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Evaluation of Head and Body Kinematics Experienced During Parachute Opening Shock

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ABSTRACT

Introduction:

The U.S. Army conducts airborne operations in order to insert soldiers into combat. Military airborne operations are physically demanding activities with a unique loading environment compared with normal duties. A significant amount of research surrounding airborne operations has focused on assessing the incidence and type of associated injuries as well as the potential risk factors for injuries. During parachute opening shock and other high-acceleration events (e.g., fixed wing flight or vehicle crashes), the neck may be vulnerable to injury if inertial loads overcome the voluntary muscular control of the cervical spine and soft tissue structures. A recent epidemiological survey of sport skydivers showed that the neck, shoulders, and back were the most frequently reported sites of musculoskeletal pain. In addition, the survey indicated that wing loading (a measure of the jumper's weight divided by the size of the parachute canopy) was a potential contributing factor for developing musculoskeletal pain. Recently, there have been efforts to measure the severity of parachute opening shock as an additional potential risk factor for injury; however, no studies have measured both head and body accelerations and no studies have measured head or body angular rate during parachute opening shock. The purpose of this study was to measure and characterize the accelerations and angular rates of both the head and body during parachute opening shock as well as investigate potential factors contributing to higher severity opening shock, which may link to the development of musculoskeletal pain or injury.

Materials and Methods:

Data were collected from the U.S. Army Parachute Team, The Golden Knights, under an approved Medical Research and Material Command Institutional Review Board protocol. Subjects were instrumented with a helmet- and body-mounted sensor package, which included three angular rate sensors and three single-axis accelerometers each. Data were collected at 2,500 samples per second. Kruskal-Wallis tests were used to determine if helmet-mounted equipment (e.g., cameras), neck length, neck circumference, or wing loading (the ratio of jump weight to the size of the main parachute canopy) affected the accelerations or angular rates of the head or body.

Results:

A total of 54 jumps conducted by 19 experienced free-fall jumpers were analyzed. For the head, the mean (± SD) resultant accelerations and angular rates were 5.8 (± 1.6) *g* and 255.9 (± 74.2) degrees per second (deg/s), respectively. For the body, the resultant accelerations and angular rates were 4.3 (± 1.5) *g* and 181.3 (± 61.2) deg/s, respectively. A wing loading above 1.4 pounds per square foot (lb/ft^2) was found to have a significant effect on head ($P = .001$) and body ($P = .001$) resultant acceleration as well as body angular rate about the Y-axis ($P = .001$).

Conclusions:

There is evidence to suggest that wing loading has an influence on individual head and body resultant accelerations. However, no significant effects were found for the other variables (e.g., neck length and circumference, helmet-mounted equipment, etc.). Future research should focus on identifying additional factors that result in changes in accelerations and angular rates of the head and body during parachute opening shock events.

INTRODUCTION

The U.S. Army conducts airborne operations in order to insert soldiers into combat. Military airborne operations include static line and free-fall jumps. Military static line jumps include a minimally maneuverable parachute that is automatically deployed shortly after the soldier exits the aircraft using a tether that remains attached to the aircraft.[1] Military free-fall jumps are a more precise form of military airborne operation using a parafoil (steerable)-type parachute comparable to civilian skydiving. Military free-fall differs from civilian skydiving in the military parachutist's ability to jump from higher altitudes (supplemented with oxygen) and with additional combat equipment.[2] Military airborne operations are physically demanding activities with a unique loading environment compared with normal duties.

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To better understand the risk for injury during airborne operations, a significant amount of research has focused on assessing the incidence and type of associated injuries as well as the potential risk factors for military static line[1,3–6] or for military free-fall.[2,7,8] Epidemiological studies of both static line and free-fall jumps have stated that the extremities are typically the most commonly injured body region.[2,9] Additional body regions with increased injury prevalence include the neck,[8] head,[6] and lower back.[10] However, many of these studies only include traumatic injuries associated with a hospital visit or medical report, and they do not reflect musculoskeletal pain that may not have resulted in immediate contact with health care. Bar-Dayan et al.[10] highlighted progressive degeneration of the lower back by comparing current and past radiographs of static line and free-fall parachuting instructors. Additionally, a recent study by Nilsson et al.[11] conducted a survey of 658 Swedish skydivers to obtain epidemiological data on self-reported musculoskeletal pain resulting from parachute opening shock and identify the associated risk factors. Nilsson et al.[11] reported that the neck (25%), shoulders (16%), thoracic spine (10%), and lower back (18%) were the most frequently reported regions for pain experienced as a result of parachute opening shock. Significant independent risk factors for parachute opening shock–induced pain included a high number of jumps in the past 12 months and a wing loading above 1.4 pounds per square foot (lb/ft^2).[11] The wing loading is a ratio of the jumper's weight (in pounds) to the size of the main parachute canopy (in square feet). A potential risk factor for parachute opening shock–induced pain not evaluated by Nilsson et al.[12] is the severity (e.g., peak acceleration, angular rate, muscle activity, internal spinal forces and moments, etc.) associated with parachute opening shock exposure.

During parachute opening shock and other high-acceleration events (e.g., fixed wing flight, vehicle crashes, etc.), the neck may be vulnerable to injury if inertial loads overcome the voluntary muscular control of the cervical spine and soft tissue structures.[13–16] Studies evaluating acceleration exposure in fixed wing aircraft have linked high-acceleration exposures (2-7 *g*) to incidences of radiculopathy, myelopathy, weakness, evidence of spinal degeneration, and a decrease in spinal height.[17–19] The risk of injury and muscle strain is further increased with the addition of head-supported mass and helmet-mounted equipment.[20–22] Similar injuries have been reported in the skydiving community as a result of parachute opening shock.[13,15,23]

To better understand the human body response during free-fall jumps, a few studies have attempted to measure or estimate the exposure experienced during parachute opening shock. Prior research measuring parachute opening shock has reported that skydivers may be exposed to maximum accelerations ranging from 3 to 5 *g*[12,24] and up to 87% of maximum voluntary contraction.[16] Additionally, prior military studies have estimated that military parachutists can experience accelerations between 5 and 15 *g*.[7] Under extreme conditions (e.g., high-altitude openings), parachute opening shock has been estimated to reach up to 32 *g*.[25,26] However, these studies estimate general whole-body acceleration and do not provide an estimate of head motion and body motion during opening shock. Additionally, no prior studies have measured the angular rate of the head or body during parachute opening shock. The motion of the head and body may be a contributing factor to the high incidence of reported neck pain resulting from parachute opening shock.

The purpose of this study was to characterize the kinematics (accelerations and angular rates) of the head and body during parachute opening shock from free-fall jumps. Furthermore, because helmet-mounted equipment and wing loading have previously been described as factors that may affect parachute opening shock,[11,24] our study also investigated variables (i.e., wing loading, use of helmet-mounted equipment, anthropometry, etc.) that may influence the parachute opening shock kinematics. During parachute opening shock, improved measurement of the kinematics and awareness of factors affecting the kinematics are critical to understanding the relationship between parachute opening shock and the development of pain or injury. Custom head- and body-mounted instrumentation and an on-body acquisition system allowed us to measure real-time kinematics of the head and body throughout the entire jump sequence. This research developed and enhanced our ability to measure parachute opening shock on the jumper and is a first step to further understanding the link between the exposure and the risk for pain and injury.

METHODS

The study was conducted with a cohort of experienced free-fall jumpers from the U.S. Army Parachute Team, The Golden Knights. Data were collected under an approved Human Subjects Research Protocol reviewed and approved by the then U.S. Army Medical Research and Materiel Command (now, U.S. Army Medical Research and Development Command) Institutional Review Board. All subjects participating in the research were part of prescheduled training jumps conducted at the Team's training facility. Participation in the study was voluntary and, if desired, subjects were able to opt out at any time. Jump altitude was not controlled as a part of the study. All jumps were performed from an altitude sufficient to reach terminal velocity in free-fall. All subjects completed at least two jumps.

Subjects were recruited and consented before performing parachute operations. Effort was taken to ensure there was no command influence during the recruitment and consenting process. After subjects were consented, demographics (jump discipline, rank, time in service, career number of jumps, gender, rank, and age) and anthropometric measurements (neck length, neck circumference, height, and weight) were taken and a brief survey was administered. The survey requested information about the subjects' injury history related to spinal injuries, any current injuries that have not resulted in an inability to conduct parachute jumps, neck strengthening exercises/programs, experience as a jumper (static line, high altitude low opening, high altitude high opening, recreational skydiving, equipment used, etc.), and wing loading (the ratio of jumper weight in pounds to size of the main parachute canopy in square feet (eqn (1)).

$$WingLoading = \frac{JumperWeight\,(pounds)}{ParachuteSize\,(square\ foot)} \quad (1)$$

To measure head and body kinematics during the opening shock event, subjects were instrumented with a distributed sensor array during jumps. Additionally, jumps were recorded using an action camera (Garmin VIRB XE; Garmin International, Inc., Olathe, KS) mounted to the subject's helmet to document event timing. Cameras were time-synchronized with all instrumentation to help identify the timing of parachute opening shock events. Each subject completed at least two jumps while instrumented.

The subjects' regularly worn helmets (approved for use by the Golden Knights) were mounted with a six-degree-of-freedom instrumentation package including three angular rate sensors (DTS ARS Pro 8K) and three single axis accelerometers (Endevco 7264C). The Golden Knights' rigger team approved the instrumentation and camera weight and mounting locations. The additional instrumentation added approximately 100 g to the mass of the helmet, while the Garmin VIRB XE camera added approximately 150 g. The head kinematics instrumentation package was mounted on the exterior of the helmet at the crown and as close to the coronal and midsagittal planes as possible. While attaching instrumentation to the subject's regularly worn helmet, the research team documented the helmet type and helmet mass. In addition to helmet type, the research team also documented whether the subject used a helmet camera (separate from the Garmin provided) during their normal jump operations to document team jumps.

A custom-built nine-channel DTS Slice (Diversified Technical Solutions [DTS], Seal Beach, CA) data acquisition system (DAS) was used to record data from the helmet-mounted instrumentation. The DAS included built-in angular rate sensors and accelerometers that measured body kinematics. The cabling from the helmet-mounted sensors was attached to the DAS and secured per the riggers instructions. In order to limit false triggers resulting from exceeding a threshold early, the DAS was set to record data just before the aircraft taking off and collected until the subjects were back on the ground.

Head- and body-mounted instrumentation was oriented to measure motions with respect to the anatomical coordinate system, with positive X coming out of the front of the body, positive Y coming out of the left side of the body, and positive Z coming out of the top of the head. Rotations were also measured about the anatomical coordinate system axes—with X-axis rotations indicating lateral rotation, Y-axis rotations indicating flexion/extension, and Z-axis rotations indicating torsion or twisting along the spine.

Time-trace data recorded by the DAS (e.g., head and body kinematics) during the jump were separated into three stages, including (1) free-fall (before parachute opening shock), (2) parachute opening shock, and (3) descent (following parachute opening shock). The beginning and end of the parachute opening shock event were identified via markers in the head kinematics data as well as time-synched video analysis using the Garmin VIRB XE cameras positioned to view the body during the opening shock event.

Data were collected at 2,500 samples per second. Accelerometer data were bandpass filtered with the passband between 0.005 and 50 Hz. The low frequency (0.005 Hz) was used to remove a trend in the accelerometer data caused by temperature changes as the subjects climbed to altitude. Angular rate data remained unfiltered. Data analysis was completed in MATLAB v2018b (Mathworks, Natick, MA).

STATISTICAL ANALYSES

Descriptive statistics (mean and SD) for the head and body kinematics were calculated for all jumps performed. Additionally, statistical analyses investigating whether there was an effect from the helmet or jumper characteristics (e.g., wing loading, neck length, neck circumference) on parachute opening shock kinematics were performed. The independent variables considered for the present analyses included helmet-mounted equipment (camera or no camera), subject, jump number, neck length, neck circumference, and wing loading (split at 1.4 lb/ft^2) The dependent variables considered for analyses included head resultant acceleration, body resultant acceleration, head angular rate about the Y-axis, and body angular rate about the Y-axis.

Because of the non-normal distribution of the data, the heterogeneity of variances, and the unbalanced test matrix, the nonparametric Kruskal-Wallis test was used to determine differences in acceleration and angular rate based on the aforementioned independent variables. Multivariate regression analyses were conducted with the continuous independent variables (neck length and neck circumference) individually, and as covariates, against the dependent variables (head and body accelerations and the head and body angular rates about the Y-axis). Results were considered statistically significant at the alpha level of 0.05. All statistical analyses were completed using the statistical package R-3.6.1 (R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Data were collected from 19 subjects completing a total of 63 jumps (mean of 3 jumps per subject ranging from 2 to 9 jumps per subject). Data were analyzed from 54 jumps. All data from one subject (three jumps) and six individual jumps from four subjects were dropped because of data acquisition malfunctions experienced during the jump.

TABLE I. Subject Demographics and Parachute Characteristics

	$N = 18$[a]	Mean (SD)	Range
Subject demographics	Age (years)	31.6 (4.6)	24-41
	Height (cm)	179.3 (5.3)	166.4-187.6
	Weight (kg)	86.3 (13.4)	64.1-117.3
	Career jumps (n)	2,819 (3,556)	550-15,000
Subject anthropometry	Neck length (cm)	11.9 (1.2)	10.0-14.1
	Neck circumference (cm)	41.0 (2.3)	35.0-46.0
Parachute characteristics	Wing loading (lb/ft^2)	1.12 (0.58)	0.53-2.50
	Parachute canopy size (ft^2)	232 (94.4)	84-325

[a]Demographic data not available for one subject.

Subject demographics, anthropometry, career jumps, and parachute characteristics (mean ± SD) are reported in Table I. Helmet types included the Cookie Fuel, Cookie *g*3 (Cookie, Clontarf, Queensland, Australia), Bonehead Composites X-sport (Bonehead Composites, Perris, CA), and three specially modified camera helmets based on either the Fuel or *g*3. The mass of the standard helmets (i.e., nonmodified) ranged from 0.9 to 1.4 kg, while the mass of the camera helmets ranged from 1.8 to 2.8 kg.

The three stages of head and body kinematic data (free-fall, parachute opening shock, and descent) were separated using video footage enabling focused analysis of the data traces (Fig. 1). During free-fall, it was possible to observe head rotation about the Z-axis (e.g., looking left and right) while the subject checked surroundings and sensors. During parachute opening shock, noticeable increases in head and body angular rate and acceleration were noted. Finally, during descent, head and body kinematics were similar to the free-fall phase with evidence of head rotation while subjects checked their surroundings.

Head and body resultant accelerations were of similar magnitude with the head experiencing slightly higher peak resultant accelerations. The mean (±SD) peak resultant accelerations during parachute opening shock for the head and body were 5.8 (±1.6) and 4.3 (±1.5) *g*, respectively. The range of resultant accelerations measured was between 1.1 and 8.8 *g* for the head and between 0.4 and 7.7 *g* for the body. Likewise, head and body angular rates were similar in magnitude with the head experiencing slightly higher angular rates. The mean (±SD) angular rates for the head and body were 255.9 (±74.2) and 181.3 (±61.2) degrees per second (deg/s), respectively. Angular rates are reported about the Y-axis for head and body (motion in the sagittal plane).

Wing loading had a significant effect on head and body resultant accelerations ($P = .001$ and $P = .001$, respectively) (Fig. 2A). Average head and body resultant accelerations for subjects with a wing loading below 1.4 lb/ft^2 were 6.0 and 4.8 *g*, respectively. Average head and body resultant accelerations for wing loading of 1.4 lb/ft^2 and higher were 5.2 and 3.6 *g*, respectively. Wing loading also had a significant effect on the angular rate about the Y-axis for the body ($P = .001$) (Fig. 2B). Average body angular rate about the Y-axis for wing loading below 1.4 lb/ft^2 was 156.9 deg/s and 193.3 deg/s for wing loading of 1.4 lb/ft^2 and above. There was no significant effect of wing loading on head angular rate about the Y-axis.

Additionally, in our limited sample, other potential factors investigated to understand their influence on parachute opening shock kinematics were not found to be statistically significant. Helmet-mounted equipment, while only used during 10 out of 54 total jumps, was not found to have a significant impact on any of the dependent measures evaluated (Fig. 3). Subject anthropometry (neck length and circumference) was not found to have a significant effect on resultant acceleration or angular rate for the head or body.

DISCUSSION

The aim of this study was to evaluate the kinematic response (e.g., accelerations and angular rates) of the head and body during parachute opening shock. Additionally, the study evaluated the influence of jumper characteristics (e.g., wing loading, neck anthropometry) and helmet-mounted equipment as potential contributing factors for changes in the kinematics of parachute opening shock. Helmet-mounted equipment and wing loading were included as potential contributing factors since they have previously been described as areas affecting parachute opening shock–induced pain.[11,24] Six-degree-of-freedom motion (three axes of acceleration and three axes of angular rate) was recorded from head- and body-mounted instrumentation to document the kinematics of parachute opening shock. The peak accelerations and angular rates measured from the head-mounted sensors (5.8 *g* and 255.9 deg/s, respectively) were generally higher than the body-mounted sensors (4.3 *g* and 181.3 deg/s, respectively).

There were some limitations in the present study with regard to the instrumentation package. The instrumentation package was a novel design intended to capture both head and body accelerations and angular rates throughout the jump sequence, but particularly during parachute opening shock, using laboratory grade instrumentation and data acquisition.[27] The use of the subjects approved regularly worn helmet limited the ability to control the exact position and mounting of the helmet-mounted instrumentation. Efforts were made to document and control position where possible. Instrumentation was consistently located at the crown of the helmet on the mid-sagittal plane. Mounting instrumentation to the helmet may result in errors due to independent helmet versus head motion.[28,29] It is expected that the errors associated with relative motion of the helmet versus the head in the present study are small because of the tight coupling of the helmets used by the subjects and the type of exposure (little to no contact to the helmet forcing rotation). The body-mounted

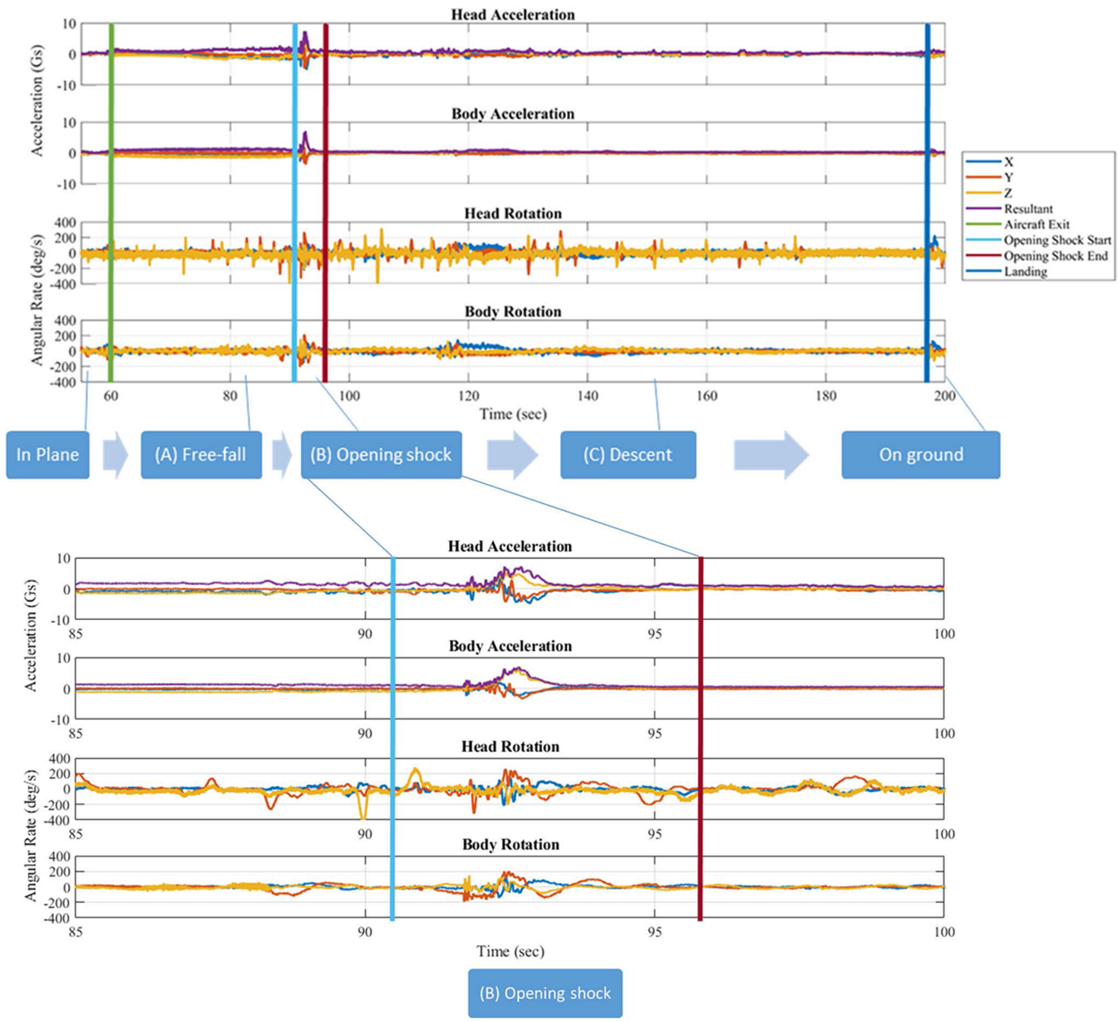

FIGURE 1. Example plot illustrating the three stages of kinematic motion during free-fall parachute operations. (A) After exiting the plane, subjects were in free-fall for 30 seconds to 1 minute, (B) followed by the parachute opening shock event (expanded in the secondary chart), and (C) finally descent to the ground. Peak accelerations occurred during the parachute opening shock event. The periodic peaks in head rotation are associated with the subjects' checking of their surroundings during free-fall and descent (confirmed in video analysis).

instrumentation was fit in a custom designed instrumentation belt strapped to the subject's abdomen near the belly button. Efforts were made to control positioning where possible; however, the parachute harness, jumpsuit fit, and subject's comfort resulted in some variation in placement. The instrumentation belt was secured under the subject's jumpsuits, which were tight fitting, aiding in securing the instrumentation package in place during the jump.

Additional study limitations included accessibility and use restrictions when working with a military population. The accessibility to subjects and limitations on changing the subjects' regularly worn helmets resulted in an unbalanced dataset with a limited sample size for comparing factors (e.g., helmet-mounted equipment) affecting the severity of parachute opening shock. It is unknown whether a more balanced dataset controlling for helmet-mounted equipment, wing loading, or subject anthropometry would have resulted in more significant findings. Additionally, the study population (The Golden Knights) was a performance and competitive skydiving team using sport parachutes, while performing solo jumps with no additional military gear. Although it is unknown whether the peak accelerations and angular rates would be similar for military free-fall jumps incorporating oxygen, body armor, standard military helmets, weapons, and equipment, the present study serves as a baseline estimate of the head and body kinematics that can occur during parachute opening shock. Military personnel may be required to jump with additional equipment or potentially a tandem load that could substantially increase the overall jump weight, wing loading ratio, and possibly increase the parachute opening shock severity. Military personnel may be required to jump from higher altitudes and open their parachute at higher altitudes than is common in sport skydiving.[2] Prior work has estimated that the severity of parachute opening shock will

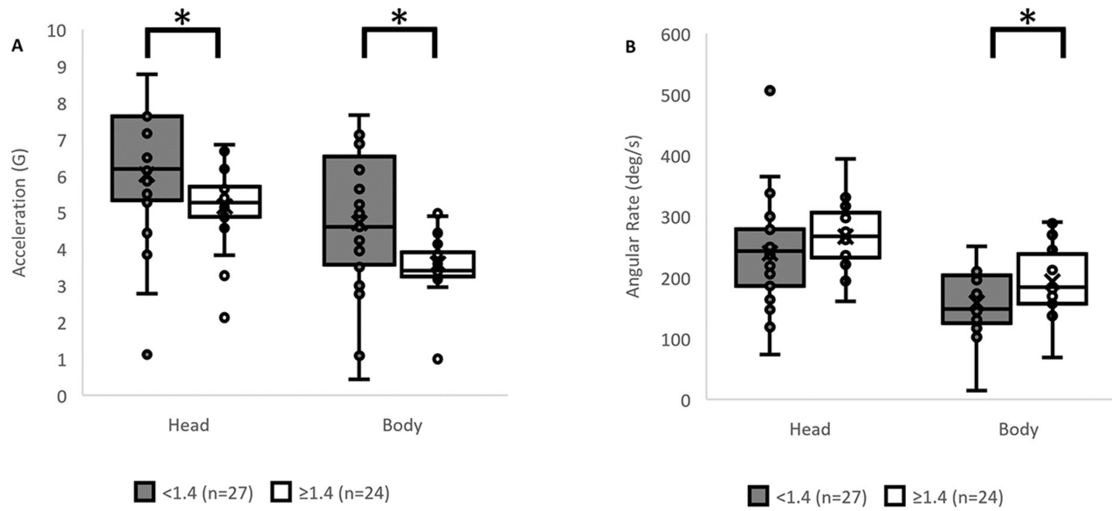

FIGURE 2. Wing loading had a significant impact on head and body resultant accelerations. A wing loading of 1.4 lb/ft^2 or higher resulted in significantly lower accelerations (A) for the head and body while resulting in significantly higher angular rate about the Y-axis (B) for the body (the head angular rate was not found to be statistically significant). Note: statistics were calculated on 51 jumps due to missing wing loading data for one jumper. * indicates significance at the alpha level of 0.05.

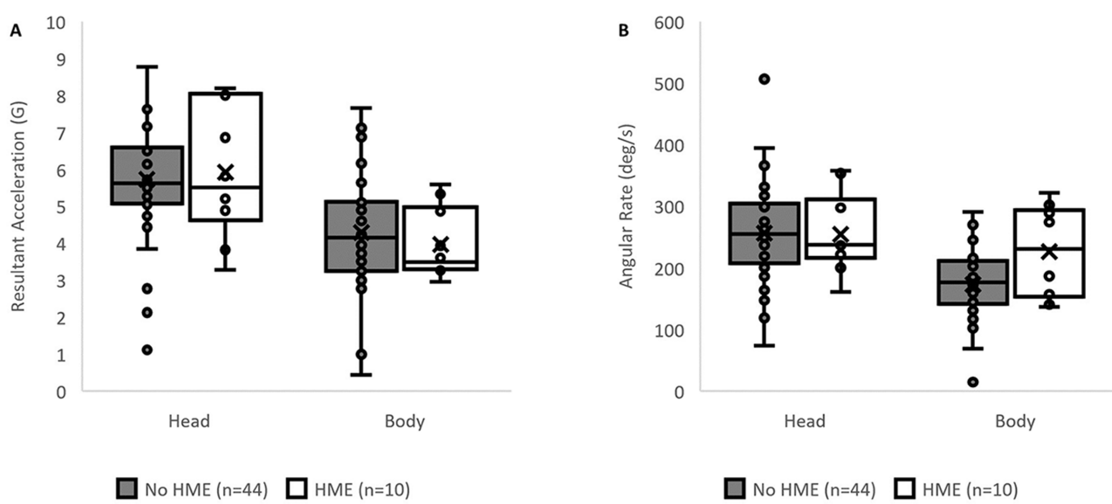

FIGURE 3. Helmet-mounted equipment (HME) was not found to have a statistically significant effect on (A) head and body resultant accelerations or (B) head and body angular rates about the Y-axis. It is expected that the unbalanced number of jumps performed with ($n = 10$) versus without ($n = 44$) HME likely influenced the statistical results.

increase when the parachute opening occurs at higher altitudes.[25,26] Further work is required to fully characterize the parachute opening shock kinematics in military operational environments.

The resultant body accelerations (4.3 ± 1.5 g) recorded in the current study are comparable to previously reported body accelerations (3.2-4.0 g) from Gladh et al.[24] The accelerations recorded by Gladh et al.[12] were measured using a sensor package mounted on the subject between the first and third thoracic vertebrae versus the lower abdomen in the current study. The study by Gladh et al.[24] included a narrower range of canopy sizes (71-150 ft^2) and wing loadings (1.19-2.39 lb/ft^2) than the present study (Table I). No prior studies, to the author's knowledge, have measured both head and body kinematics during parachute opening shock. This study directly addresses the need to collect head kinematics raised by Gladh et al.[24] to aid in understanding the effects on the cervical spine. Additionally, no prior studies have measured and reported the angular rates measured from the head and body during parachute opening shock.

There are many factors that may affect parachute opening shock kinematics and severity. The relationship between canopy size (a factor in wing loading), descent rate, and parachute opening shock severity (in terms of parachute inflation mechanics) has been previously described in an online published white paper by Potvin and Peek.[30] Under normal openings, it is proposed that smaller parachutes (likely resulting in higher wing loading) would have higher severity opening shock compared to large parachutes. Whereas, during hard openings (typically caused by rapid inflation of the canopy), it is proposed that larger parachutes would have higher severity opening shock. The frequency of hard openings is not provided; however, anecdotal reports suggest that smaller canopies have more frequent and less predictable hard openings.[30] The focus of the white paper published by Potvin and Peek[30] is geared toward canopy performance and parachute inflation. It does not discuss the resulting human response resulting from parachute opening shock. Recent studies have started to investigate the relationship between parachute opening shock and effects on the musculoskeletal system.[11,16,24] In a study performing a survey of parachute opening shock–induced pain in Scandinavian skydivers, Nilsson et al.[11] noted that skydiving with a wing loading greater than 1.4 lb/ft^2 was associated with an increased risk for neck pain. Findings as reported in literature as well as this study suggest complex interactions between exposure and resulting neck pain. While not proven, parachute opening shock–induced neck pain may be the result of multiple normal openings at a slightly higher severity rather than single hard openings. Additional research is required to investigate this hypothesis. Additionally, while not significant in the final model, helmet-mounted equipment is discussed as a factor that may contribute to parachute opening shock–induced pain.[11]

In the present study, wing loading was found to have a statistically significant effect on resultant head and body acceleration as well as body angular rate. Jumps with wing loading equal to or above 1.4 lb/ft^2 had lower peak head and body resultant accelerations, but higher body angular rates about the Y-axis (Fig. 2). Although the head angular rate difference was not statistically significant, it did follow the same trend as the body angular rate (higher peaks for wing loading above 1.4 lb/ft^2). Wing loading was treated as a categorical variable with a split at 1.4 lb/ft^2 based on the results from Nilsson et al.[11] Helmet-mounted equipment and neck anthropometry were not found to have a statistically significant effect on the parachute opening shock kinematics. The lack of significant findings for helmet-mounted equipment is likely due to the unbalanced and limited dataset (only 10 jumps performed with helmet-mounted equipment compared to 44 performed without) as well as the wide range of peak responses observed during the jumps with helmet-mounted equipment (Fig. 3). Additionally, it is possible that other indicators of parachute opening shock severity (e.g., muscle activity, relative head versus body motion, internal spinal loads) may be more sensitive to changes in helmet-mounted equipment and anthropometry.

The differing response of the head and body accelerations compared to the angular rates with respect to wing loading was unexpected and may indicate that additional measures are needed to quantify parachute opening shock severity and the associated musculoskeletal injury risk. Although this paper only reported on the parachute opening shock kinematics, the data were collected as part of a larger study that included additional physiological measures of parachute opening shock severity (e.g., muscle activity) as well as pre- and post-jump physiological measures (e.g., cervical range of motion, muscle strength, and H-reflex) that may aid in further understanding the risk factors and mechanisms for parachute opening shock–induced neck pain.

The current study describes parachute opening shock in terms of head and body kinematics as well as investigating potential factors influencing the severity of the exposure. Kinematic results for the body were comparable to prior published accelerations.[12,24] There is evidence from this study to suggest that wing loading has an influence on individual head and body resultant accelerations and angular rates, and may contribute to the risk for parachute opening shock–induced neck pain. However, how the measured parachute opening shock kinematics relate to spinal degradation over a career of multiple jumps requires further study. Similarly, the effects of the number and frequency of normal as well as hard openings over a career as well as the effects of hard landings are unknown. Additional work investigating factors influencing parachute opening shock severity are needed to identify areas that can be leveraged to reduce exposure and potential concerns over injury. Future research should focus on identifying factors (e.g., military equipment, jump altitude, helmet characteristics, wing loading, etc.) that result in higher accelerations and angular rates of the head and body during parachute opening shock events. Additionally, future research focusing on changes in physiological responses over a period of time and the frequency and severity of parachute opening shock is required to understand the relationship between parachute opening shock severity and subacute (i.e., non-catastrophic) injury likely to contribute to chronic injury and pain.

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SUPPLEMENTARY MATERIAL

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CONFLICT OF INTEREST STATEMENT

None declared.

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