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U.S. Civil Air Show Crashes, 1993 to 2013:

Burden, Fatal Risk Factors, and Evaluation of a Risk Index for Aviation Crashes

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Abstract

This study provides new public health data about U.S. civil air shows. Risk factors for fatalities in civil air show crashes were analyzed. The value of the FIA score in predicting fatal outcomes was evaluated. With the use of the FAA's General Aviation and Air Taxi Survey and the National Transportation Safety Board's data, the incidence of civil air show crashes from 1993 to 2013 was calculated. Fatality risk factors for crashes were analyzed by means of regression methods. The FIA index was validated to predict fatal outcomes by using the factors of fire, instrument conditions, and away-from-airport location, and was evaluated through receiver operating characteristic (ROC) curves. The civil air show crash rate was 31 crashes per 1,000 civil air events. Of the 174 civil air show crashes that occurred during the study period, 91 (52%) involved at least one fatality; on average, 1.1 people died per fatal crash. Fatalities were associated with four major risk factors: fire [adjusted odds ratio (AOR) = 7.1, 95% confidence interval (CI) = 2.4 to 20.6, $P < .001$], pilot error (AOR = 5.2, 95% CI = 1.8 to 14.5, $P = .002$), aerobatic flight (AOR = 3.6, 95% CI = 1.6 to 8.2, $P = .002$), and off-airport location (AOR = 3.4, 95% CI = 1.5 to 7.5, $P = .003$). The area under the FIA score's ROC curve was 0.71 (95% CI = 0.64 to 0.78). Civil air show crashes were marked by a high risk of fatal outcomes to pilots in aerobatic performances but rare mass casualties. The FIA score was not a valid measurement of fatal risk in civil air show crashes.

FAA Order 8900.1 (Volume 3, Chapter 6, Section 1) states that "aviation events include airshows, closed course air races, parachute demonstration jumps, balloon meets, and fly-ins conducted before an invited assembly of persons, for which the FAA issues a Certificate of Waiver or Authorization" (1). The majority of events occur at or directly adjacent to an airport. FAA certificates of waiver or authorization for these events permit temporary relief from certain designated federal aviation regulations but "under conditions ensuring the equivalent level of safety" (2). The scope of waivers varies from permitting low-altitude aerobatic flight to waiving aircraft speed limitations or limitations while an event is operating in the vicinity of an airport (2). However, few published reports describe the public

health burden associated with civil air shows or the risk factors for fatal crash outcomes in this setting. For the purpose of this paper, the term “air show” refers to an “aviation event.”

Li and colleagues developed a simple index for measuring the risk of fatal outcomes in aviation crashes (3). The index is called an abbreviation score for the three risk factors that it assesses: fire, instrument meteorological conditions, and being away from the airport (3). However, this score has not been validated as a risk measurement for fatal outcomes in civil air show crashes.

The overall objective of the current research was to provide a better understanding of surrounding circumstances and pilot performance factors in civil air show crashes so as to facilitate preventive measures. The paper describes the mortality burden of civil air show crashes, compares the characteristics of fatal and nonfatal crashes, and identifies risk factors associated with fatal civil air show crashes in the United States from 1993 to 2013. It also assesses the validity of the FIA score in measuring the risk of fatalities in commercial air show crashes that occurred during the study period.

METHODS

Data Source and Primary Outcome Measures

Study data came from the National Transportation Safety Board (NTSB) aviation crash surveillance system. The board is an independent federal agency that investigates all civil aviation crashes in the United States as well as serious mishaps that occur in other transportation modes, such as highway, railway, marine, and pipeline. For each serious transportation crash, the board undertakes an investigation to determine the probable cause of the event, and it makes recommendations to prevent crashes in the future. To ensure the objectivity of its reporting and recommendations, the board has neither regulatory nor enforcement powers (4).

An “aviation accident” is defined by the board as “an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage” (4). “Death” is defined as a fatality occurring within 30 days of the crash (4). “Serious injury” is defined as an injury that requires 48 h or more of hospitalization; causes a bony fracture (excluding simple fractures of the nose, fingers, or toes); damages any internal organ; results in severe hemorrhage, muscle, tendon, or nerve damage; causes second- or third-degree burns; or involves any burns affecting more than 5% of the body’s surface (4). “Substantial damage” is aircraft damage or failure requiring major component repair or replacement under normal circumstances (4).

When an aviation crash occurs, the board dispatches a field investigation team from its regional offices. Crash data are collected and recorded on NTSB Form 6120.4, Factual Report; this report details more than 200 items about the crash circumstances, aircraft, and pilot. FAA Order 8020.11B contains detailed procedures that ensure the quality and

technical depth of notification, investigation, and reporting procedures for aviation crashes (4).

In the present paper, civil air show crashes were defined as aviation accidents and incidents that occurred during an air event on or adjacent to an airport and for which the FAA had granted a certificate of waiver or authorization. Civil air show crashes were identified by querying the NTSB's online Aviation Accident Database with the keywords "air show," "airshow," "air-show," "exhibition," "air race," and "air expo." Six hundred forty-seven crashes were initially identified with this text search (Figure 1). After elimination of duplicate records, the 346 remaining records were reviewed by two researchers. One hundred seventy-two crashes were excluded because the crash occurred away from the airport or before or following the air event. One hundred seventy-four crashes were included in the analysis.

The FAA does not collect air event-specific flight-hour data, and records were not kept of the number of flights or events that occurred at air events throughout the United States during the study period. To estimate civil air show crash rates, the number of U.S. air shows during this period was used as the crash rate denominator. The International Council of Air Shows provided the estimate of the number of civil air events that occurred during the study period.

Statistical Analysis

Crash rates per number of U.S. civil air events were calculated using numerator data from the NTSB's Aviation Accident Database and denominator data from the International Council of Air Shows. Data from the civil air show crashes that occurred between January 1, 1993, and December 31, 2013, were analyzed in Stata, Release 12.0 (5).

Fisher's exact test was used to examine fatal and nonfatal crashes for differences in binary and categorical exposures. *T*-tests were used to examine differences in continuous exposure measurements between fatal and nonfatal crashes. Several steps were required to perform the statistical analysis for predictors of fatal crash outcomes. First, the association of fatal outcomes with the following factors was assessed: fire, meteorological conditions, off-airport location, loss of power, loss of flight controls, maintenance malfunctions, pilot error, aircraft platform, homebuilt aircraft, aerobatic flight, time of day, pilot age, total pilot flight hours, use of a shoulder harness, and type of air event. Multiple linear regression analysis permitted calculation of the variance inflation factors, which were all below 2.0.

Modelwise deletion was used to exclude missing values during all analyses; fatal crashes that had missing values for any of the variables used in the analytic model were excluded. Nested models were compared by using likelihood ratio tests and the Akaike information criterion. When two nested models were compared through likelihood ratio tests, only the cases common to both regression models following modelwise deletion were used for comparison.

Models were selected on the basis of a combination of knowledge of crash survivability, potential confounders, and the projected feasibility of model use in the emergency response

setting. Potential interactions were evaluated by creating interaction terms and evaluating their effects on measures of association in the regression models. Model fit was assessed by means of Pearson's and Hosmer–Lemeshow goodness-of-fit tests and deviance measures. Model performance was examined by using the area under receiver operating characteristic (ROC) curves.

Evaluation of FIA Scores

With the methods described by Li and colleagues, a composite score was constructed from three well-recognized predictors of fatal outcomes: fire, instrument meteorological conditions, and off-airport location (3). The score was constructed with the following two assumptions: (a) the risk factors all have the same magnitude of influence on fatal outcomes, and (b) the risk factors have an additive effect on fatal outcomes that does not vary by combination of predictors. To test the first assumption, model performance was evaluated after the fire predictor was provided various weights. To test the second assumption, the rates of fatal outcomes were compared by means of different combinations of predictors (3).

A composite score was calculated for each of the crashes in the study. Computed values for sensitivity, specificity, and area under the ROC curves were used to assess the validity of the score in measuring fatal outcomes. The ROC curve depicts the composite score's ability to discriminate between fatal and nonfatal crashes. The curve represents the probability that a randomly selected fatal crash is rated higher by the composite score than a nonfatal crash selected at random. To assess the robustness of the composite score for predicting fatal commercial air show crashes, the analysis was replicated for two outcome measures: fatal crash and pilot fatality.

MORBIDITY AND MORTALITY RESULTS

From 1993 to 2013, 174 aircraft crashed (91 fatal and 83 nonfatal) while participating in civil air events in the United States; these crashes resulted in 104 deaths and 44 nonfatally injured pilots and passengers. From 1993 to 2013, an estimated average of 270 civil air events per year occurred. The estimated industrywide commercial air show crash rate during this period was 31 crashes per 1,000 air events. The fatality rate was 18 deaths per 1,000 air events.

From 1993 to 2013, approximately half the air show–related crashes resulted in at least one fatality and, among fatal crashes, an average of 1.1 people died. For both fatal and nonfatal crashes combined, the average fatality rate was 0.6 death per crash. Fatalities occurred in 46% of pilots and 34% of passengers, while 17% of pilots and 25% of passengers sustained nonfatal injuries, and 37% of pilots and 41% of passengers were uninjured. These differences were not statistically significant.

Of the 174 crashes, 91 (52%) involved at least one fatality, and 83 (48%) were nonfatal (Table 1). No significant differences were found between the proportions of propeller planes, jets, helicopters, gliders, gyroplanes, and balloons in each outcome group. In addition, no significant difference existed between the proportion of home-built aircraft and formation flights in each outcome group. Fatal and nonfatal crashes occurred at roughly the same time

during the day, and crash pilots were similar in age and total flight hours. No significant difference was found in the proportion of crashes that were precipitated by loss of power, loss of flight control, and improper maintenance in a comparison between the fatal and nonfatal outcome groups. However, fatal crashes were more likely than nonfatal crashes to involve fire [relative risk (RR) = 2.0, 95% CI = 1.6 to 2.5, $P < .001$], to occur at an off-airport location (RR = 1.6, 95% CI = 1.2 to 2.1, $P = .002$) and during an aerobatic flight (RR = 1.9, 95% CI = 1.5 to 2.5, $P < .001$), and have pilot error as a contributing factor (RR = 2.0, 95% CI = 1.2 to 3.3, $P < .001$). Air show attendees were less likely than performers, competitors, and participants in a designated fly-in event to be involved in a crash (RR = 0.3, 95% CI = 0.1 to 1.1, $P = 0.01$).

Location

Crashes occurred in 37 states during the study period (Figure 2). More than one-quarter of all crashes occurred in one of three states: California (17, 10%), Nevada (16, 9%), and Texas (14, 8%). These results likely reflect the distribution of air show locations in the United States. Six (3%) of the 174 civilian crashes took place on military bases.

Time Trends

Over the 21-year period of the study, the number of annual crashes exhibited no general trend; approximately the same number of crashes occurred during the first and second halves of the study period, the largest number (15, 9%) being in 2011.

There was no clear time trend in the proportion of fatal crashes. The time trend for the proportion of fatal crashes is important because it is unlikely that a fatal crash would go unreported, whereas a minor crash might not be reported in the absence of witnesses. A trend in the proportion of fatal crashes could represent a change in reporting practices for nonfatal crashes; however, there was no clear evidence of a trend during the study period.

All the crashes occurred between 05:30 and 23:45. Three-quarters occurred between 12:15 and 16:30. Crashes occurred with the greatest frequency on weekends, a reflection of the weekend being the most common times to hold air shows, with the highest number on Saturday (79, 45%), which was followed by Sunday (47, 27%) and Friday (23, 13%). Two-thirds of crashes occurred during the months of June (26, 15%), July (37, 21%), August (21, 12%), and September (32, 18%).

Flight Characteristics

All flights were conducted under Code of Federal Regulations Part 91. Air show performers accounted for 102 (59%) of air show-related crashes and were followed by air race competitors (23, 13%), other airport users (13, 7%), commercial air tour occupants (nine, 5%), fly-in participants (eight, 5%), soaring-competition participants (four, 2%), and an aerial photographer. Thirty-four (20%) of the flights that crashed were formation flights. Six of the nine commercial air tour crash reports contained information about the number of previous air tour flights conducted for compensation or hire by the pilot that day. One air tour pilot crashed during the first flight of the day, two on the fourth flight of the day, two after conducting "multiple flights," and the last after conducting four to six flights.

Visibility

All but one flight took place in daylight and good visibility. The crash that occurred in poor weather was a repositioning flight following an air show in which the pilot inadvertently flew into instrument meteorological conditions, resulting in a controlled flight into terrain.

Pilot Characteristics

All flights had a single pilot. The median pilot age was 54. Pilots 60 and older were involved in nearly a third of crashes. The characteristics of their crashes compared with those of pilots younger than 60 were unremarkable, except for one 61-year-old, who suffered a myocardial infarction during flight. Thirty-five pilots (20%) held commercial pilot certificates, and 80 (46%) held airline transport certificates. Total pilot flight hours ranged from 118 to 41,000 h, with a median of 4,047 h. Time in aircraft type was recorded for 75% of pilots involved in crashes and ranged from 3 to 10,000 h, with a median of 248 h. Flight time in the previous 30 days was recorded for 94 (54%) of the pilots in crashes and ranged from 1 to 150 h, with a median of 15 h.

Pilot health, including drug and alcohol use, was a factor in six crashes, including the aforementioned myocardial infarction. Unauthorized drugs found in biological samples from pilots involved in crashes included pseudoephedrine, phenylpropanolamine, fluoxetine, diltiazem, phentermine, diazepam, and alcohol.

Sixteen pilots (10%) did not wear a shoulder harness when one was available for use. Thirteen (81%) of them were not conducting aerobatic flights.

Airplane Characteristics

The aircraft included 147 (84%) propeller planes, 12 (7%) jets, nine (5%) rotary-wing aircraft, four (2%) gliders, one gyroplane, and one balloon, with 65 (37%) being experimental aircraft. The gyroplane and 29 (17%) fixed-wing aircraft were homebuilt. Of the 168 motorized aircraft, 162 (96%) had one engine, five (3%) had two engines, and one (1%) had three engines. No difference in fatalities was found by type of aircraft. Likewise, homebuilt aircraft were no more likely to crash than those that were commercially built.

Phase of Flight

The phase of flight during which the problem became apparent was most commonly maneuvering (94, 54%), which was followed by takeoff (23, 13%) and landing (20, 11%).

Crash Outcomes

More than half of all reported crashes (52%) were fatal to at least one person. Aircraft were destroyed in 71 (41%), and postcrash fires occurred in about one-fourth of the crashes. Three crashes resulted in injuries to spectators. In these crashes, 10 spectators died, 67 sustained serious injuries, and two sustained minor injuries. All but one of the casualties (10 deaths and 66 serious injuries) resulted from a single crash in which an air race pilot crashed into the airport ramp following the failure of an elevator trim system. The other serious spectator injury occurred when a glider pilot lost directional control during the initiation phase of an air-tow takeoff, causing the glider to collide with a spectator and an automobile. The two

minor injuries occurred when jet fuel sprayed a mother and daughter during an inverted crash of a jet aircraft.

Maintenance

NTSB reports noted improper maintenance as a contributing factor in 14 crashes (8%). Examples of such cases included improper installation of components or parts that resulted in control separation and fire and, apparently, careless inspections. Owner-modified mechanical systems and manufacturer-created weak points combined with fatigue and stress were also cited as contributing factors to crashes.

Air Traffic Control

Air traffic control and airport-related factors were mentioned in 19 crash reports (11%).

Regression Modeling to Predict Fatal Outcomes

Multiple logistic regression modeling demonstrated that the adjusted odds ratios for fatal outcomes were 7.1 (95% CI = 2.4 to 20.6, $P < .001$) for fire, 5.2 (95% CI = 1.8 to 14.5, $P = .002$) for pilot error, 3.6 (95% CI = 1.6 to 8.2, $P = .002$) for aerobatic flight, and 3.4 (95% CI = 1.5 to 7.5, $P = .003$) for crash location off airport grounds (Table 2). Other variables included in the multiple logistic regression model were total pilot flight hours, time of day, and aircraft type (helicopter versus fixed-wing); none of these variables had an odds ratio greater than 1.0. Variables considered but not selected for the model because they did not improve model fit were weather conditions, wind speed, pilot age, shoulder harness use, homebuilt aircraft, experimental aircraft, loss of power, loss of flight controls, component failures, maintenance-related conditions, object-related conditions, and type of air event. The final adjusted regression model had 159 unique variable patterns; using the Hosmer–Lemeshow goodness-of-fit test, an χ^2 P -value of .34 was calculated. The P -value for the deviance χ^2 was .53. The area under the ROC curve was .81 (95% CI = 0.75 to 0.88).

Evaluation of FIA Scores

Fatal crash rates trended upward with FIA score (Figure 3). Three crash reports did not provide enough information to calculate an FIA score. Overall, the fatal crash rates were 30%, 74%, and 71% for FIA scores of 0, 1, and 2, respectively. None of the crashes in the data set had an FIA score of 3. The corresponding χ^2 test for trend P -value was $< .001$. The specificities for fatal crash outcomes were .71, .40, and .89 for FIA scores 0, 1, and 2, respectively (Table 3). The sensitivities for fatal crash outcomes were .71, .23, and .05 for FIA scores 0, 1, and 2, respectively (Table 3). With a cutoff of 1, the FIA score had a sensitivity of .28 and a specificity of .29. The area under the FIA score ROC curve was .71 (95% CI = 0.64 to 0.78). When the FIA score was reevaluated by using pilot death as the outcome (instead of fatal crash), the area under the ROC curve was .53 (95% CI = 0.45 to 0.61).

As noted earlier, the four-point composite score assumes that fire, meteorological conditions, and off-airport location contributed equally to fatal outcomes. Because fire has been shown in other studies to be more hazardous to occupants than weather or crash location, alternative scoring methods, in which fire received more weight than the other two

predictors, were evaluated. The sensitivity, specificity, and area under the ROC curves from the models that assigned greater weight to fire were similar to those of the simpler, four-point scoring system. The four-point FIA score also assumes that the three risk factors have an additive effect on fatal outcomes. Thus, the FIA score assumes no interaction between the predictors. A series of logistic regression models were fitted with different combinations of two-way interaction terms (3). This assessment revealed no interactions among the predictors.

DISCUSSION OF RESULTS

This study examined the public health burden associated with civil air events by using more than 20 years of data from the NTSB's accident analysis database. According to the International Council of Air Show Safety, approximately 300 military and civilian air shows take place annually in the United States. Of those, an estimated 260 to 270 are civil air shows that take place on or adjacent to civilian airports. Military aviation mishaps are investigated by service-specific safety centers that do not publish accident analysis data for the public. However, the NTSB publishes factual and probable cause reports on every reported civilian aircraft crash occurring within the United States in an accident analysis database. Thus, this database provides information that the public sector can use to inform airport safety measures so as to prevent or mitigate air show-related public health risk factors.

The results of this analysis suggest that outcomes of fatal air show-related crashes are associated with fire, pilot error, aerobatic flight, and away-from-airport crash location. The association of fire with fatal outcomes is consistent with studies that associate post-crash fires with an up to eightfold increase in the risk of fatality among emergency medical services (6), occupational (7, 8), general aviation (9–11), and foreign aviation crashes (12, 13), following adjustment for pilot characteristics and crash-precipitating factors. Likewise, away-from-airport crash locations are also associated with fatal outcomes relative to on-airport locations in many countries and contexts (7, 12, 13). Lower on-airport crash speeds, immediate availability of emergency personnel, and the absence of hazardous terrain all contribute to lower crash fatalities in airport settings (10). Consistent with this study's finding that aerobatic flight increases the risk of air show-related fatal crashes, aerobatic flights have been described in the literature as the most significant risk factor for fatal injury, comprising 50% of U.S. general aviation crashes involving air transport pilots over a 20-year period (14). In an analysis of the dangers of these maneuvers that used NTSB-reported crash data from 1982 to 2006, de Voogt and van Doom found that more than 80% of the 494 crashes involving aerobatic maneuvers were fatal (15). Similar to the primary type of pilot error identified in air show-related crashes, the primary contributing factor in the previously published aerobatic-crash data set was a failure to maintain altitude in visual meteorological conditions. Half the pilots included in the aerobatic crash study had accrued more than 7,500 flight hours of experience; pilots in air show-related crashes were still highly experienced but had fewer total flight hours (median of 4,047 h). Homebuilt aircraft were more likely to be involved in fatal aerobatic crashes in the literature, in addition to having more structural, component, and engine failures than aircraft that were commercially built (15). However, this result was not found in the present air show-related crash data. This difference may be

explained by a decrease in the number of crashes of homebuilt aircraft over time, as twice the number of homebuilt aircraft crashed during aerobatic flights in the first 10 years than during the final 10 years of the previously published study of risk factors related to aerobatic flight (15). In that study, adverse weather conditions did not contribute to any aerobatic crashes during the 25-year study period. That finding is consistent with the findings here that adverse weather conditions did not significantly contribute to air show–related crashes.

The FIA score, Li and colleagues' simple risk index for fatal outcomes, did not provide a valid measure for the risk of fatal outcomes in air show–related crashes (3). Compared with the 44,828-crash evaluation of the FIA score for all types of aviation crashes, the FIA score performed relatively poorly in the 21-year air show–related crash cohort. The ROC value was 0.71 (95% CI = 0.64 to 0.78) for air show–related crashes in this study; the ROC CIs did not overlap those of commuter and air taxi crashes (ROC = 0.86, 95% CI = 0.80 to 0.85) or general aviation (ROC = 0.81, 95% CI = 0.81 to 0.82) crashes in the Li et al. study; however, the upper limit of the air show ROC CI touched the lower limit of that of major airlines (ROC = 0.86, 95% CI = 0.78 to 0.95) (3). The small sample size in this study makes the assessment of the FIA score less precise; nevertheless, the FIA score does not appear to be a robust measure of fatal outcomes in air show–related crashes relative to other types of crashes. The relatively low sensitivity of an FIA score of 1 or greater for predicting fatal crash outcomes makes it less useful as a screening tool for rescue teams and emergency medical responders at air events (Table 3). In addition, the relatively low specificity of FIA scores of 2 and 3 indicates that to prevent fatal outcomes that focus only on fire, weather, and away-from-airport location may not be sufficient for effective prevention or mitigation of the severity of air show–related fatal crashes (Table 3). Because air events are usually conducted on airports under visual flight rules, it makes sense that away-from-airport location and instrument meteorological conditions may not play as much of a role in crash outcomes compared with their effects in flights conducted for other purposes. The lack of significance of instrument meteorological conditions in the predictive model for fatal outcomes among air show–related crashes, and the moderately low RR of away-from-airport compared with that for on-airport crash location with fatal air show outcomes, further supports this explanation (Table 2).

From 1993 to 2013, 174 aircraft crashed during civil air events, killing 114 and injuring 112 people. The majority of deaths and injuries occurred among air show pilots, with a single air race crash resulting in all 10 spectator fatalities and all but three of the 68 spectator injuries. Aerobatic flights contributed to two minor injuries, which resulted from a jet fuel spray during a crash sequence in which a jet aircraft failed to recover from inverted flight. Although denominator data are unavailable for the calculation of spectator morbidity and mortality rates, the rate of air show–related spectator injury and death is likely relatively low with respect to the 21-year period and the hundreds of thousands of individuals who had likely attended air events during the study period.

The association of spectator mass casualties with a single catastrophic air show crash in this data set is consistent with documented events such as the 1988 Ramstein (Germany) Air Base disaster and the 2002 Sknyliv, Ukraine, airfield crash. The Ramstein disaster killed 67 spectators and three pilots after a midair collision of an Italian Air Force demonstration team

during a heart-shaped formation maneuver for a 300,000-member audience (16). The Sknyliv air show disaster occurred when two Ukrainian Air Force 14th Air Corps pilots ejected after failing to recover from a low-altitude rolling maneuver (17). The aircraft crashed into a crowd of 10,000 spectators, killing 77 and injuring approximately 550 audience members (17). These catastrophic incidents indicate that, while they pose a relatively rare threat to spectators, mass casualties are a potential outcome of air events that should be incorporated into risk management strategies. Coordinating with the local health care system, conducting mass casualty drills, briefing air show participants, and providing emergency instructions to air show patrons could be effective methods of mitigating poor outcomes in the event of a mass casualty (18, 19, 20).

Nine air show–related crashes involved “commercial air tours,” which are defined by the FAA as “flights conducted for compensation or hire in an airplane or helicopter where a purpose of the flight is sightseeing.” Commercial air tours can be conducted under Federal Aviation Regulations Parts 91, 121, and 135. The industrywide commercial air tour crash rate is more than 10 times that of airline transport flights (0.2 per 100,000 flight hours) and more than twice that of Part 135 operators (1.3 per 100,000 flight hours) (21, 22). All the crashes included in this study occurred in Part 91 flights, which, within the air tour industry, have a crash rate that is 50% higher than that of Part 135 air tour operators (3.5 versus 2.3 crashes, respectively, per 100,000 flight hours) (21). Thus, not only are air tours more likely to crash than flights conducted by other similar commercial aviation operations, but the Part 91 air tour flights associated with air shows are more likely to crash than those conducted by Part 135 air tour operators (23).

Five of the six air show–related air tour crashes occurred after “multiple” flights, and four occurred after at least four flights. Fatigue plays an important role in pilot safety and performance. Studies have indicated that conducting multiple short flights during the workday increases the risk of fatigue among pilots (21, 24, 25). Time of day, number of flight legs, early wake-up times, prolonged duty periods, and the addition of unplanned legs exacerbate fatigue among these pilots (25, 26). In the same manner, air tour pilots are exposed to risks associated with multiple takeoffs, landings, and maneuvers, which can result in an increased workload throughout the day relative to long-haul pilots. To reduce the risk of fatigue, Part 135 outlines crew rest requirements and flight-hour limitations by week, month, and year. It also limits single-pilot crews to 8 h of total flight time in a 24-h period. However, air tour pilots flying under Part 91, such as the nine who crashed during the study period, are not subject to flight hour restrictions or crew rest requirements. Given the known risks associated with fatigue, the NTSB has recommended mandating a 30-min break following three consecutive hours of flight and also limiting air tour pilots to eight air tour flights per day, but the FAA has not incorporated this recommendation into the federal aviation regulations governing commercial air tours (27).

A major limitation of this study is the lack of denominator data required to calculate air show–related crash, death, and injury rates. Without reliable estimates of the number of air show flights or flight hours flown in this subset of aviation crashes, estimation of the incidence of air show–related crashes, which would provide additional context to the current results, proves difficult. Given the lack of this information, the available denominator was

limited to a crude estimate of the number of air events conducted in the United States during the study period.

What is more, the use of absolute figures such as number of flights or number of flight hours flown has undergone criticism in the literature for not providing adequate risk-based denominator data for appropriate analysis and interpretation. However, risk analysis differs fundamentally from the crash analysis performed in this study. Risk analysis is a broader approach that requires highly specific denominator data. For instance, a complete risk analysis of aerobatic flight would require detailed information about each takeoff, landing, and maneuver encountered during flight. Crash analysis, which has a narrower scope than risk analysis, acts as an initial inquiry that can inform targeted interventions to prevent or mitigate the morbidity and mortality associated with air show–related crashes (28).

Another important limitation of this study is the lack of suitable comparison flights for performance of risk analysis for the flights that resulted in crashes. Ideally, flights that resulted in crashes should be compared with similar flights that did not result in crashes. However, information on similar noncrash flights is not available from the NTSB. Thus, to evaluate the risk of crashing during air shows, data must be collected for flights that did not result in crashes.

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FIGURE 1.
PRISMA-style flow diagram demonstrating crash selection process.

FIGURE 2.
Civil air show crashes, by state, 1993–2013.

FIGURE 3.

Civil air show fatal crash outcomes, by FIA score, 1993–2013 (no air show crashes in Alaska during study period).

TABLE 1

Baseline Civil Air Show Crash Characteristics, by Outcome, Nonfatal Versus Fatal, 1993–2013

Flight Factor	Nonfatal (<i>n</i> = 83)	Fatal (<i>n</i> = 91)	Relative Risk (95% CI)	<i>P</i> -Value (2-sided)
Flight operating characteristics				
Aircraft platform				
Propeller plane, no. (%)	70 (84)	77 (84)	1.0 (0.7–1.5)	>.99
Jet, no. (%) ^a	3 (4)	9 (10)	1.5 (1.0–2.1)	.14
Helicopter, no. (%)	7 (8)	2 (2)	0.4 (0.1–1.4)	.09
Glider, no. (%)	1 (1)	3 (3)	1.5 (0.8–2.6)	.48
Gyroplane, no. (%)	1 (1)	0 (0)	1.0 (0.2–3.9)	>.99
Balloon, no. (%)	1 (1)	0 (0)	1.0 (0.2–3.9)	>.99
Homebuilt aircraft, no. (%)	12 (14)	22 (24)	1.3 (1.0–1.8)	.13
Aerobatic flight, no. (%)	15 (18)	46 (51)	1.9 (1.5–2.5)	<.001
Formation flight, no. (%)	12 (14)	22 (24)	1.3 (1.0–1.8)	.13
Time of day, mean (SD) ^b	13:47 (2:50)	13:50 (2:44)	na	.91
Risk Factors ^c				
Fire postcrash, no. (%)	6 (7)	34 (38)	2.0 (1.6–2.5)	<.001
Instrument weather conditions, no. (%)	0 (0)	1 (1)	1.0 (0.2–3.9)	>.99
Away (off-airport) crash location, no. (%)	21 (25)	40 (44)	1.6 (1.2–2.1)	.002
Pilot characteristics				
Pilot age, mean (SD)	53 (12)	52 (12)	na	.81
Total flight hours, mean (SD)	6,480 (7,318)	7,262 (7,887)	na	.51
Air show participation				
Performer, no. (%)	40 (48)	62 (68)	1.5 (1.1–2.1)	.009
Air race competitor, no. (%)	12 (15)	11 (12)	0.9 (0.6–1.4)	.66
Soaring competitor, no. (%)	1 (1)	3 (3)	1.5 (0.8–2.6)	.62
Fly in, no. (%)	4 (5)	6 (7)	1.2 (0.7–2.0)	.75
Attendee, no. (%)	10 (12)	2 (2)	0.3 (0.1–1.1)	.01
Airport user (not in air show), no. (%)	10 (12)	4 (5)	0.5 (0.2–1.2)	.06
Crash precipitating factors ^c				
Loss of power, no. (%)	22 (27)	8 (9)	0.5 (0.3–0.9)	.002
Loss of flight control, no. (%)	7 (9)	7 (8)	1.0 (0.6–1.6)	>.99
Improper maintenance, no. (%)	7 (9)	7 (8)	1.0 (0.6–1.6)	>.99
Pilot error, no. (%)	54 (68)	79 (89)	2.0 (1.2–3.3)	.001

NOTE: Of the 174 crashes in this study, eight crash reports (5%) lacked total pilot flight hour data; one (1%) lacked loss of power data; four (2%) lacked maintenance data, and five (3%) lacked pilot error data. No. = number; CI = confidence interval; SD = standard deviation; na = not applicable.

^aReference group.

^bTime calculated with a 24-h clock.

^cTotal not 100% because some crashes had multiple risk or precipitating factors.

TABLE 2

Results of Logistic Regression Analyses of Civil Air Show Risk Factor Variables, with Fatal Crash as Outcome Variable, 1993–2013

Risk Factor	Crude			Adjusted ^a		
	OR	95% CI	P-Value	AOR	95% CI	P-Value
Fire, relative to no fire	7.7	(3.0–19.6)	<.001	7.1	(2.4–20.6)	<.001
Pilot error, relative to no reported pilot error	3.8	(1.7–8.5)	.001	5.2	(1.8–14.5)	.002
Aerobatic flight, relative to nonaerobatic flight	4.6	(2.3–9.3)	<.001	3.6	(1.6–8.2)	.002
Away from airport crash location, relative to on-airport location	2.4	(1.2–4.5)	<.001	3.4	(1.5–7.5)	.003

NOTE: OR = odds ratio; AOR = adjusted odds ratio; area under ROC curve = 0.8139.

^a Adjusted logistic regression model included fire, pilot error, aerobatic flight, location relative to airport, total pilot flight hours, time of day, and aircraft type (helicopter versus fixed wing).

TABLE 3

Sensitivity and Specificity of FIA Score During Prediction of Fatal Crash Outcomes of Civil Air Show Crashes, 1993–2013

FIA Score	Sensitivity	Specificity
0	0.72	0.71
1	0.23	0.40
2	0.05	0.89
3	na	na
1	0.28	0.29