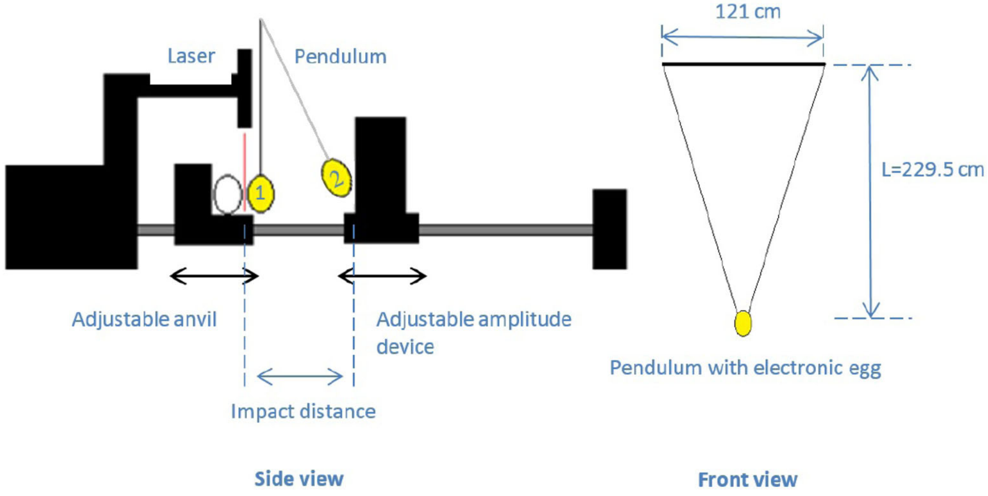

Figure 1. Experimental setup to simulate collisions. Left: Side view of the pendulum setup. Right: Front view of the pendulum holding the electronic egg. Here 1 = equilibrium position, 2 = starting position for impact experiment.

3 to 5% is considered acceptable. For systems with more mature hens this poses a problem, since shell quality decreases with age (Roberts, 2004). The trend is to increase the age of laying hens, with a production goal of 500 first-quality eggs per hen within 100 wk of age (http://www.isapoultry.com, January 2016). This raises the question of which factors mostly affect hairline fractures in eggs of laying hens, and in particular mature hens — and, subsequently, which solutions will be most efficient.

Our research focuses on the influences of mechanical egg properties, as well as collision severity, on fracture occurrence in consumption eggs of relatively old (88 wk) hens. We simulated side collisions using a specially designed pendulum. Dynamic stiffness, mass, shape index, and damping ratio of eggs were measured. The accelerations during the collisions were measured with an electronic egg.

We compared 3 models that relate the severity of the collision to fracture occurrence, and selected a model based on kinetic energy at the moment of impact. The kinetic energy could be related to maximum acceleration with high precision. This allowed us to relate hairline fracture occurrence with the accelerations measured during collisions and transitions in the transport chain, and predict the effect of reducing collision severity.

MATERIALS AND METHODS

Experimental Setup and Data Set

To establish the relationship between fracture occurrence, collision severity, and egg properties, a pendulum setup was designed and built (see Figure 1). Collisions were carried out with an electronic egg (brand: Masitek, Moncton, Canada), which is a hard plastic device with the mass and shape of an average egg (64.4 mm height, 47.5 mm width, shape index 0.74, and 62.7 grams mass) that contains sensors that measure accelerations (Singh et al., 2007). Collisions between eggs and objects were simulated with this device. During each collision, the magnitude of the maximum acceleration was recorded. The collisions took place at the long sides of the eggs. The plastic egg was suspended with two fishing lines to ensure that it swings in one direction. The horizontal distance between the equilibrium position and the amplitude (impact distance) of the pendulum was adjusted based on the desired level of impact. A metal anvil held the real eggs. The anvil consisted of a metal strip attached to a plastic base. To secure and check that each egg collision took place precisely at the equilibrium position of the pendulum, a laser beam was used that pointed to the correct location of the side of the real egg.

Each egg experienced one collision. Prior to each collision in the pendulum setup, 4 egg characteristics (mass, shape index (Altuntaş and Şekeroğlu, 2008), dynamic stiffness, and damping ratio) were measured. Dynamic stiffness and damping ratio were measured with the Columbus Egg Tester (Leuven, Belgium). The kinetic energy E of the electronic egg at the moment of impact was computed based on a simple pendulum model:

$$\begin{aligned} v &= \sqrt{2gL\,(1-\cos{(\alpha)})} \\ E &= \tfrac{1}{2}mv^2, \end{aligned} \tag{1}$$

with $v\,(\mathrm{m\,s^{-1}})$ the magnitude of the velocity of the plastic egg just before the collision, $L = 2.295\ m$ vertical distance from the center of the egg to the pendulum pivot point, g the gravitational constant ($9.81\ \mathrm{ms^{-2}}$), α the angle between the pendulum line at position 2 (see Figure 1) and the virtual laser line, and $m = 62.7\ g$ the mass of the electronic egg. Additionally, collisions between the electronic egg and the metal anvil were performed. Table 1 shows the experimental settings.

In total, 1,235 intact consumption eggs were used in the experiment, all from Dekalb white commercial

Table 1. Settings of the pendulum experiments.

Treatment	Impact distance (mm)	E (mJ)[1]	n electronic egg on egg[2]	n electronic egg on metal[2]
1	106.5	1.52	599	10
2	158.5	3.37	274	10
3	190.5	4.87	180	10
4	242.5	7.90	121	10
5	261.5	9.19	61	10

[1] E denotes the kinetic energy of the electronic egg upon impact with an egg or the anvil, as calculated with model (1).
[2] n denotes sample size.

farm hens of 88 wk old, and fed with "Green Tops 3" feed containing 40 g kg^{-1} calcium, to which 0.5% grit (containing 380 g kg^{-1} calcium carbonate) was added. Three d in row a batch of eggs was collected directly from the egg belt behind the laying nest. The collection took place at 7:30 a.m. in the morning after which the eggs were transported in plastic trays from the farm towards the lab. The eggs were used in the experiment the same day. The maximum storage was 10 hours. The climate conditions were not actively controlled, and were typically 23°C, with a relative humidity of 40 to 60%. Fractures were detected with the Columbus Egg Tester, developed by (De Ketelaere et al., 2000). An egg was labeled "intact" or "fractured" in the dataset used later on for modeling and analysis. We found that the reliability of the Columbus was quite high (sensitivity = 0.89, specificity = 0.99), but might be not high enough for experiments with very high or very low fracture probabilities. Therefore, all eggs were double checked (with the Columbus Egg Tester and manually), and the manual inspection was conclusive. Before the experiment started, all eggs were tested for fractures, and consequently 5.5% fractured eggs were removed. For analysis and model building, only collisions were considered that left the eggs intact.

Fracture Occurrence Model

We tested 3 models to relate fracture occurrence with the severity of the impact. The first was a logistic model, similar to the one used in (Mertens et al., 2006), which has as input the magnitude of the maximum acceleration measured during the collision.
Interpolation model a:

$$y = \frac{1}{1+\exp(\theta_1 - \theta_2 x)} \tag{2}$$

where $y \in (0, 1)$ is fracture occurrence probability for each egg, x the maximum acceleration of the incoming egg during impact, and θ a vector of positive-valued parameters to be fitted to the data. This model structure satisfies the boundary conditions of 100% fracture occurrence for infinite acceleration, and 0% for zero acceleration. The signs are chosen in such a way that the maximum likelihood parameter, $\theta^{ML} > 0$, which enables parameter searching and Monte-Carlo sampling in log-space. The second model, **interpolation model b**, has the same structure as model **a**, but with x the kinetic energy of the incoming egg at the moment of impact. An alternative model structure that was tested, is
Interpolation model c:

$$y = \frac{(\theta_1 x)^{\theta_2}}{\theta_3 + (\theta_1 x)^{\theta_2}} \tag{3}$$

where x is the kinetic energy of the incoming egg at the moment of impact. For models **a**, **b**, and **c**, the maximum likelihood parameters were estimated, as well as their confidence regions. The statistical likelihood of a parameter vector $p(\theta)$ was calculated with the binomial probability model:

$$\ln\ p(\theta) = \sum_{i=1}^{n} \ln(y_i(\theta)^{y_{d,i}}\ (1 - y_i\ (\theta)\ )^{1-y_{d,i}}), \tag{4}$$

where $y_d \in (0, 1)$ is the fracture data, containing n data points, and index i ranging over all measurements. For model comparison and selection of variables we used the Bayesian information criterion (**BIC**),

$$BIC = -2\ln\left(p\theta^{ML}\right) + k\ln(n) \tag{5}$$

where θ^{ML} is the maximum likelihood parameter vector, k the number of parameters, and n the number of data points (the total number of intact eggs). To be able to compute the uncertainty of predicted egg fracture probability, we computed the confidence levels of the predictions. For this, the probability distribution of θ was obtained by the Markov chain Monte Carlo sampling method (ter Braak and Vrugt, 2008), and summarized by its 95% confidence region, following the methodology in (van Mourik, et al., 2014).

Computational Settings

For estimating θ^{ML} we used a hybrid algorithm consisting of a global search of the genetic search routine "GA" in Matlab with a population of 1,000, followed by a gradient based search with the "lsqnonlin" routine in Matlab, starting from the optimum found by "GA." For Monte Carlo sampling, we used k chains, 2 10^4 iterations per chain, 2 10^3 burn-in iterations, and a thinning rate of 10. We used a log-uniform prior. The confidence regions were represented with 1,000 samples. We checked that these settings gave consistent (compared with different settings) and repeatable results. Similar settings were used in van Mourik et al. (2014). For a detailed explanation of the Monte Carlo sampling algorithm, we refer to ter Braak and Vrugt (2008).

Table 2. Egg mechanical property statistics of 1,235 intact eggs.

	Minimum	Maximum	Mean	Standard deviation
Mass (g)	51.6	87.7	65.3	4.9
Shape index (-)	0.52	0.99	0.76	0.03
Damping ratio (-)	6.2	1.4	2.4	0.7
Dynamic stiffness (kN m^{-1})	4.9	150	15	4.2
Diameter (mm)	34.3	57.8	44.5	1.4
Height (mm)	46.5	85.2	59.1	2.4

Table 3. Sample sizes (n), proportions of fractured eggs, and their standard deviations (SD) for 5 treatments with different kinetic energy.

Kinetic energy (mJ)	n (-)	Fractured eggs (-)	Fractured eggs (%)	SD (%)
1.52	599	2	0.3	- [1]
3.37	274	21	7.7	3.2
4.87	180	58	32.2	6.8
7.90	121	112	92.6	4.7
9.19	61	59	96.7	- [1]

[1] The standard deviations of treatments 1 and 5 could not be determined with confidence, since for both treatments only 2 data points differ from the rest.

RESULTS

Relationship between Fracture Occurrence and Egg Mechanical Properties

The statistics of the egg properties are summarized in Table 2. For an impact with a fixed kinetic energy of 3.37 mJ, fracture occurrence was 7.7% (Table 3), which correlated negatively with dynamic stiffness (14%), mass (15%), shape index (9%), and damping ratio (12%). The correlation percentage denotes the percentage of variation in the data set that is explained by the variable.

Relationship between Fracture Occurrence and Collision Severity

Table 3 shows the sample sizes and hairline fracture occurrence statistics for impacts with varying kinetic energy. The relationship between percentage of fractured eggs and kinetic energy is highly nonlinear. Between treatments 1 and 2, the fracture percentage differs by a factor 25. Between treatments 3 and 5, this is a factor 3. In both cases, the kinetic energy differs by a factor of 2. This justifies the choice of nonlinear modeling. The standard deviations of treatments 1 and 5 could not be determined with confidence, since for both treatments only 2 data points were different from the rest. By estimating the uncertainty of fracture occurrence via Monte Carlo sampling, a confidence region for the complete experimental range was calculated (see "Fracture occurrence model").

Selection of Interpolation Model. Interpolation models **a** and **b** were found to be quite similar regarding the fit. Both models have the same fitting accuracy, but model **b** has one parameter less, and is therefore statistically more likely (Sum of Squared Errors (**SSE**) = 244, BIC = 501 for model **b** versus SSE = 244, BIC = 510 for model **a**). Model **c** gives poor results (SSE = 444, BIC = 901). Figure 2 shows the confidence region for model **b**. From now on, this model is used. Linking the predictions of this model to measurements in practice, requires a relationship between kinetic energy and acceleration.

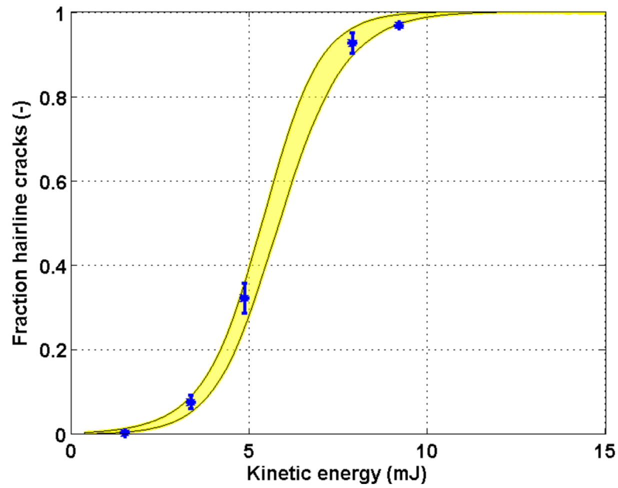

Figure 2. The 95% confidence regions for interpolation model **b**. The ∗s denote the experimental data, the bars denote standard deviation.

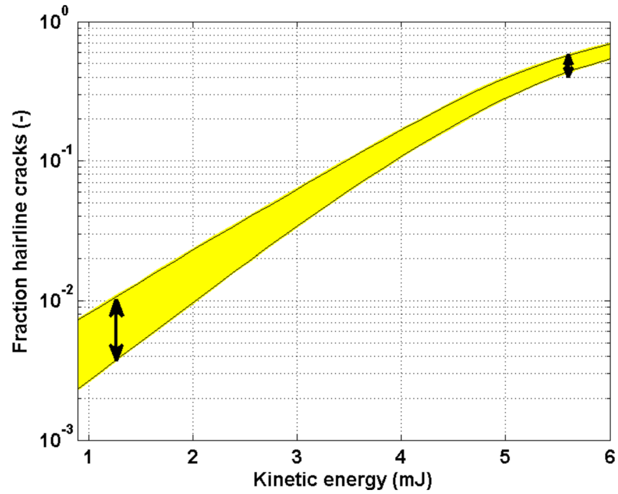

Figure 3. The 95% confidence predictions for the complete model **b**. The 2 double-sided arrows correspond to collisions between the electronic egg and real eggs at 20 g (left arrow) and 40 g (right arrow).

Relationship between Kinetic Energy and Acceleration. The relationship between kinetic energy at the moment of impact and magnitude of the maximum acceleration was modeled linearly, and was found to be

$$G = 14.24 + 4.67E, \tag{6}$$

where G is the magnitude of the maximum acceleration averaged per treatment. Here $R^2 = 0.989$. The model error is very small, and assumed negligible in the remainder. More details are given in the Appendix.

Model Summary

The model that relates measured maximum acceleration with hairline fracture occurrence is $E = 0.214G - 3.05$

$$y = \frac{1}{1 + \exp(\theta_1 - \theta_2 E)}, \tag{7}$$

where vector θ is represented by its sampled probability distribution.

Predictions

We investigated the experiment-based and model-based sensitivities of egg damage towards changes in egg properties and collision severity. Starting point was the experimental setting with a 7.7% fracture rate. First, the influence of improving egg properties, e.g., by means of genetic selection, or improved feed, was investigated. The data set was manipulated by removing the 25% least stiff and the 25% lightest eggs from the dataset, which in both cases reduced the fracture occurrence from 7.7% down to 5.9%. Removing the 25% lightest and 25% least stiff eggs combined reduced fracture occurrence from 7.7% down to 4.4 %.

Next, we investigated the influence of improvement in egg transport resulting in less severe shocks. Starting from the same experimental setting, the model predicts with 95% confidence that collisions with a 7.7% fracture occurrence correspond to maximum accelerations of 29 to 32 g. The maximum acceleration of an egg running through the transport chain is typically 15 to 45 g. A decrease from 30 g to 20 g is predicted to reduce the fracture occurrence down to 0.3 to 1%, and an increase from 30 g to 40 g is predicted to increase fracture occurrence to 42 to 55% (see Figure 3).

DISCUSSION

The main findings of our research are that data analysis and model predictions indicate that a substantial change in egg properties will cause only a moderate reduction in hairline fracture occurrence (a factor of 2), and that a moderate reduction in maximum acceleration will drastically reduce the fracture probability of an egg (a factor of 10). This suggests that in order to reduce egg fracture occurrence in eggs of old hens, avoiding high-impact collisions is of first priority. These findings are discussed below.

Predictions

The model prediction that an increase to 40 g will increase egg fractures to 42 to 55% indicates that a major reduction in fracture occurrence might be realized just by avoiding the most severe collisions. We expect that a reduction of the most severe shocks is feasible by means of better machine settings and perhaps improving transport material.

The 2 egg properties that correlated most strongly with egg fracture were dynamic stiffness and weight. For dynamic stiffness the observed correlations between egg properties and breaking probability are qualitatively in line with previous results (Coucke, 1998; Ketelaere et al., 2002), where a moderate correlation of breakage with dynamic stiffness was found. An earlier report found no significant correlation with mass (Ketelaere et al., 2002). A strict comparison with these and our findings is not in place, since in these papers breaking force (static force required to break the egg) was measured instead of kinetic energy of a moving object. Egg selection by way of removing the 25% stiffest and 25% lightest eggs from the dataset resulted in a considerable shift in the distribution of egg properties. The minimum dynamic stiffness increased from 55 kN m^{-1} to 139 kN m^{-1}, and the minimum egg mass shifted from 52.8 g to 62.0 g. We expect that realizing the abovementioned change in egg properties, by means of breeding or feed optimization, will be a considerable challenge.

Eggs

The batch of eggs used in our experiments seems representative for the industry, regarding the 2 egg properties correlating strongest with eggshell damage. We compared our batch to a reference batch from the literature, gathered from 6 strains of 76-week-old hens (Ketelaere et al., 2002). The dynamic stiffness in our batch was 149 kN m^{-1} $\pm$ 18 kN m^{-1} (standard deviation), with a minimum of 55 kN m^{-1}. For the reference batch, the average dynamic stiffness per strain varied between 140 and 170 kN m^{-1}. The egg mass in our batch was 65.4 g $\pm$ 5.1 g, which is somewhat heavier than the reference batch eggs for which the averages per strain varied between 60 g and 64 g.

Model Assumptions

Model (7) does not incorporate egg properties, since these were found to have a relatively small influence. However, for collisions with a very small impact, e.g., after considerable improvement of the transport chain, a model extension to include mechanical egg properties may become relevant.

The model is based on single collisions on the side on the egg. We expect this is the most relevant collision type, since in the current transport chains most of the severe collisions take place while an egg is rolling against another egg or an object. At this point we do not know the statistical distribution of collision locations on the eggshell in practical situations, as well as the effect of these locations on breaking probability. The added value of such a model extension might be worthwhile to investigate. Another valuable extension might be the effect of multiple collisions.

The relationship between maximum acceleration and kinetic energy at the moment of impact depends on the type of material (see Appendix). Hence, a model refinement to predict very small fracture rates may require the inclusion of the influence of material rigidity.

A more rigid material causes higher maximum accelerations due to limited shock absorbance. This may explain the poor performance of interpolation model **a**, in which the choice of input is maximum acceleration. Strictly speaking, acceleration is not an input, but an output resulting from incoming speed and stiffness of the colliding objects. The stiffness varies considerably per egg (see Appendix), and hence the stiffness variation may propagate into the model output, and result in a worse fit.

Some caution is needed concerning the predictions for low-impact collisions. Models **b** and **c** give different predictions (see Appendix). The above-mentioned prediction of 0.3 to 1% is conservative, compared to model **c**, which predicts a 10 times lower fracture occurrence. Selection of model **b** was based only on statistical evidence, and on our specific data set. However, in the low impact region there is not much statistical evidence to distinguish the models. The model presented here is descriptive. A valuable alternative could be a mechanistic model approach that focuses on understanding the architecture of the eggshell (Hunton, 1995; Dennis et al., 1996), and how this relates to fracture formation during impact (Bain et al., 2006; Macleod et al., 2006).

Further steps in model validation and development concern incorporating the distribution of accelerations measured in different transitions in the transport chain, hen age, genetic strain, and type of feed.

Outlook

We think that further research focused on alleviating the model demarcation posed by its assumptions will help detecting specific problem locations and transitions within the transport chain, based on accelerations measured with the electronic egg, the type and number of collisions, and the types of materials. Furthermore, we think that model refinement by incorporating management related factors such as hen age, feed type, genetics, and egg selection may help in improving the egg production and transport industry by predicting the effectiveness of new management and design strategies regarding avoidance of hairline fractures.

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Appendix

Extrapolation and reliability

This section compares model predictions based on extrapolation and interpolation. Both plots in Figure A1 show that the uncertainty represented by the confidence regions is considerable, despite the large number of data. This uncertainty indicates that the interpolation models cannot make very sharp predictions for ratio of hairline fractures as a function of collision impact. The left plot shows that both models fit the data slightly differently. The maximum likelihood

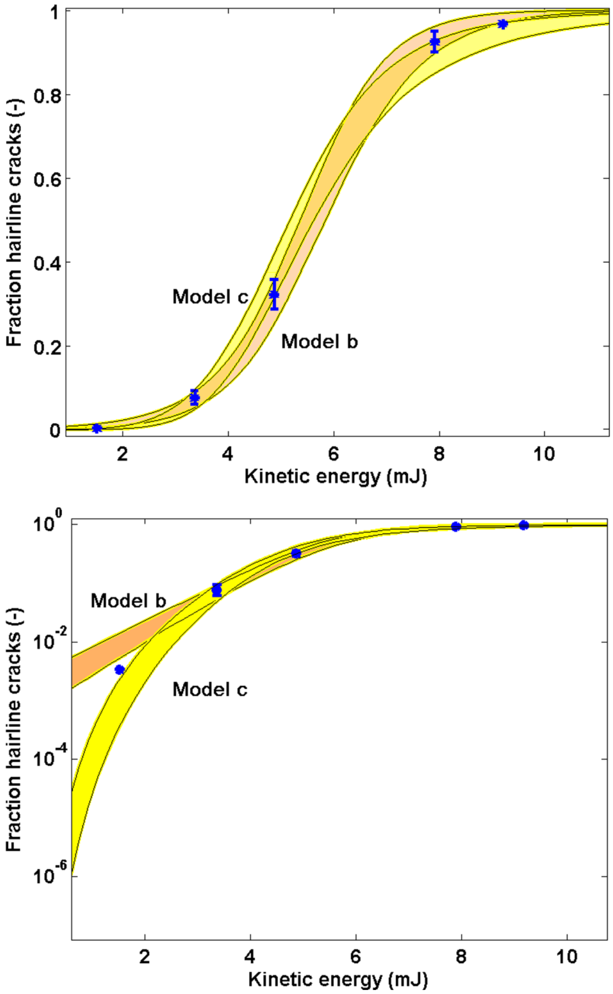

Figure A1. The 95% confidence predictions for models **b** and **c**. The ∗s denote the experimental data, the bars denote standard deviation. Upper: Plot on linear axes. Lower: Plot on logarithmic y-axis.

prediction curves (not shown) are slightly different, and the confidence regions around them differ somewhat in size, especially for higher impacts. However, taking the uncertainty into account, the large overlap of the confidence regions indicates that the predictions are not distinguishable from a statistical point of view.

The right plot reveals that both models do not fit the lowest impact data very well. However, it cannot be concluded that this is due to model flaws, since this is the most uncertain data point; it is based on 2 cases of egg fracture out of 599 samples, making it highly sensitive to any extra fracture occurrence. It is clearly visible that the models each give completely different, non-overlapping predictions for the low-impact region outside the experimental range. Hence, with predictions of fracture occurrence based on very low impacts, caution should be used.

Table A1. Output signal statistics of the electronic egg during 2 types of collisions.

	Electronic egg on metal		Electronic egg on egg	
Kinetic energy (mJ)	Mean G^1 (m s^{-2})	SD	Mean G^1 (m s^{-2})	SD
1.52	36.55	0.26	20.52	1.54
3.37	54.43	0.41	30.87	2.23
4.87	63.21	0.69	37.39	2.84
7.90	83.82	0.92	50.68	2.72
9.19	89.54	0.70	-[2]	-[2]

[1] G denotes the maximum acceleration during a collision.
[2] No value could be given with confidence, since only 2 eggs remained intact.

Material Rigidity

The relationship between kinetic energy at the moment of impact, and maximum acceleration was measured for collisions between an electronic egg, and 1) a real egg, and 2) the metal anvil. Table A1 shows the statistics. Two linear regression models based on the maximum acceleration averaged per treatment, are

$$\begin{aligned} G &= 28.93 + 6.81E \\ R^2 &= 0.989 \quad \textit{electronic egg on metal} \\ G &= 14.24 + 4.67E \\ R^2 &= 0.996 \quad \textit{electronic egg on egg} \end{aligned} \tag{8}$$

where G is the acceleration. According to these equations, for collisions that are kinetically equal, eggs that collide with metal will experience a far higher maximum acceleration than eggs that collide with other eggs. This stems from the fact that an anvil is far less flexible than an egg. The latter absorbs the impact more, thereby reducing the shock. Since eggs vary in stiffness, the standard deviations relative to the means for collisions with metal are much smaller (a factor of 10) compared to collisions with eggs.