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Risk Factors for Injuries During Military Static-Line Airborne Operations: A Systematic Review and Meta-Analysis

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Objective: To identify and analyze articles in which the authors examined risk factors for soldiers during military static-line airborne operations.

Data Sources: We searched for articles in PubMed, the Defense Technical Information Center, reference lists, and other sources using the key words *airborne, parachuting, parachutes, paratrooper, injuries, wounds, trauma,* and *musculoskeletal*.

Study Selection: The search identified 17 684 potential studies. Studies were included if they were written in English, involved military static-line parachute operations, recorded injuries directly from events on the landing zone or from safety or medical records, and provided data for quantitative assessment of injury risk factors. A total of 23 studies met the review criteria, and 15 were included in the meta-analysis.

Data Extraction: The summary statistic obtained for each risk factor was the risk ratio, which was the ratio of the injury risk in 1 group to that of another (baseline) group. Where data were sufficient, meta-analyses were performed and heterogeneity and publication bias were assessed.

Data Synthesis: Risk factors for static-line parachuting injuries included night jumps, jumps with extra equipment, higher wind speeds, higher air temperatures, jumps from fixed-wing aircraft rather than balloons or helicopters, jumps onto certain types of terrain, being a female paratrooper, greater body weight, not using the parachute ankle brace, smaller parachute canopies, simultaneous exits from both sides of an aircraft, higher heat index, winds from the rear of the aircraft on exit entanglements, less experience with a particular parachute system, being an enlisted soldier rather than an officer, and jumps involving a greater number of paratroopers.

Conclusions: We analyzed and summarized factors that increased the injury risk for soldiers during military static-line parachute operations. Understanding and considering these factors in risk evaluations may reduce the likelihood of injury during parachuting.

Key Words: parachutes, parachuting, wind speed, night, temperature, parachute ankle brace, terrain, wounds, trauma, musculoskeletal

Key Points

- Risk factors associated with military static-line airborne operations included night jumps, jumps with extra equipment, higher wind speeds, higher air temperatures, winds from the rear of the aircraft on exit, jumps from fixed-wing aircraft, jumps onto certain types of terrain, being a female paratrooper, not using the parachute ankle brace, smaller parachute canopies, simultaneous exits from both sides of an aircraft, entanglements, being an enlisted soldier, and jumps involving a greater number of paratroopers.
- Trainers, operators, and medical personnel should consider these risk factors in their injury-risk evaluations and during specific airborne maneuvers to help paratroopers arrive safely at the battleground.

Perhaps the most ancient of tactical athletes is the infantry soldier. Since the beginning of recorded history, men have faced each other in combat, first with edged and blunt weapons and later with firearms. The critical tasks of infantry have changed little from ancient to modern times. For offensive operations, the task is to move toward the hostile force and destroy or capture that force through the use of weapons and movement. The task for defensive operations is to repel the enemy's assault through the use of weapons, close combat, and counterattack. Infantry units have some of the most physically demanding training of all military occupational specialties and place a great emphasis on discipline, fitness, and aggression.[1,2]

All infantry units have the same basic mission and similar training, but the methods modern infantry units use to arrive at the battleground are different. Whereas overlap can occur depending on the tactical situation, light infantry generally travel on foot, mechanized infantry arrive in armored personnel carriers, air-assault infantry arrive by exiting rotary-wing aircraft (ie, helicopters), and airborne infantry arrive by parachuting from aircraft. Each entry technique requires appropriate training for successful execution.[3]

Among modern battlefield-entry techniques, airborne operations involve the most training, technical skills, and hazards. The US Army airborne training comprises a 3-week course that focuses on developing specific knowledge and skills, especially use of the parachute, aircraft-exit techniques, and ground-landing procedures, with additional emphasis on improving physical fitness. After the soldier completes the basic airborne course, additional mandatory airborne training is conducted within the unit to refine skills and keep the soldier airborne qualified. New technologies (eg, improvements in parachutes; aircraft; and protective devices, such as ankle braces) are being introduced and require additional training for incorporation into airborne operations.[4,5]

Athletes prepare for their sports by improving or maintaining their physical fitness and performing sport-specific training.[6,7] Sport-specific training can have many potential hazards, such as opponent contact, uneven ground conditions, equipment malfunctions, and adverse weather.[8–11] As athletes, airborne soldiers prepare by maintaining a high level of physical fitness and practicing jumps from aircraft. Soldiers in airborne operations face many potential hazards, such as adverse weather conditions, exits from fast-moving aircraft, parachute malfunctions, and landing-zone hazards. Therefore, both sports and airborne operations may be associated with adverse conditions that can increase the injury risk during physical activity. An early step in the injury-prevention process is understanding factors that might place individuals at risk of injury and quantifying the risk in these factors.[12]

Parachuting is an activity performed as a sport and by occupational groups, such as firefighters (smoke jumpers) and rescue personnel. Information obtained from military parachuting is of interest to the armed forces and may also inform these other parachuting groups of potential injury risks. Therefore, the purpose of our study was to provide a systematic review of the literature regarding risk factors involved in military static-line parachute operations. A *static line* is a cord attached to both the aircraft and the soldier's parachute. As the soldier exits the aircraft, the cord automatically pulls open the soldier's pack that contains the parachute canopy, slowing the soldier's descent. We previously performed a narrative review of airborne injury risk factors,[13] but since then, numerous additional studies have been published. Our research expands considerably on the past work[13] by integrating the new investigations; performing a systematic review; and where possible, conducting meta-analyses to more adequately quantify the risks. Routine military airborne operations have been well described in other publications.[13,14]

METHODS

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[15] and the review protocol described in this section.

Information Sources and Search

PubMed and the Defense Technical Information Center (DTIC) were searched to find studies on risk factors for airborne-related injuries. For the DTIC search, we examined only unclassified articles (ie, approved for public release, distribution unlimited). Key words were *airborne* OR *parachuting* OR *parachutes* OR *paratrooper* AND *injuries* OR *wounds* OR *trauma* OR *musculoskeletal*. The reference lists of obtained articles were searched for articles not found in the retrieval services. The files of a senior researcher (J.K.) with airborne injury experience were also examined. In 3 cases, we contacted authors to clarify data-collection methods. No limitations were placed on the dates of the searches, and the final search was completed in December 2014.

Study Selection and Data-Collection Process

Articles were selected for the review if they (1) were written in English, (2) involved static-line parachute operations, (3) involved military personnel, (4) involved injuries either documented directly on the drop zone or obtained from safety or medical records, and (5) provided a quantitative assessment of any potential airborne-related injury risk factors. Injuries had to occur during parachuting operations from the time personnel exited the aircraft to the time they departed from the landing zone. We examined publication titles and reviewed the abstract if the article appeared to describe injuries during military airborne operations. The full text of the article was retrieved if the abstract suggested that injury risk factors were addressed. Quantitative risk-factor data could be contained within the text of the article, in tables, or in graphs. Data presented in graphs were estimated. If the authors did not explicitly report on a specific risk factor but data were available in the article to calculate it, then we included the article and the data in the review.

We did not include studies that involved (1) free-fall operations or high-altitude, low-opening operations; (2) ejections from aircraft involving parachutes; (3) airborne soldiers involved in other-than-direct parachute operations; and (4) self-reported injuries (eg, questionnaires). Information contained in abstracts was also not included. Abstracts were not often peer reviewed and were difficult to locate because they generally were not included in reference databases.

Summary Measure

The summary statistic was the risk ratio (RR) and its 95% confidence interval (CI) that we extracted from each article. The RR was the ratio of the risk of injury in 1 group to that of another (baseline) group. In calculation of injury risk, the numerator was the number of paratroopers injured, and the denominator was the number of aircraft exits. For each potential risk factor, the reference (baseline) group was defined with an RR equal to 1.00. An RR greater than 1.00 indicated a higher risk in 1 group than in the baseline group, and an RR less than 1.00 indicated a lower risk. Data in many studies had to be reanalyzed to obtain RRs. When this was necessary, we used the OpenEpi Calculator (www.openepi.com, Emory University, Atlanta, GA) to calculate RRs and their 95% CIs.[16] We noted in the text when we could not provide these values but the data indicated the direction of a particular factor (ie, increased or decreased risk).

Meta-Analyses and Publication Bias

The Comprehensive Meta-Analysis Statistical Package (version 3.2; Biostat, Englewood, NJ) was used to perform meta-analysis on variables when at least 2 studies and sufficient information were available for this calculation. For all meta-analyses, we employed a random model that used RRs and their 95% CIs. The meta-analysis produced a summary RR (SRR) and a summary 95% CI that represented the pooled results from all of the individual investigations. Heterogeneity or homogeneity of the SRR was assessed using the Q and I^2 statistics.[17] *Heterogeneity* was the degree of variability in the RRs used in a particular meta-analysis. The I^2 statistic indicated the percentage of heterogeneity among studies, with smaller values indicating less heterogeneity and larger values, more heterogeneity. In

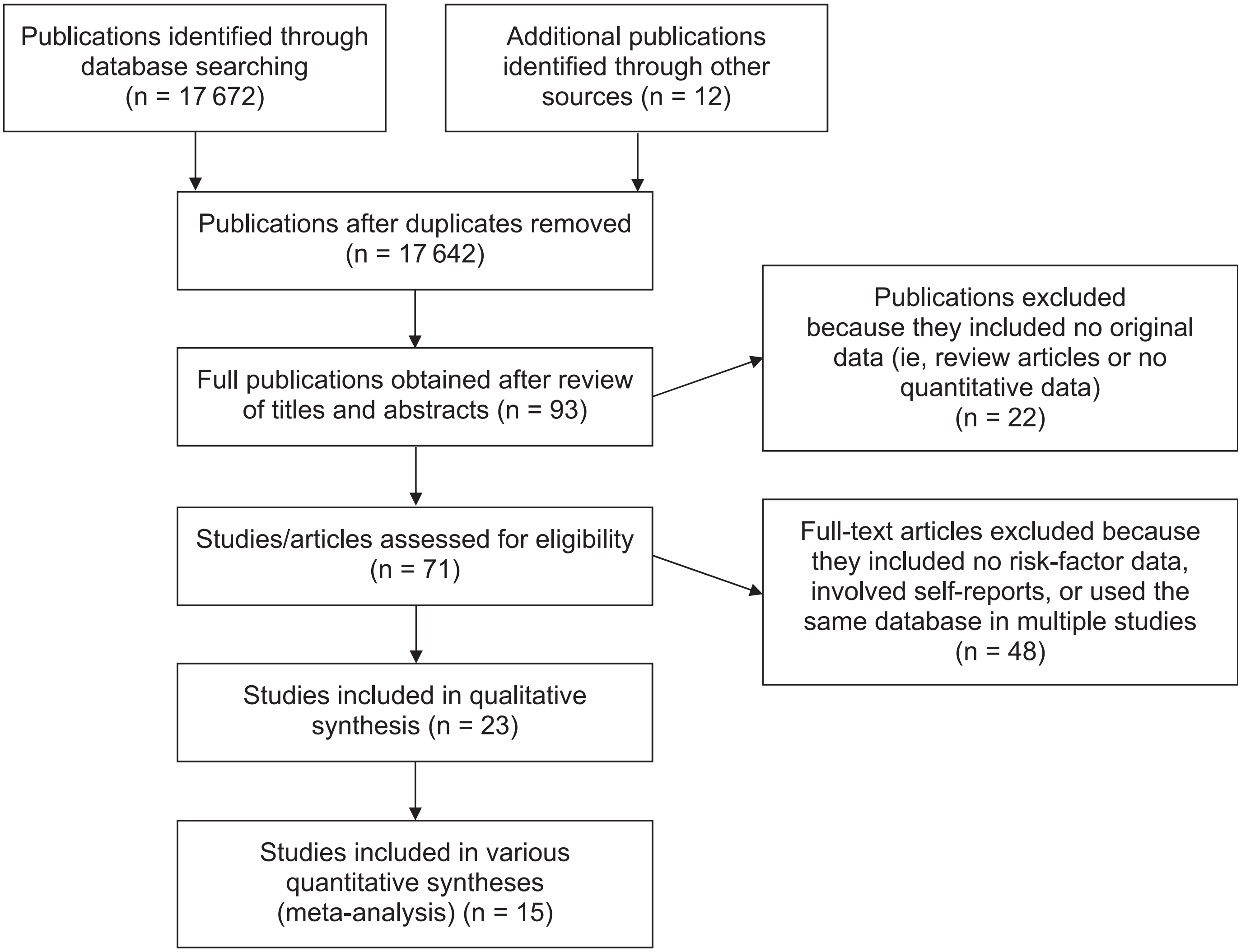

Figure 1. Publications included and excluded at each stage of the literature review.

calculating the I^2 statistic, negative values were set equal to zero, which indicated *very little heterogeneity*.[18] Tables always contained meta-analyses with all studies of a particular risk factor included; however, in a few cases, studies that appeared to account for a large portion of the heterogeneity were eliminated from the analysis, and the results were included in the text.

We also used the Comprehensive Meta-Analysis Statistical Package to provide funnel plots and calculate Begg and Mazumdar correlations to examine publication bias. Publication bias based on funnel plots was assessed by examining the symmetry of the distribution of studies around the log of the pooled effect size. We used the Begg and Mazumdar test[19] to calculate the rank-order correlation between the treatment effect and the standard error, with the latter driven primarily by sample size. A correlation suggested that publication bias existed. At least 3 studies were required for funnel plots and Begg and Mazumdar correlations.

RESULTS

The inclusion and exclusion of publications at each stage of the literature search are shown in Figure 1. The search resulted in 4175 total citations in PubMed, 13 497 in the DTIC search, and 12 from other sources. The 12 citations originally obtained from other sources (available files of the senior researcher) were also found in the PubMed search. After reviewing titles and abstracts, we obtained 71 full-text publications from PubMed and 22 from DTIC. Of the 22 DTIC publications, 18 were technical reports that were also published as peer-reviewed journal articles and found in PubMed. The other 4 DTIC technical reports did not contain risk-factor information, so no DTIC technical reports were included in the review. After reviewing the 71 full-text articles, we observed that 25 studies fully met the review criteria. However, 3 studies[5,20,21] used a database to which data were added progressively over time. Given that these reports[5,20,21] contained the same injury risk factors, only the most recent study with the largest number of aircraft exits was considered.[5] Therefore, we included 23 studies in the review. One study was published in 2 journals.[22,23] Three selected studies[5,20,24] involved the authors of this report, indicating a possible conflict of interest.

Description of Studies

The 23 investigations included in this review were observational cohort investigations. Injury data were recorded as normal airborne operations were ongoing.

Table 1 provides the injury case definitions, military units, types of paratroopers, dates of data collection, total jumps recorded, and quantitative risk factors included in the study. *Injury* case definitions differed, but many investigations included any type of physical damage to the body that occurred during jump operations.* Two studies[28,31] included most injuries sustained during jump operations but excluded minor injuries, such as contusions, abrasions, and lacerations. Five investigations[27,32,36,39,42] included only injuries that resulted in limited duty, during which the soldier was excused from performing specific tasks by medical personnel due to the injury. A few studies[36,38,43] included only specific types of injuries, such as lower extremity injuries and fractures[33] and ankle injuries. One study[29] did not provide an injury definition, and another[27] examined only injuries that occurred at altitude (before ground contact) and resulted in limited duty.

Most authors[22,26–28,31–33,36–44] collected injuries from available safety or medical records. Other researchers recorded injuries directly on the drop zone,[5,20,24,25,30,35] often with follow-up by examining medical records.[5,24,25,35] In 1 case,[29] how injury data were obtained was unclear. Most studies involved paratroopers from the United States.† Other studies involved service members from Australia,[31,39,40] Belgium,[28,29] Brazil,[41] Israel,[26] and the United Kingdom.[25,30]

The publication dates of the studies ranged from 1946 to 2014, a 68-year period. The total number of aircraft exits in the studies ranged from an estimated high of 1 115 860[38] to a low of 554,[40] with an estimated total of 2 775 567 jumps. This is an underestimate of the total number of jumps because 1 study[33] did not report the total jumps and another[25] noted that a small number of jumps may not have been properly recorded. Numerous potential risk factors were recorded in the studies (Table 1).

Injury Risk Factors

The 2 most studied airborne-related injury risk factors were time of day and jumps with or without equipment. Investigations examining these variables are shown in Table 2. Only 1 of the 8 studies examining time of day indicated that daytime jumps had a higher injury risk than night jumps.[25] Early studies[25,26,28] appeared to have more variability than later ones.[5,24,30,34,42] The SRR from the meta-analysis indicated an almost doubling of injury risk, but both the Q and I^2 statistics indicated high heterogeneity in this estimate. Little publication bias was noted, with funnel plots (Figure 2A) showing studies generally distributed symmetrically about the pooled effect size, and the Begg and Mazumdar correlation was low.

Table 2 also showed that the carriage of additional equipment elevated injury risk in all 7 studies examining this factor. The SRR from the meta-analysis suggested that the injury risk was more than doubled when paratroopers jumped with extra equipment, but again, high heterogeneity existed in this estimate, as indicated by the Q and I^2 statistics. The funnel plot (Figure 2B) indicated that studies were generally distributed around the mean effect size (with 1 outlier) and the Begg and Muzumdar correlations were low and not significant.

* *References 5, 20, 22, 24, 25, 30, 34, 35, 37, 40, 41.*

† *References 5, 20, 22, 24, 27, 33–38, 42, 43.*

The associations between airborne injuries and various weather variables, including wind speed, temperature, humidity, heat index, and wind direction are demonstrated in Table 3. We could not perform meta-analyses because different investigations had different strata (eg, wind-speed groupings), did not report denominators (number of aircraft exits), or lacked 95% CIs. Recordings of wind speed differed (average, lowest, maximal), but higher winds increased the injury risk. Some researchers[28,30] suggested a dose-response relationship between wind speed and injuries, but others[5,24,25] reported little difference in injury risk until a critical speed was exceeded. Pirson and Verbiest[28] found little difference in injury risk until the temperature exceeded about 25°C, but Knapik et al[5] suggested that higher temperatures or a higher heat index modestly increased the injury risk in a dose-response manner. The effects of humidity were not clear. Lillywhite[30] noted that winds from the rear of the aircraft elevated the injury risk.

The association between airborne-related injuries and the type of aircraft is illustrated in Table 4. Jumps from fixed-wing aircraft resulted in a higher injury risk than jumps from balloons in all 3 studies[25,28,30] that examined this association. The SRR demonstrated high heterogeneity primarily due to the much larger RR in 1 study.[30] Excluding that study from the meta-analysis resulted in an SRR of 1.53 (95% CI = 1.14, 2.07), Q statistic *P* value of .88, and I^2 value of 0. In the full analysis (all 3 studies[25,28,30]), interpreting the funnel plots was difficult due to the small number of investigations, but the studies were distributed on both sides of the mean effect (Figure 2C). The Begg and Mazumdar correlation was relatively high but not different due to the small number of investigations. When comparing fixed- and rotary-wing aircraft, the latter demonstrated a lower risk in 2 of 3 studies.[5,30] The study showing a higher risk in rotary-wing aircraft[42] involved a very small number of aircraft exits (777 in this comparison). Excluding that study[42] from the meta-analysis resulted in an SRR of 6.98 (95% CI = 3.60, 13.54), Q statistic *P* value of .89, and I^2 value of 0. In the full analysis, the funnel plots were difficult to interpret with only 3 studies[5,30,42]; however, the studies were distributed on both sides of the mean effect (Figure 2D), and the Begg and Mazumdar correlation was low, suggesting little publication bias (Table 4). The C130 Hercules aircraft had a lower injury risk than other aircraft in 2 investigations[41,42] but not in a third.[5]

The association between airborne injuries and various types of landing zones is presented in Table 5. The wide variety of landing-zones precluded meta-analysis. Landing zones described as "rough" resulted in a higher injury risk than those described as "sand dunes" or "flat/grassy."[26,41] Landing strips[22,32] resulted in a higher injury risk than those described as "fields"[32] or "paved runways."[22] Water landings resulted in a lower risk than ground landings.[40] Several landing zones were described in 1 study, with little difference in risk for all but 1 zone called Geronimo.[5]

The association between airborne injuries and soldiers' personal characteristics, including sex, age, body weight, and height, is shown in Table 6. We could not perform meta-analyses because 1 of the 2 studies on sex reported odds ratios rather than RRs,[33] the 2 studies reporting on body weight[29,40] used different strata, and only 1 study[29] reported on height. Both studies reporting on sex[33,37] indicated that women had a higher injury risk than men.

Table 1. Methods Used in Military Static-Line Parachute Injury Risk-Factor Studies Continued on Next Page

Investigation	Injury Case Definition	Military Group; Type of Paratroopers or Circumstances	Data-Collection Period	Total Aircraft Exits, No.	Risk Factors Included in Study
Essex-Lopresti,[25] 1946	Any physical damage recorded on drop zone by medical officer	6th Airborne Division, United Kingdom; trained paratroopers in training exercises	January–November 1944	20 777[a]	Time of day, wind speed, aircraft, body weight
Hallel and Naggan,[26] 1975	Medical treatment on drop zone, medical advice sought several days after jump, or hospitalization	Paratroopers, Israel; basic course, refresher course, and paratroopers on training exercises	NA	83 718[b]	Time of day, landing zone, experience
Hadley and Hibst,[27] 1984	Physical damage to body at altitude (before ground contact) with at least 1 d of limited duty	82nd Airborne Division, Ft Bragg, NC; trained paratroopers in training exercises	1979–1980	186 717	Aircraft exit timing
Pirson and Verbiest,[28] 1985	Severe or moderate physical damage on drop zone (excluded contusions and abrasions) obtained from accident reports written by physicians	Airborne trainees, soldiers in refresher courses, Belgium; basic course and trained paratroopers on training exercises	1974–1983	201 977	Time of day, equipment, wind speed, temperature, humidity, aircraft, parachute type
Pirson and Pirlot,[29] 1990	NA	ParaCommando Regiment, Belgium; basic airborne course	February 1985–March 1988	14 356 and 15 043	Body weight, body height
Lillywhite,[30] 1991	Any physical damage to body recorded on drop zone and treated by medical personnel	5th Airborne Brigade, United Kingdom; trained paratroopers in training exercises	Before February 1989	34 236	Time of day, equipment, wind speed, wind bearing, aircraft, number exiting
Farrow,[31] 1992	Physical damage to body requiring evacuation from drop zone, withdrawal from exercise, duty restriction, or hospitalization (excluded abrasions and lacerations)	Parachute Battalion Group, Australia; trained paratroopers in training exercises	March 1987–December 1988	8886	Equipment, aircraft exit type
Kragh et al,[32] 1996	Physical damage with limited duty (obtained in database maintained by medical personnel)	3rd Ranger Battalion, US; trained paratroopers in military exercises	NA (55 mo of data collection)	7948	Time of day, landing zone
Amoroso et al,[33] 1997	Injuries from US Army Safety Center accident reports	US Army; basic course and trained paratroopers	1985–1994	NA[c]	Sex
Craig and Morgan,[34] 1997	Emergency department visits resulting from airborne activities from aircraft boarding to exit on drop zone (obtained from emergency department records)	XVIII Airborne Corps, Ft Bragg, NC; trained paratroopers in training exercises	May 1993–December 1994	200 571	Age
Amoroso et al,[35] 1998	Physical damage recorded on drop zone with follow-up in medical records	Airborne School, Ft Benning, GA (1st Battalion, 507th Parachute Infantry); basic airborne trainees	NA	3674	Ankle brace
Schumacher et al,[36] 2000	Ankle pain, swelling, deformity, fracture, or contusion from parachuting and resulting in limited duty (obtained from database)	3rd Ranger Battalion, US; trained paratroopers in training exercises	November 1994–December 1997	13 782	Ankle brace

Table 1. Continued From Previous Page

Investigation	Injury Case Definition	Military Group; Type of Paratroopers or Circumstances	Data-Collection Period	Total Aircraft Exits, No.	Risk Factors Included in Study
Craig and Lee,[37] 2000	Emergency department visits resulting from airborne activity from aircraft boarding to exit on drop zone (obtained from emergency department records)	XVIII Airborne Corps, Ft Bragg, NC; trained paratroopers in training exercises	May 1994–April 1996	242 949	Sex, age
Kotwal et al,[22] 2004	Physical damage to body treated by medical officer and incurred as a direct result of parachuting from aircraft exit to release of parachute harness on ground (obtained from electronic database maintained by medical personnel)	75th Ranger Regiment deployed to Afghanistan and Iraq; trained paratroopers performing combat jumps	October 2001–March 2003	2536	Landing zone
Schmidt et al,[38] 2005	Ankle injury hospitalizations from patient medical records	Airborne School, Ft Benning, GA (1st Battalion, 507th Parachute Infantry); basic airborne trainees	January 1985–December 2002	1 115 860[d]	Ankle brace
Hay,[39] 2006	Injury requiring evacuation from drop zone, admission to medical facility, withdrawal from exercise, or limited duty (obtained from unit medical records)	3rd Battalion, Royal Australian Regiment and A Field Battery; trained paratroopers in training exercises	January–December 2004	1375	Equipment
Knapik et al,[24] 2008	Physical damage to body reported by medics on the drop zone with follow-up using clinic or hospital records	Airborne School, Ft Benning, GA (1st Battalion, 507th Parachute Infantry); basic airborne trainees	April 2005–December 2006	102 784	Time of day, equipment, wind speed, ankle brace
Hughes and Weinrauch,[40] 2008	Injuries recorded in unit medical records	4th Battalion Royal Australian Regiment; trained paratroopers in training exercises	February 2004–February 2005	554	Landing zone, body weight
Neves et al,[41] 2009	Data recorded in accident reports completed by physician after each jump mission where an injury occurred	Brazilian Airborne Brigade; circumstances not clear	January 2005–August 2006	26 616	Aircraft, landing zone
Deaton and Roby,[42] 2010	Any personnel reporting to the military surgeon for care related to airborne operations on the drop zone and placed on limited duty	US Marine Reconnaissance unit in Iraq; trained paratroopers in training exercises	October 2008–January 2009	972	Time of day, equipment, aircraft, experience

Table 1. Continued From Previous Page

Investigation	Injury Case Definition	Military Group; Type of Paratroopers or Circumstances	Data-Collection Period	Total Aircraft Exits, No.	Risk Factors Included in Study
Luippold et al,[43] 2011	Inpatient or outpatient ankle injury in 2-wk period during and after jump week in airborne school (obtained from patient medical records)	Airborne School, Ft Benning, GA (1st Battalion, 507th Parachute Infantry); male basic airborne trainees	October 1988–December 2006	342 090[d]	Ankle brace
Knapik et al,[20] 2011	Physical damage to body seen by medical personnel on drop zone and recorded on operational reports with follow-up in clinic or hospital	Airborne School, Ft Benning, GA (1st Battalion, 507th Parachute Infantry); basic airborne trainees	March–September 2010	30 755	Parachute type
Knapik et al,[5] 2014	Any physical damage to body reported by medics on drop zone with follow-up using medical records at clinic or hospital	82nd Airborne Division, elements of the XVIII Airborne Corps, and 18th Air Support Operations Group, Ft Bragg or Pope Field, NC; trained paratroopers in training exercises	June 2010–November 2013	131 747	Time of day, equipment, wind speed, temperature, humidity, heat index, aircraft, parachute type, jump order, military rank, landing zone, entanglement

Abbreviation: NA, not available.

[a] Author stated that number of jumps may be slightly underestimated, possibly by 200–300 jumps.
[b] Free-fall jumps were included but composed <5% of total aircraft exits.
[c] Number of aircraft exits was not provided in article.
[d] Number of jumps was approximate and assumed 5 jumps per trainee. Some trainees did not complete all jumps.

Table 2. Association Between Airborne Injuries and Time of Day and Equipment Carriage on Jump

Risk Factor	Study	Conditions	No. of Aircraft Exits[a]	Risk Ratio (95% CI)[b]	Summary Risk Ratio (Summary 95% CI)	Q Statistic *P* Value	I^2 Statistic	Begg and Mazumdar Correlation (*P* Value)
Time of day (night/d)[c]	Essex-Lopresti,[25] 1946	Fixed-wing aircraft	2166/17 494	0.75 (0.51, 1.08)	1.76 (1.38, 2.25)	<.01	82	−0.11 (.36)
	Hallel and Naggan,[26] 1975	All	20 529/63 189	2.44 (2.05, 2.89)				
	Pirson and Verbiest,[28] 1985	Balloon, no equipment	9948/34 332	4.03 (1.35, 11.98)				
	Lillywhite,[30] 1991	Fixed- and rotary-wing aircraft	2196/18 412	1.44 (0.99, 2.11)				
	Kragh et al,[32] 1996	With equipment	4358/3211	1.87 (1.34, 2.63)				
	Knapik et al,[24] 2008	Fixed-wing aircraft	7664/94 524	2.25 (1.81, 2.81)				
	Deaton and Roby,[42] 2010	All	467/505	1.80 (0.43, 7.50)				
	Knapik et al,[5] 2014	All	44 128/87 619	1.76 (1.56, 1.98)				
Equipment/no equipment[d]	Pirson and Verbiest,[28] 1985	Day jumps	44 573/55 547	1.98 (1.08, 3.63)	2.60 (1.87, 3.62)	<.01	79	0.19 (.27)
	Lillywhite,[30] 1991	Fixed- and rotary-wing aircraft	23 943/3173	16.21 (5.21, 50.47)				
	Farrow,[31] 1992	All	3199/5687	4.12 (2.41, 7.04)				
	Hay,[39] 2006	All	693/682	1.97 (0.80, 4.85)				
	Knapik et al,[24] 2008	Fixed-wing aircraft	20 104/81 932	1.65 (1.38, 1.97)				
	Deaton and Roby,[42] 2010	All	385/587	4.57 (0.93, 22.54)				
	Knapik et al,[5] 2014	All	58 243/73 503	2.29 (2.02, 2.59)				

Abbreviation: CI, confidence interval.

[a] Aircraft exits (denominators) presented as night/day or equipment/no equipment.

[b] Risk ratio for time of day is calculated as night/day; for equipment, it is calculated as equipment/no equipment.

[c] Risk ratio for day jumps = 1.00.

[d] Risk ratio for jumps without equipment = 1.00.

The association between injuries and height was not clear. Greater body weight appeared to elevate the injury risk of ground landings, but the risk during water landings was not clear due to the extremely limited data. The 2 studies involving age produced contradictory results.[34,37]

Table 7 demonstrates the association between airborne-related ankle injuries and the parachute ankle brace (PAB). Not wearing the PAB almost doubled the risk of an ankle injury. The elevated risk was relatively consistent among studies, as indicated by the Q and I^2 statistics, which both suggested little heterogeneity. We noted little publication bias; the funnel plot (Figure 2E) showed the studies were generally distributed symmetrically about the pooled effect size, and the Begg and Mazumdar correlation was relatively low.

The association between airborne injuries and a variety of other potential risk factors is provided in Table 8. Parachutes with larger canopies reduced the injury risk.[5,20,28] Staggered exits from opposite sides of aircraft with 2 doors reduced injuries at altitude.[27] Exits that were not simultaneous[31] or exits from tailgates[5] reduced the injury risk. Entanglements among paratroopers substantially increased the risk of injury.[5] Students in basic airborne courses had a lower injury risk than soldiers in refresher courses or on military exercises.[26] Soldiers familiar with a parachute system tended to have a lower injury risk than those learning a new parachute system, but the number of jumps was small.[42] Military officers had a lower injury risk than enlisted soldiers.[5] The order in which paratroopers exited the aircraft had little influence on injury risk,[5] but the injury risk was higher when the number of paratroopers exiting the aircraft was greater.[30]

DISCUSSION

We found factors that increased injury risk during military static-line airborne operations, including night jumps, jumps with extra equipment, higher wind speeds, higher environmental temperatures, jumps from fixed-wing aircraft (compared with balloons and rotary-wing aircraft), jumps onto certain types of terrain, female sex, greater body weight, not using the PAB, smaller parachute canopies, and simultaneous exits from both sides of an aircraft. Other factors that appeared to increase risk but were examined in only 1 investigation included a higher heat index, winds from the rear of the aircraft, entanglements, less experience with a particular parachute system, enlisted rank (compared with officers), and jumps involving a greater number of paratroopers.

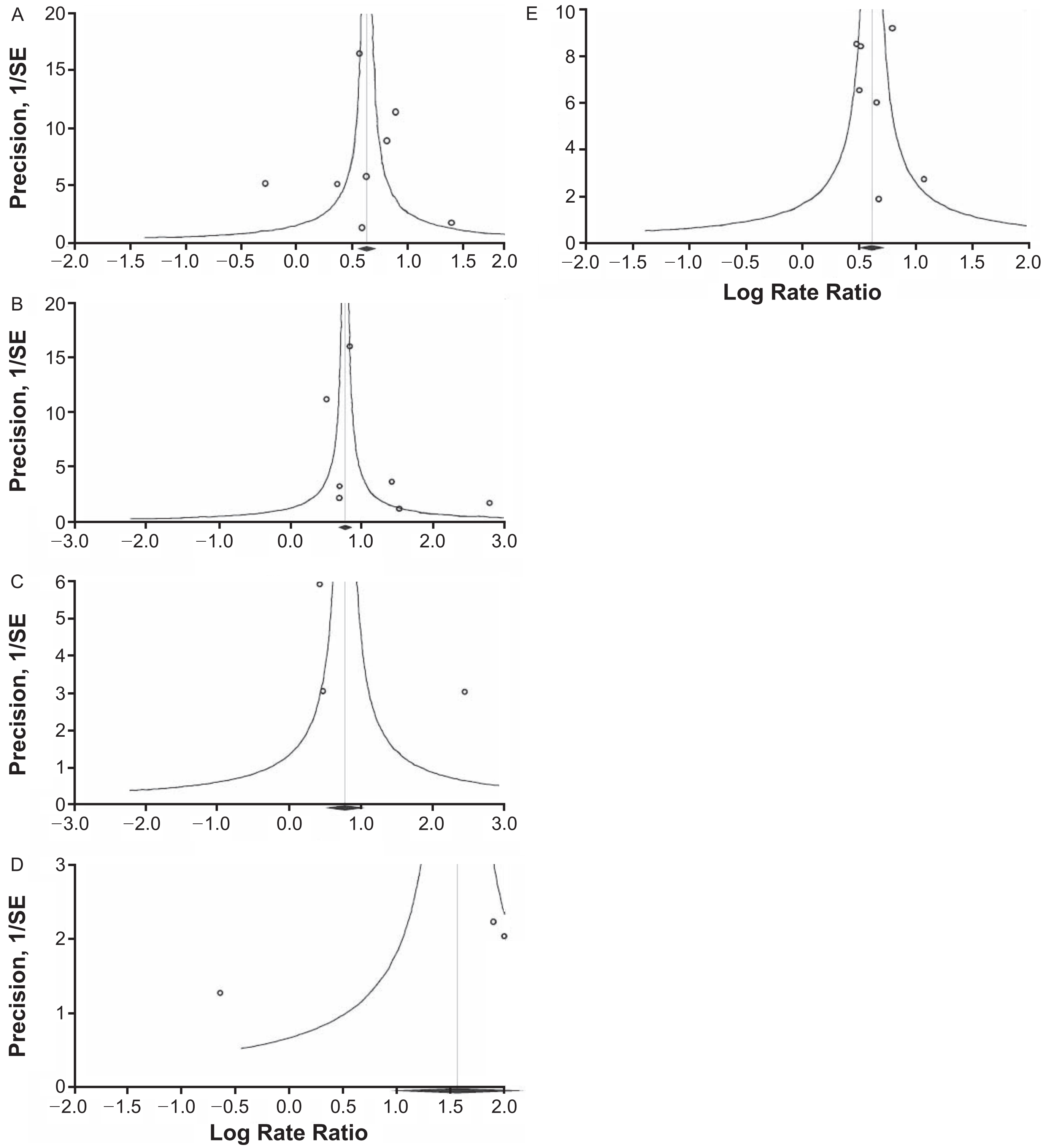

Figure 2. Funnel plots of studies involved in the meta-analyses. A, Time of day. B, Equipment. C, Fixed-wing aircraft versus balloons. D, Fixed-wing aircraft versus rotary-wing aircraft. E, Parachute ankle brace.

Night Jumps and Extra Equipment

The individual studies and meta-analyses showed that both night jumps[5,24,26,28,30,32,42] and jumps with extra equipment[5,24,28,30,31,39,42] increased the injury risk; however, considerable variability existed in the RRs of the individual studies. Publication bias was minimal, and the effects of both risk factors were very robust. In the 1 study[25] that showed little difference between day and night jumps, the author noted that the night jumps were generally conducted in "good weather conditions." In the few investigations[24,30] in which multivariate analyses were performed, both night jumps and jumps with extra equipment were independent risk factors for injury when considered with other risk factors, such as wind speed and temperature. During night jumps, individuals are less able to see the ground, perceive distance and depth, and appreciate the direction of horizontal drift. These and other factors possibly contributed to less controlled landings and a reduced ability to see obstacles on the drop zone, which may be associated with the higher injury rates.

Jumps with extra equipment typically involved loaded rucksacks, special weapons, or weapon containers.[5,24,28,31,39] This equipment can substantially increase the total weight on the parachute and result in a faster descent rate, leading to greater impact forces on ground contact that could increase injury risk.

Weather Variables

Higher wind speeds increased injury risk, and the few authors[5,24,30] who performed multivariate analysis indicated that higher wind speed was an independent risk factor for injury. Combining data from studies was not possible for reasons cited earlier (different recording methods, different strata or levels of a variable, and lack of information about the number of aircraft exits). Nonetheless, careful examination of the data suggested little difference in injury risk until wind speeds exceeded 8 to 11 knots.[5,24,30] In the US Army, airborne training operations are discontinued when winds are greater than 13 knots.[4] Wind increases horizontal drift and parachute oscillations. When horizontal velocity from drift and oscillation are added to the vertical descent velocity, ground impact forces are elevated, and landing control may be compromised; these factors may lead to a higher injury risk. Winds can push a jumper away from preplanned drop zones into obstacles, rougher terrain, or trees. High winds can also drag paratroopers on the ground after they land and before they have time to collapse their parachute canopies.

Whereas the effect of humidity was not clear, higher environmental temperatures or a higher heat index (a value calculated from temperature and humidity) modestly increased the injury risk.[5,28] In 1 multivariate analysis,[5] higher temperature was clearly an independent injury risk factor when considered with night jumps, extra equipment, wind speed, and other variables. Assuming similar humidity and barometric pressure, increases in temperature decrease air density,[46] resulting in faster parachute descent rates and greater ground impact velocities.

Lillywhite[30] reported that winds from the rear of the aircraft increased injury risk. The author hypothesized that, in this situation, aircraft-exit dynamics cause the jumper to drift backward. If the jumper does not correct the backward drift by pulling on the canopy risers, he or she will be forced into a backward landing. A backward-drifting soldier has difficulty executing proper landing procedures and is likely to impact the ground sequentially with the feet, buttocks, and head, which may lead to a higher injury risk.[30] Proper landing procedures consist of executing a parachute landing fall (PLF). Since the early 1940s, the United States and many European paratroopers have used the PLF to dissipate the forces of ground contact because it appeared to reduce the injury risk compared with earlier landing methods.[47,48] A PLF begins with the feet and knees together, toes pointed toward the ground, and knees slightly bent and rotated to the side. The upper extremities are raised with the forearms held tightly in front of the face, and the chin is tucked. As the feet contact the ground, the paratrooper rolls sideways and sequentially onto the outer side of the legs, thighs, buttocks, and trunk. The soldier then rolls onto his or her back to complete the PLF.

Aircraft

A wide variety of aircraft have been examined.[5,25,28,30,41,42] Jumps from fixed-wing aircraft appeared to have about twice the injury risk of jumps from balloons. However, Essex-Lopresti[25] noted that jumps from balloons were generally conducted "in better weather." Nonetheless, all studies[25,28,30] comparing fixed-wing aircraft with balloons demonstrated less injury risk with the balloons. Jumps from rotary-wing aircraft usually demonstrated a lower injury risk than jumps from fixed-wing aircraft in 2 studies[5,30] but not in 1 study[42] involving only 777 jumps. Jumps from rotary-wing aircraft were typically conducted at higher altitudes and off tailgates instead of out of side doors. Higher altitudes allow jumpers more time to control the canopy and prepare for ground landings. In tailgate exits, static lines are attached to cables in a way that is less likely to produce static-line injuries. More space between jumpers likely reduces entanglements and injuries at altitude.

Landing Zones

Landing-zone characteristics had a large influence on injury risk.[5,22,26,32,40,41] Jumps onto landing zones described as "rough" were about 3 times more likely to produce injuries than jumps onto sand or "flat/grassy" areas.[26,41] This was probably due to uneven ground and obstacles, such as rocks and bushes, on the rougher landing zones that make the proper execution of a PLF difficult.

Jumps onto land had about 4 times the risk of jumps into water,[40] possibly due to the shock-absorbing quality of water. However, in unplanned water landings, the possibilities of parachute entanglements and difficulties doffing heavy equipment that can pull the jumper deeper into the water also exist.[32] Two investigations[26,32] indicated that jumps onto landing strips had a higher injury risk than jumps onto "field" areas. Areas outside the narrow landing strip tend to have very uneven terrain, embankments, drainage ditches, and other hazards that may be encountered on ground contact. Landing strips are important targets for capture during airborne operations.[32]

Knapik et al[5] noted a considerably higher injury risk at a landing zone called Geronimo than other drop zones. Possible reasons were not addressed in that article[5] but were addressed in another report[20] using some of the same data. The higher injury risk was likely associated with this single operation involving a night jump and combat loads (factors known to elevate risk) onto a landing zone that was unfamiliar to a large number of participating soldiers. The fact that landing zone was not an independent risk factor for injury in either study[5,20] at least partly supports the hypothesis.

Personal Characteristics

Overall, women had a higher airborne-related injury risk than men even though men likely weighed more than women and body weight appeared to modestly elevate risk.

Table 3. Association Between Airborne Injuries and Weather Variables Continued on Next Page

Risk Factor	Study	Conditions	Weather Recording	No. of Aircraft Exits	Strata	Risk Ratio (95% Confidence Interval)[a]
Wind speed	Essex-Lopresti,[25] 1946	All	Ground level	7106	0–5 knots	1.00
				8710	6–10 knots	1.24 (0.97, 1.57)
				4558	11–15 knots	1.27 (0.96, 1.68)
				403	16–20 knots	3.30 (2.07, 5.26)
	Pirson and Verbiest,[28] 1985	All	Maximal wind speed at ground level during operation	NA[b]	1 knot	1.00[c]
					2.5 knots	1.10
					5.5 knots	1.15
					7.5 knots	1.75
					9.5 knots	2.50
					11.5 knots	2.00
					13.5 knots	3.00
					15.5 knots	4.50
	Lillywhite,[30] 1991	Fixed- and rotary-wing aircraft	Not clear	NA[b]	0–2 knots	1.00[c]
					3–5 knots	1.30
					6–8 knots	1.30
					9–11 knots	2.30
					12–13 knots	4.40
	Knapik et al,[24] 2008	Fixed-wing aircraft	Average wind speed at ground level during operation	58 904	0–1 knots	1.00
				22 705	2–5 knots	0.85 (0.65, 1.11)
				19 076	6–9 knots	1.34 (1.06, 1.70)
				2098	10–13 knots	1.86 (1.35, 2.56)
	Knapik et al,[5] 2014	All	Lowest wind speed at ground level during operation	70 036	0–1 knot	1.00
				51 801	2–5 knots	0.88 (0.77, 1.00)
				7791	6–11 knots	1.55 (1.25, 1.92)
			Highest wind speed at ground level during operation	7009	0–1 knot	1.00
				50 135	2–4 knots	0.64 (0.49, 2.84)
				45 443	5–7 knots	0.87 (0.67, 1.14)
				22 103	8–10 knots	1.17 (0.89, 1.55)
				4938	≥11 knots	1.88 (1.35, 2.61)
Temperature	Pirson and Verbiest,[28] 1985	All	Mean temperature from 1 whole h to next at ground level	NA[b]	<25°C	1.00[c]
					≥26°C	1.73
	Knapik et al,[5] 2014	All	Temperature at ground level during jumps	19 682	≤10°C	1.00
				39 478	11°C–21°C	1.08 (0.88, 1.32)
				56 161	22°C–32°C	1.17 (0.97, 1.41)
				10 334	≥33°C	1.26 (0.97, 1.64)

Table 3. Continued From Previous Page

Risk Factor	Study	Conditions	Weather Recording	No. of Aircraft Exits	Strata	Risk Ratio (95% Confidence Interval)[a]
Humidity	Pirson and Verbiest,[28] 1985	All	Mean humidity from 1 whole h to next at ground level	NA[b]	45%	1.00[c]
					55%	0.71
					65%	0.50
					75%	0.86
					85%	0.57
					95%	0.50
	Knapik et al,[5] 2014	All	Humidity at ground level during jumps	26 893	≤40%	1.00
				43 988	41%–60%	0.96 (0.81, 1.13)
				40 446	61%–80%	0.83 (0.70, 0.98)
				14 209	≥81%	0.98 (0.78, 1.21)
Heat index	Knapik et al,[5] 2014	All	Calculated from temperature and humidity at ground level[d]	21 381	≤10°C	1.00
				37 669	11°C–21°C	1.03 (0.85, 1.26)
				45 490	22°C–32°C	1.11 (0.92, 1.34)
				18 778	≥33°C	1.24 (0.99, 1.54)
Wind direction	Lillywhite,[30] 1991	Fixed- and rotary-wing aircraft	Not clear	17 844	All other	1.00
				7285	Rear	1.44 (1.17, 1.78)

Abbreviation: NA, not available.

[a] Some articles did not include 95% confidence intervals.
[b] Data for these variables were not provided in article.
[c] Risk ratios are approximate, based on extrapolations from graphs.
[d] Equation of Steadman.[45]

Table 4. Association Between Airborne Injuries and Type of Aircraft

Comparison	Study	Conditions	No. of Aircraft Exits	Aircraft	Risk Ratio (95% CI)	Summary Risk Ratio (Summary 95% CI)	Q Statistic *P* Value	I^2 Statistic	Begg and Mazumdar Correlation (*P* Value)
All aircraft	Essex-Lopresti,[25] 1946[a]	0–15-knot wind speeds[b]	810	Balloon	1.00	Fixed-wing aircraft/balloon[c] 2.99 (0.89, 9.96)	<.01	93	0.67 (.15)
			19 564	Dakota (fixed wing)	1.60 (0.83, 3.08)				
	Pirson and Verbiest,[28] 1985[a]	Day jumps	93 007	Balloon	1.00				
			65 711	C-130 Hercules (fixed wing)	1.52 (1.09, 2.13)				
	Lillywhite,[30] 1991[a]	All	7120	Balloon	1.00				
			25 093	C-130 Hercules (fixed wing)	11.54 (5.96, 22.34)				
			2023	Helicopters (types not specified)	1.56 (0.48, 5.07)				
	Neves et al,[41] 2009	All	12 925	C-130 Hercules (fixed wing)	1.00				
			803	C-115 Buffalo (fixed wing)	2.20 (1.31, 3.69)				
			2014	C-95 Bandeirante (fixed wing)	2.94 (2.14, 4.04)				
	Deaton and Roby,[42] 2010	All	503	C-130J Hercules (fixed wing)	1.00				
			267	CH-53 Sea Stallion (rotary wing)	1.87 (0.38, 9.22)				
			193	MV-22 Osprey (fixed and rotary wing)	1.71 (0.29, 10.17)				
	Knapik et al,[5] 2014	All	83 498	C-130 Hercules (fixed wing)	1.00				
			33 045	C-17 Globemaster (fixed wing)	1.06 (0.93, 1.22)				
			9051	C-23 Sherpa (fixed wing)	0.29 (0.20, 0.44)				
			2160	C-160 Transall (fixed wing)	0.46 (0.24, 0.89)				
			73	C-212 CASA Aviocar (fixed wing)	[d]				
			2667	CH-47 Chinook (rotary wing)	0.21 (0.90, 0.50)				
			1253	UH-60 Blackhawk (rotary wing)	[d]				
Fixed wing/rotary wing	Lillywhite,[30] 1991	All	2023	Helicopters (types not specified)	1.00	Fixed-wing/rotary-wing aircraft[e] 3.46 (0.91, 13.23)	.01	77	0.01 (>.99)
			25 093	C-130 Hercules (fixed wing)	7.38 (2.76, 19.74)				
	Deaton and Roby,[42] 2010	All	271	CH-53 Sea Stallion (rotary wing)	1.00				
			506	C-130J Hercules (fixed wing)	0.53 (0.11, 2.63)				
	Knapik et al,[5] 2014	All	3920	All rotary wing (CH-47, UH-60)	1.00				
			127 827	All fixed wing (C-130, C-17, C-23, C-160, C-212)	6.67 (2.78, 16.67)				

Abbreviation: CI, confidence interval.

[a] Included in the meta-analysis.

[b] No balloon jumps were conducted at wind speeds >12 knots.

[c] Risk ratio is calculated as fixed-wing aircraft/balloon.

[d] No injuries occurred with these aircraft, but the number of jumps was small.

[e] Risk ratio is calculated as fixed-wing/rotary-wing aircraft.

Table 5. Association Between Airborne Injuries and Landing Zones

Study	Conditions	No. of Aircraft Exits	Landing Zone	Risk Ratio (95% Confidence Interval)
Hallel and Naggan,[26] 1975	All	79 610	Sand dunes	1.00
		3912	"Rough"	3.19 (2.49, 4.09)
Kragh et al,[32] 1996	Day jumps	2985	"Field"	1.00
		226	Landing strip	2.37 (1.07, 5.29)
	Night jumps	2563	"Field"	1.00
		792	Airport	1.21 (0.71, 2.07)
		1003	Landing strip	2.72 (1.76, 4.67)
Kotwal et al,[22] 2004	Night jumps	1902	Paved runway	1.00
		634	Landing strip	1.7 (1.0, 2.9)
Hughes and Weinrauch,[40] 2008	All	307	Water	1.00
		247	Land	4.83 (1.70, 13.73)
Neves et al,[41] 2009	Not clear	1599	Flat/grassy	1.00
		14 151	"Rough"	2.93 (2.12, 4.06)
Knapik et al,[5] 2014	All	63 853	Sicily	1.00
		23 722	Luzon	0.68 (0.56, 0.82)
		16 393	Normandy	1.08 (0.90, 1.29)
		15 965	Holland	0.91 (0.75, 1.11)
		5887	Nijmegen	0.88 (0.65, 1.20)
		2304	Salerno	0.75 (0.45, 1.26)
		1654	Geronimo	4.16 (3.16, 5.48)
		723	Saint Mere Eglise	0.32 (0.08, 1.28)
		700	Rock	0.99 (0.44, 2.22)
		351	Gela	0.33 (0.05, 2.33)
		115	Clute	[a]
		80	Contentin	2.94 (0.72, 11.97)

[a] No injuries occurred on this landing zone.

We found no data on the actual body weights of airborne-qualified men and women, but across the entire US Army, the average body weight was 79 kg for men and 62 kg for women, with men weighing 1.27 times more than women.[49] During airborne operations, the higher injury risk for women was especially apparent for lower extremity injuries and fractures.[33] In the US Army, men and women have similar overall fracture incidences,[50] but women tend to be in military occupational specialties with lower overall injury risks.[51] When men and women performed similar activities in recruit training, women had more than twice the risk of fractures[50] and lower extremity injuries.[52] Women have a lower bone-section modulus; a lower bone-strength index (ratio of section modulus to bone length); and a thinner and narrower cortical area, which provides less bone strength.[53] These factors may increase females' susceptibility to fractures on ground impact during parachuting.

Interestingly, from 1985 to 1994, airborne injury incidences among women were declining and approaching those of men.[33] The opening to women of military occupational specialties that require regular airborne training may have influenced this trend.[33] As noted, when their physical activity is similar, women are more likely to be injured than men.[52,54] Aerobic fitness appears to account for a large portion of this difference,[55] and the aerobic-fitness level of women entering the US Army has improved over time.[56] The increase in the amount of airborne training and improvements in aerobic fitness may account for at least portions of the temporal decline in airborne injuries among women.

Height did not appear to be strongly associated with injury risk, but only Pirson and Pirlot[29] examined this variable. Trends toward a higher injury risk with increasing body weight during ground landings were suggested in the only 2 studies[29,40] examining this association. Greater body weight would result in faster descent velocities and greater forces on ground impact, which would be expected to increase the injury risk. The association between injuries and body weight in water landings is not clear.

For age, contradictory data were reported in 2 studies that used similar data from emergency department records, with 1 investigation[34] showing a higher risk in younger paratroopers and the other[37] showing a higher risk in older paratroopers. More research is needed on personal risk factors.

Parachute Ankle Brace

Use of the PAB clearly reduced the risk of ankle injuries during airborne operations. In an older systematic review focusing on the PAB, Knapik et al[57] also concluded that the PAB reduced ankle injuries, especially ankle fractures and ankle sprains. Our study updates this earlier review[57] by adding 1 investigation[43] unavailable at the time of the earlier publication. Studies involving both basic airborne students[24,35,38,43] and trained paratroopers[36] showed a reduced risk among individuals wearing the PAB. The RRs were similar among studies, as reflected by the low heterogeneity (Q and I^2 statistics), and little evidence of publication bias existed among studies. These data are consistent with research on athletes showing a reduction in ankle injury risk when an ankle brace was worn prophylactically.[58–60] The PAB likely reduces injury risk by preventing excessive ankle inversion on ground impact. Some anecdotal observations had suggested that the PAB increased the risk of lower body injuries exclusive of the ankle, but Knapik et al[24] reported that this was not the case.

Table 6. Association Between Airborne Injuries and Soldiers' Personal Characteristics

Personal Characteristic	Study	Conditions	Strata	No. of Aircraft Exits	Odds Ratio or Risk Ratio (95% Confidence Interval)[a]
Sex	Amoroso et al,[33] 1997[b]	All	Men	NA[c]	1.00
			Women		2.03 (1.39, 2.99)
	Craig and Lee,[37] 2000	All	Men	NA[c]	1.00
			Women		1.39 (1.12, 1.73)
Age	Craig and Morgan,[34] 1997	All	18–29 y	NA[c]	2.20 (1.94, 2.45)
			≥30 y		1.00
	Craig and Lee,[37] 2000	All	17–29 y	NA[c]	1.00
			30–39 y		1.35 (1.21, 1.50)
			≥40 y		1.48 (1.13, 1.93)
Body weight	Pirson and Pirlot,[29] 1990	All	58–63 kg	1265	1.00
			64–69 kg	3956	0.96 (0.31, 2.98)
			70–75 kg	4807	1.06 (0.35, 3.15)
			76–81 kg	3199	1.39 (0.46, 4.21)
			82–87 kg	1125	1.97 (0.58, 6.73)
	Hughes and Weinrauch,[40] 2008	Water landings	<70 kg	34	1.00
			71–80 kg	67	0.51 (0.07, 3.45)
			81–90 kg	96	[d]
			91–100 kg	42	[d]
			≥100 kg	8	[d]
		Ground landings	<70 kg	47	1.00
			71–80 kg	90	1.53 (0.32, 7.31)
			81–90 kg	103	1.77 (0.38, 8.01)
			91–100 kg	51	2.19 (0.44, 10.77)
			≥100 kg	16	3.87 (0.70, 21.36)
Height	Pirson and Pirlot,[29] 1990	All	162–167 cm	1288	1.00
			168–173 cm	4959	1.30 (0.38, 4.48)
			174–179 cm	5393	1.91 (0.58, 6.34)
			180–185 cm	2747	1.41 (0.38, 5.19)
			186–191 cm	656	1.31 (0.22, 7.81)

Abbreviation: NA, not available.

[a] All data are risk ratios except from Amoroso et al,[33] who reported the odds ratio.
[b] Odds ratio is for lower extremity injury.
[c] Data were not provided in the article.
[d] No injuries occurred at these body weights.

Table 7. Association Between Airborne-Related Ankle Injuries and the Parachute Ankle Brace

Study	Conditions	No. of Aircraft Exits, No PAB/PAB	Risk Ratio (95% Confidence Interval) No PAB/PAB	Summary Risk Ratio (Summary 95% Confidence Interval)	Q Statistic *P* Value	I^2 Statistic	Begg and Mazumdar Correlation (*P* Value)
Amoroso et al,[35] 1998	Fixed-wing aircraft	1849/1825	1.96 (0.68, 5.76)	1.84 (1.63, 2.08)	.34	12	0.24 (.23)
Schumacher et al,[36] 2000	All	7857/5928	2.93 (1.41, 6.10)				
Schmidt et al,[38] 2005[a]	Fixed-wing aircraft	126 603/68 140[b]	2.21 (1.78, 2.74)[c]				
		28 429/68 140[b]	1.65 (1.22, 2.24)				
Knapik et al,[24] 2008	Fixed-wing aircraft	69 323/33 461	1.92 (1.38, 2.67)				
Luippold et al,[43] 2011[a]	Fixed-wing aircraft	Not applicable[d]	1.67 (1.33, 2.13)[e]				
		Not applicable[d]	1.61 (1.28, 2.04)[e]				

Abbreviation: PAB, parachute ankle brace.

[a] Two separate time periods examined; both included here and in the meta-analysis.
[b] Assumes 5 jumps per soldier.
[c] Odds ratio was recalculated to risk ratio based on data in the article and assuming 5 jumps per soldier.
[d] Data were not provided in the article.
[e] Risk ratios were expressed as PAB/no PAB in the original article but were inverted here (no PAB/PAB) for consistency with the other studies.

Table 8. Association Between Airborne Injuries and Other Potential Risk Factors

Variable	Study	Conditions	No. of Aircraft Exits	Strata	Risk Ratio (95% Confidence Interval)	Summary Risk Ratio (Summary 95% Confidence Interval)	Q Statistic *P* Value	I^2 Statistic
Parachute type[a]	Pirson and Verbiest,[28] 1985	Day jumps, no equipment	55 530	672 (28 m^2)[a]	1.00			
			58 505	665 (22 m^2)[a]	5.19 (3.09, 8.70)			
	Knapik et al,[20] 2011[b]	Day jumps, no equipment	9351	T-11 (155 m^2)[a]	1.00	T10/T11=1.73 (1.45, 2.06)	.91	0
			21 404	T-10 (121 m^2)[a]	1.78 (1.01, 3.12)			
	Knapik et al,[5] 2014[b]	All	25 345	T-11 (155 m^2)[a]	1.00			
			106 402	T-10 (121 m^2)[a]	1.72 (1.44, 2.08)			
Aircraft exit	Hadley and Hibst,[27] 1984	All	90 894	Staggered exit[c]	1.00			
			95 823	No staggered exit[c]	5.22 (1.16, 23.53)			
	Farrow,[31] 1992	All	5524	Not simultaneous[d]	1.00			
			3362	Simultaneous	2.05 (1.25, 3.37)			
	Knapik et al,[5] 2014	All	11 762	Tailgate	1.00			
			117 579	Right/left door	3.61 (2.49, 5.21)			
Entanglement	Knapik et al,[5] 2014	All	131 713	No entanglement	1.00			
			36	Entanglement	107.02 (54.43, 210.41)			
Airborne experience	Hallel and Naggan,[26] 1975	All	52 721	Basic course	1.00			
			18 137	Refresher course	2.02 (1.30, 3.11)			
			8723	Military exercise	2.55 (1.85, 3.50)			
Parachute experience	Deaton and Roby,[42] 2010	All	611	Experienced	1.00			
			361	Inexperienced	2.82 (0.68, 11.73)			
Military rank	Knapik et al,[5] 2014	All	68 285	Junior enlisted (E1–E4)	1.00			
			43 250	Senior enlisted (E5–E9)	0.94 (0.83, 1.07)			
			1371	Warrant officer (WO1–WO5)	1.13 (0.66, 1.92)			
			15 381	Junior officers (O1–O3)	0.68 (0.55, 0.85)			
			243	Senior officers (O4–O9)	0.45 (0.06, 3.23)			
Jump order	Knapik et al,[5] 2014	All	45 677	1–10	1.00			
			39 917	11–20	0.96 (0.82, 1.10)			
			31 661	21–30	1.02 (0.87, 1.19)			
			9576	31–40	0.87 (0.68, 1.12)			
			4561	≥41	0.90 (0.64, 1.27)			
No. exiting	Lillywhite,[30] 1991	Fixed- and rotary-wing aircraft (no balloon jumps)	9977	1–22	1.00			
			11 229	23–64	1.40 (1.09, 1.79)			
			3887	65–90	2.52 (1.92, 3.30)			

[a] Number in parentheses under strata column is the reported inflated canopy area.
[b] Included in the meta-analysis.
[c] Combines high-altitude and midaltitude entanglements.
[d] Includes tailgates, single side, and balloons.

Other Injury Risk Factors

Other injury risk factors included smaller parachute canopies, certain types of aircraft exits, entanglements, military rank, and the number of paratroopers exiting the aircraft. Larger parachute canopies reduced descent velocity, which reduced ground impact forces.[5,20,28] The design of the T-11 parachute system resulted in fewer oscillations than the T-10 system, which would also reduce horizontal velocity and further reduce ground impact forces.[5,20]

The risk of injury was lower during nonsimultaneous aircraft egress, whether jumpers exited the aircraft by 1 door or off a tailgate or had 1-second staggered exits from opposite sides of the aircraft through right and left doors (eg, C-130 or C-17).[5,27,31] The reduced injury risk was at least partly due to the reduced risk of entanglements.[27] Entanglements occur when the equipment of 2 or more jumpers becomes intertwined during descent. During exits from aircraft with 2 doors, high-altitude entanglements can occur with simultaneous exits from both sides of the aircraft.[27] Whereas a 1-second delay is now required for jumps out of 2-door aircraft,[27] this timing is difficult to maintain if a jumper on 1 side rushes the door or hesitates at it. In addition to high-altitude entanglements, midaltitude entanglements (ie, after full canopy deployment) are possible if 1 jumper drifts into another or if 1 jumper's parachute is directly on top of another. In the latter case, the higher jumper can land on top of the lower parachute. During training, parachutists are instructed to pull on their parachute risers to direct their parachutes away from other jumpers. However, midaltitude entanglement may occur rapidly, and the jumper may not be aware until the situation occurs. Entanglements can substantially increase injury risk. Depending on the nature of the entanglement and the posture of the paratroopers when the entanglement occurs, the situation can result in less controlled landings on ground contact.

New airborne students appeared to have a lower injury risk than paratroopers in refresher courses or on military exercises. The lower injury risk may result from new students in basic courses better adhering to established procedures they have just learned and having training personnel thoroughly check and monitor them. The lower injury risk for officers than enlisted service members may be related to officers generally exiting the aircraft first, exiting with less equipment on equipment-loaded jumps, and not rushing to exit the aircraft before it passes beyond the drop zone. Therefore, they are more likely to make a correct and stronger exit and have more air space, a better view of the landing zone to prepare for landing, and lower ground impact velocity. In addition, officers tend to have higher educational levels than enlisted soldiers,[61] and individuals with higher educational levels may have a lower injury risk. A graded relationship appears to exist between injury-related morbidity and mortality and educational achievement or various measures of intelligence in both military[62,63] and civilian[64,65] studies. Greater educational achievement may be associated with behaviors conducive to injury prevention[66] or the ability to more effectively process information relating to risk reduction.

Injury risk appeared to be elevated if more paratroopers were exiting the aircraft. This may be associated with the fatigue induced by longer waiting times in preparation for jumps and while standing and waiting to exit the aircraft. In addition, on jumps with more paratroopers, more crowding occurs on the aircraft, leading to discomfort and difficulty maintaining staggered exits, which could result in high-altitude entanglements.[30]

Limitations

Our study had limitations. First, data were collected over a long period (68 years). Technological improvements, including developments in parachutes, aircraft, and protective devices, have occurred during this time. Second, all studies were observational cohort investigations. This type of research is invariably affected by confounders, including the technological developments that may vary among studies. Third, we limited our analysis to military operations but found that very few investigators[67,68] had quantitatively examined risk factors for parachuting outside of military operations. The analyses offer insights into risk factors that may be applicable to sport parachuting and safety (eg, smoke jumpers) and rescue operations.

CONCLUSIONS

We identified risk factors associated with military static-line airborne operations. Trainers, operators, and medical personnel should recognize and appreciate these factors and include them in their injury risk evaluations. Understanding and considering these factors during specific airborne maneuvers will increase the probability that the largest number of paratroopers will arrive safely at the battleground ready for their operational missions.

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