Decelerations of Parachute Opening Shock in Skydivers

Kristofer Gladh; Riccardo Lo Martire; Björn O. Äng; Peter Lindholm; Jenny Nilsson; Anton Westman

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INTRODUCTION: High prevalence of neck pain among skydivers is related to parachute opening shock (POS) exposure, but few investigations of POS deceleration have been made. Existing data incorporate equipment movements, limiting its representability of skydiver deceleration. This study aims to describe POS decelerations and compare human- with equipment-attached data.

METHODS: Wearing two triaxial accelerometers placed on the skydiver (neck-sensor) and equipment (rig-sensor), 20 participants made 2 skydives each. Due to technical issues, data from 35 skydives made by 19 participants were collected. Missing data were replaced using data substitution techniques. Acceleration axes were defined as posterior to anterior ($+\boldsymbol{a}_x$), lateral right ($+\boldsymbol{a}_y$), and caudal to cranial ($+\boldsymbol{a}_z$). Deceleration magnitude [a_{max} (G)] and jerks ($G \cdot s^{-1}$) during POS were analyzed.

RESULTS: Two distinct phases related to skydiver positioning and acceleration direction were observed: 1) the x-phase (characterized by $-\boldsymbol{a}_x$, rotating the skydiver); and 2) the z-phase (characterized by $+\boldsymbol{a}_z$, skydiver vertically oriented). Compared to the rig-sensor, the neck-sensor yielded lower a_{max} (3.16 G vs. 6.96 G) and jerk (56.3 $G \cdot s^{-1}$ vs. 149.0 $G \cdot s^{-1}$) during the x-phase, and lower jerk (27.7 $G \cdot s^{-1}$ vs. 54.5 $G \cdot s^{-1}$) during the z-phase.

DISCUSSION: The identified phases during POS should be considered in future neck pain preventive strategies. Accelerometer data differed, suggesting human-placed accelerometry to be more valid for measuring human acceleration.

KEYWORDS: accelerometry, biomechanics, G-force, neck pain.

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Skydiving is a major air sport performed under unique conditions. Typically, the practitioner jumps out of an airplane at 4000 m (13,000 ft) above ground level and accelerates in free fall, reaching terminal speeds of >200 km/h.[31] A ram-air parachute is deployed, reducing the falling speed to circa 20 km/h within seconds. This abrupt deceleration is referred to as parachute opening shock (POS) and is suggested to reach average magnitudes of 3–6 times the Earth's gravitational acceleration (3–6 G),[6,23] with occasional hard openings of 9–12 G reported.[23] POS decelerations have been suggested to cause strain on the neck[19,21] and traumatic neck injuries obtained during POS have been reported.[7,19,32] A recent epidemiological study revealed an elevated 1-yr prevalence of self-reported musculoskeletal neck pain among Swedish skydivers, where 25% of respondents ascribed their pain directly to POS.[21] Jumping with a high bodyweight to canopy size ratio (wing loading) and having made >90 skydives over the past 12 mo were identified as independent risk factors for neck pain.[21] This seems reasonable since skydiving is highly repetitive—athletes often perform several hundred jumps/season, performing up to 10 skydives a day.[29] In comparison, neck pain is common among fighter pilots who are repeatedly exposed to similar G magnitudes as those suggested for skydivers.[3] A survey study of the effect of cumulative acceleration exposure on neck pain among fighter pilots found that exposure frequency and duration of accelerations of 2–9 G positively correlate with frequency and severity of neck pain episodes.[14] Such acceleration exposures are believed sufficient to cause accumulated microtraumas to the cervical structures.[10] Frequency of exposure to acceleration within the same G-level range is a known risk factor for neck pain among skydivers as well, although the comparison is limited due to differing acceleration profiles and the fact that pilots are seated in chairs with backrest. The literature on POS deceleration is scarce. The biomechanical load induced

From the Department of Neurobiology, Care Sciences and Society, Karolinska Institutet, Karolinska University Hospital, Huddinge, Sweden; the Department of Anesthesia and Intensive Care Medicine, Karolinska University Hospital, Huddinge, Sweden; the Centre for Clinical Research Dalarna and the School of Education, Health and Social Studies, Falun, Sweden.

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Address correspondence to: Kristofer Gladh, Department of Neurobiology, Care Sciences and Society, Division of Physiotherapy, Karolinska Institutet, Alfred Nobels allé 23 100, SE-141 83 Huddinge, Sweden; kristofer.gladh@gmail.com.

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by acceleration depends on characteristics such as vector direction, magnitude, and duration.[5] Another variable of potential interest is the level of deceleration jerks (rate of change of acceleration). In automobile side collisions, high jerks have been shown to cause greater head flails and higher reflex-induced antagonist muscle responses compared to low jerks, suggesting an increased risk of whiplash injury during motor vehicle accidents.[35] To date, POS deceleration magnitudes have only been addressed either unreferenced,[6] or without describing data collection and/or management procedures.[23] Since reported data originates from load cells in the equipment risers measuring force, no information regarding direction of deceleration is provided.[23,24] Further, since human biological tissues are viscoelastic and deform under external force,[34] equipment-based data may be questioned as whether it reflects actual skydiver deceleration, especially during high jerks, subjecting tissues to large amounts of energy per time unit. Results from our pilot study of POS decelerations from eight skydives indicated differences between accelerometers placed on the equipment rig and on the skydiver,[9] but need to be confirmed by data from a larger sample.

The aim of this paper was to describe the characteristics of deceleration during POS and to evaluate the influence of accelerometer placement on the skydiver vs. equipment. Based on the results from our preliminary study, we hypothesized that accelerometers placed on the skydiver would yield lower deceleration magnitude and jerk figures.

METHODS

Subjects

In this observational study, 20 experienced skydivers were included: 15 men and 5 women, who were recruited through mailing lists for skydiving instructors and through personal communication. Subject demography and skydiving-related background information were collected using an online questionnaire validated for use in Swedish skydivers,[22] and are described by mean (standard deviation, min-max). For male and female participants, height was 1.81 (0.05, 1.70–1.92) m and 1.66 (0.04, 1.63–1.72) m, respectively, and weight was 82 (10, 61–97) kg and 64 (5, 57–67) kg. Mean age of all participants was 36 (6, 25–50) yr, parachute canopy size 111 (22.0, 71–150) ft^2, wing loading 1.78 (0.36, 1.19–2.39) lb/ft^2, helmet weight 0.68 (0.16, 0.25–0.91) kg, skydives made the past 12 mo were 158 (124, 10–500), and skydives made to date were 1908 (1196, 445–5000).

Criteria for inclusion were an age of 18–60 yr and an active membership in the Swedish Parachute Association with a valid D-license, i.e., the highest degree of skydiving license. Criteria for exclusion were ongoing neck problems, pregnancy, known patch allergy, and unwillingness to follow special safety regulations imposed for this study. The participants submitted written consent and were informed that collected data would be instantly anonymized, and that they could withdraw from the study at any time. This study was approved in advance by the Regional Medical Research Ethics Committee, Stockholm (2013/163-31/4).

Equipment

The equipment setup used was designed to record accelerometry and surface electromyography during POS, and has previously been evaluated regarding subject safety and data quality.[9] The accelerometric data was sampled at 1000 Hz by two triaxial capacitive microelectronic mechanical system accelerometers (ADXL210, Analog Devices, MA; ± 10 G range, 8–500 Hz bandwidth) connected to the Biomonitor ME6000 system (Mega Muscle Tester, Mega Electronics Ltd, Kuopio, Finland). Neck muscle activity was simultaneously recorded using surface electromyography, but was presented elsewhere.[18] The first accelerometer was placed on the equipment, inserted and fixed inside a special bag fastened to the right shoulder strap of the rig (rig-sensor), and the second accelerometer was placed on the skydiver, fixed with strong tape just below the cervicothoracic junction over vertebrae T1–T3 (neck-sensor).[9]

The participants wore a specific elastic two-layer torso-piece suit covering all devices and cables of the monitor system. All cables were attached with strong tape before being assembled proximally along the left thigh and connected to the logger. The logger, placed in a portable case, was attached laterally to the left leg just above the knee with three straps. Falling speed and altitude were logged with a barometric altimeter (Altimaster Neptune III v. 6.0.2, Alti-2, Inc., DeLand, FL). A small video camera (GoPro Hero2, Woodman Labs, San Francisco, CA) with a separate safety cutaway system and sampling rate of 100 frames per second was attached around the subject's waist with the purpose of documenting the parachute opening. Before the subject went airborne, the setup as a whole was examined and cleared for skydiving by the jump leader present at the local drop zone.

Except for the measuring setup, the participants executed the skydives wearing their own personal skydiving equipment. The parachute models used in this trial were: Velocity ($N = 4$), Stiletto ($N = 1$), Spectre ($N = 3$), Sabre 1 ($N = 2$), Katana ($N = 2$) (all manufactured by Performance Designs, DeLand, FL), JFX ($N = 1$), Crossfire 2 ($N = 3$) (both manufactured by NZ Aerosports Ltd, Auckland, New Zealand), Electra ($N = 1$) (Zodiac Aerospace, Plaisir Cedex, France), Impulse ($N = 1$) (Atair Aerodynamics, Skofja Loka, Slovenia), Sensei ($N = 1$) (Aerodyne Research, DeLand, FL), and Neos ($N = 1$) (Icarus, Pinebluff, NC).

Procedure

All parachutes were packed according to the participants' usual preference. The participants received instructions to perform the parachute deployment and undergo POS according to their normal routine. To increase data stability, all participants were scheduled for two consecutive skydives. The participants jumped from a mean (SD) altitude of 3872 (244) m [12,703 (801) ft] above ground level, descended in a standard belly-down position, and reached a terminal falling speed of 210 (7) km/h. Parachutes were deployed at an altitude of 1320 (127) m [4331 (417) ft] above ground level. After POS deceleration, the skydivers reached a steady descent speed of 29 (6) km/h. A

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trained physician and experienced skydiver accompanied the participants in-air during the trial wearing a helmet-mounted camera (GoPro, Hero 2, HD 2-14, Woodman Labs) to document the participants' body position during deployment.

Statistical Analysis

According to a standard international human coordination system for linear motion,[8] frontal deceleration along the coronal axis was denoted $+\boldsymbol{a}_x$, deceleration to the right along the sagittal axis was denoted $+\boldsymbol{a}_y$, and cranial deceleration along the transverse axis was denoted $+\boldsymbol{a}_z$. Deceleration magnitudes were calculated using Pythagoras' theorem:

$$a = \sqrt{\left(\boldsymbol{a}_x^2 + \boldsymbol{a}_y^2 + \boldsymbol{a}_z^2\right)}$$

where the scalar a represents the resultant magnitude from decelerations in $\boldsymbol{a}_x$, $\boldsymbol{a}_y$, and $\boldsymbol{a}_z$ at each data point, representing 1 ms. The duration of POS was determined by identifying deceleration onset and offset, set by consensus between two independent examiners (agreements for blinded assessments before forming consensus: $ICC_{2.1} = 0.99$) using a visual detection method frequently used for EMG onset detection.[12] Subsequently, the amount of deceleration from each axis ($\boldsymbol{a}_x$, $\boldsymbol{a}_y$, and $\boldsymbol{a}_z$) in percentage of total deceleration a, averaged over POS, were calculated and denoted $\%a$ using the following formula:

$$\%a = \frac{1}{T} \cdot \sum_{i=1}^{\text{offset}} \left(\frac{\boldsymbol{a}_{j_i}^2}{a_i^2}\right)$$

where T is the duration of POS and $\boldsymbol{a}_j$ represents values of either $\boldsymbol{a}_x$, $\boldsymbol{a}_y$, or $\boldsymbol{a}_z$. The $\boldsymbol{a}_{j1}$ and a_1 represent the corresponding values at POS onset while $\boldsymbol{a}_{j\ \text{offset}}$ and a_{offset} represent the values at POS offset. Before extraction of remaining outcome measures, the raw data was filtered digitally with a moving average of 0.1 s. Remaining variables were average deceleration amplitude in $\boldsymbol{a}_x$, $\boldsymbol{a}_y$, and $\boldsymbol{a}_z$ (G), deceleration total magnitude denoted a_{max} (G), and maximum and average deceleration jerk denoted $jerk_{max}$ and $jerk_{avg}$ ($G \cdot s^{-1}$), respectively. Jerks were calculated as:

$$a(t) = da/dt$$

where $a(t)$ represents the differential coefficient of a over the time period t. $Jerk_{max}$ was calculated numerically for each pair of consecutive data points (t = 1), while for $jerk_{avg}$ t equaled the time period spanning from POS onset to the time of the highest deceleration during the initial peak. The $jerk_{avg}$ has previously been identified during early POS as a potential point of interest.[9]

Due to logistical and weather issues, three participants made only one skydive whereof one participant used only the rig-sensor. Following technical complications, accelerometer data was missing entirely for another subject, who was excluded from the study. Thus data from 35 skydives performed by 19 participants were included in the analysis. Missing data was assessed in a missing value analysis (SPSS 22.0, IBM, Armonk, NY), which supported that data was missing at random (Little's MCAR test: $P > 0.41$), and replaced using an EM-algorithm.[27] Due to a non-normal distribution in some data matrices and heterogeneity of variance (mainly in rig-sensor data), the data set was log-transformed before statistical analysis. The repeated-measures analysis of variance (ANOVA) was used to test statistical differences between jumps and sensor placement for a_{max} and jerk, respectively. Instead of just averaging the measures from both jumps of each participant before the analysis, assuming the jumps were similar, jump was added as a factor in the model. Tukey´s HSD test was used for post hoc analysis. A P-value below 0.05 was considered statistically significant. The results were unlogged before presentation to facilitate their interpretation. Effect sizes (ES) were calculated using Cohen's d[4] and interpreted as: 0.20–0.49 = small, 0.5–0.79 = medium, and 0.8 and greater = large.[17]

RESULTS

According to video footage and accelerometer data, all participants entered POS with a horizontal body alignment and were exposed to a distinct initial decelerating jerk in $-\boldsymbol{a}_x$ that rotated the skydiver backward to an upright feet-down body position (**Fig. 1**). Body rotation was detectable in the data as a short initial $-\boldsymbol{a}_x$ jerk that subsequently decreased toward 0 G while $\boldsymbol{a}_z$ synchronously rose until a form of steady state was observed for both axes (Fig. 1 and **Fig. 2**). This steady state—the end of the rotation—was used to define the temporal transition between two phases of POS, denoted the x-phase and the z-phase (Fig. 1). The end of the z-phase was determined visually as a returned to about 1 G when POS ended and the skydiver started to descend steadily. The mean duration (95% CI) for the x-phase was 0.58 s (0.54–0.63) and for the z-phase 2.90 s (2.67–3.15).

During the x-phase, the main part of the neck-sensor deceleration occurred in $\boldsymbol{a}_x$, while deceleration from the rig-sensor was more evenly distributed (**Table I**). During the z-phase, deceleration in $\boldsymbol{a}_z$ was dominant for both accelerometers. Since the direction of deceleration affects the neck biomechanics, phases were described separately and added as a factor in the ANOVA model (3-way ANOVA: jump, sensor, and phase) for within and between sensor comparisons.

No significant effects emerged for any outcome containing Jump as an independent factor (main effects for a_{max}; $F_{1,36} = 4.1$, $P = 0.052$; $jerk_{max}$: $F_{1,36} = 2.9$, $P = 0.096$; $jerk_{avg}$: $F_{1,36} = 0.5$, $P = 0.476$). Regarding data on a_{max}, ANOVA showed significant interaction effects for Sensor*Phase (**Table II**, **Fig. 3**). During the x-phase, the neck-sensor showed lower a_{max} than the rig-sensor (3.16 G vs. 6.96 G, $P < 0.001$, ES = 5.54), while no such differences emerged in the z-phase (4.04 G vs. 4.61 G, $P = 0.065$, ES = 0.74). Phase comparisons yielded somewhat lower a_{max} for the neck-sensor during the x-phase compared to the following z-phase, while the rig-sensor showed higher values in the x-phase compared to the z-phase (Table II).

The ANOVA of $jerk_{max}$ showed significant interaction effects for Sensor*Phase (Table II, **Fig. 4**). The neck-sensor showed lower $jerk_{max}$ than the rig-sensor in both the x-phase ($56.3\ G \cdot s^{-1}$ vs. $149.0\ G \cdot s^{-1}$, $P < 0.001$, ES = 3.35) and the z-phase ($27.7\ G \cdot s^{-1}$ vs. $54.5\ G \cdot s^{-1}$, $P < 0.001$, ES = 2.25). Phase

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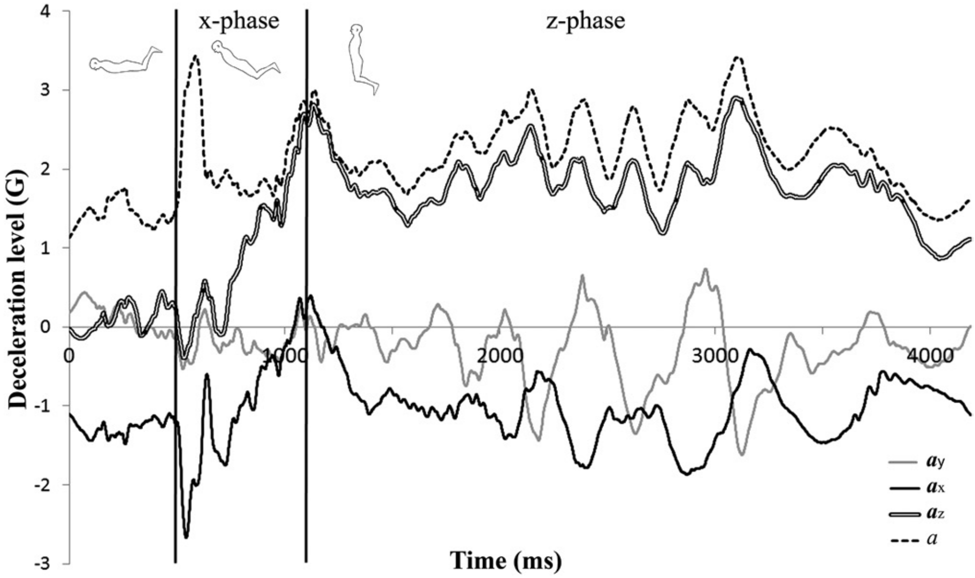

Fig. 1. An example graph of a typical skydive showing three-dimensional acceleration data from the neck-sensor along with the resultant deceleration. The temporal definitions of the x-phase and the z-phase are demonstrated and phases marked out to the reader. Deceleration level is shown on the y-axis, and time (ms) on the x-axis.

comparisons yielded significantly higher jerk_{max} in the x-phase compared to the z-phase for both accelerometers (Table II, Fig. 4). The ANOVA of jerk_{avg} showed significant main effects for Sensor, where the neck-sensor showed lower values than the rig-sensor ($19.3\ G \cdot s^{-1}$ vs. $55.6\ G \cdot s^{-1}$, ES = 3.80) (Table II).

DISCUSSION

The aim of this study was to describe the characteristics of POS deceleration and to evaluate the influence of accelerometer placement (skydiver vs. equipment) on deceleration data. Two distinct phases were observed during POS and defined by skydiver body orientation: the first as the x-phase with rotational kinematics and deceleration in $-\boldsymbol{a}_x$; and the second as the subsequent z-phase with constant upright body alignment and deceleration in $+\boldsymbol{a}_z$. In line with our hypothesis, the neck-sensor showed consistently lower magnitude (a_{max}) and jerk values than the rig-sensor, and both accelerometer sensors showed higher jerks during the x-phase compared to the z-phase.

The participants were recruited from different regional skydiving clubs and reflected the gender distribution (5 women, 15 men) in the skydiving population.[33] In order to maintain ecological validity, the participants used their own equipment and parachutes were packed according to the participants' preferences. Moreover, the protocol contained a typical skydiving exit altitude [mean 3872 m (12,703 ft)] and typical POS deployment altitude [mean 1320 m (4331 ft) - slightly elevated for safety reasons]. Due to the D-license inclusion criteria, the generalization of results is limited to experienced skydivers. The participants had a high mean wing loading (1.78 lb/ft^2) and had performed a large amount of skydives during the past year (mean 158), within levels found to be risk factors for neck pain.[21] Thus, results extend to experienced skydivers using small canopies, a group more likely to be exposed to POS in hazardous amounts than other skydivers.

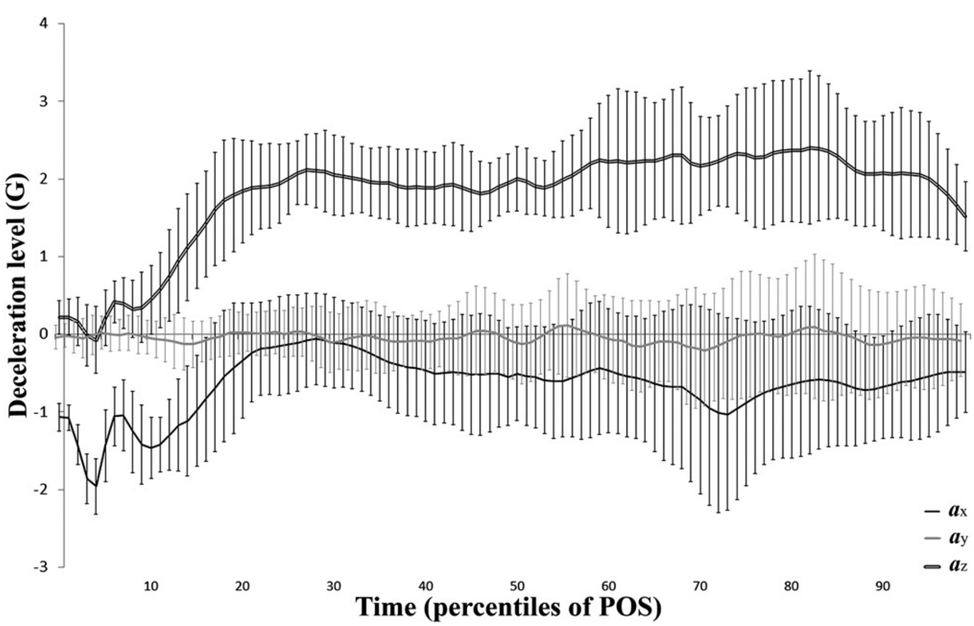

Fig. 2. Continuous directional deceleration data normalized to 100 percentiles of POS duration presented as mean (95% CI) for each percentile. Deceleration level (G) is shown on the y-axis and time (percentiles of POS) on the x-axis. Y-axis marks deceleration onset.

Since gender has not emerged as a risk factor for neck pain related to POS in previous research,[21] data was not analyzed for gender differences. Accelerometers and cables were attached firmly with minimal movement or stretch/entanglement possibilities, which reduced noise related to setup design. Deceleration exposure of the neck-region was accurately measured by the neck-sensor aligned with the cervico-thoracic spine at the T1 level, where muscle activity was shown to be highest during POS.[18] However, due to normal cervico-thoracic kyphosis of the spine,

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Table I. Descriptive Results from Each Axis (x, y, and z) and Percentage of Total Deceleration Averaged Over Each Phase.

	X-PHASE		Z-PHASE	
	MEAN (SD)	**% *a***	**MEAN (SD)**	**% *a***
Neck				
Avg a_x (G)	−1.30 (0.18)	64.6	−0.55 (0.58)	16.4
Avg a_y (G)	−0.00 (0.15)	8.9	−0.01 (0.22)	6.3
Avg a_z (G)	0.60 (0.29)	26.5	2.08 (0.28)	77.3
Rig				
Avg a_x (G)	−0.94 (0.29)	30.0	−0.07 (0.16)	12.4
Avg a_y (G)	0.18 (0.55)	25.9	−0.04 (0.24)	16.4
Avg a_z (G)	1.19 (0.16)	44.1	2.20 (0.30)	71.2

the neck-sensor generally became slightly more inclined than the rig-sensor. This biased accelerometer comparisons regarding $\boldsymbol{a}_x$ and $\boldsymbol{a}_z$ variables (visible in Fig. 2 as $\boldsymbol{a}_x$ is < 0 G in the z-phase), motivating a descriptive approach of such data.

The difference in a_{max} and jerk values between accelerometers found during the x-phase may be explained by a sudden deceleration of the harness (confirmed by video data) before reaching compliance with the human body. Further rig movement was visible during the parachute inflation, especially during early pressurization before slider descent, which may explain the high variance found in rig-sensor data compared to the neck-sensor. To avoid such signal contamination in future studies focusing on human deceleration, we recommend accelerometers to be placed on the human. The mean a_{max} levels from the neck-sensor found in this study are within the previously suggested range of 3–5 G.[6] Researchers have studied POS decelerations of military parachutists and found decelerations ranging from +5 G_z to +15 G_z.[26] However, paratroopers often wear full battle gear and use parachutes like the circular T-10 or modified cruciform T-11 models,[16] which differ in design and are deployed at different altitudes and speeds compared to the ram-air parachutes used in skydiving,[2,6] resulting in different wing loadings and opening characteristics.

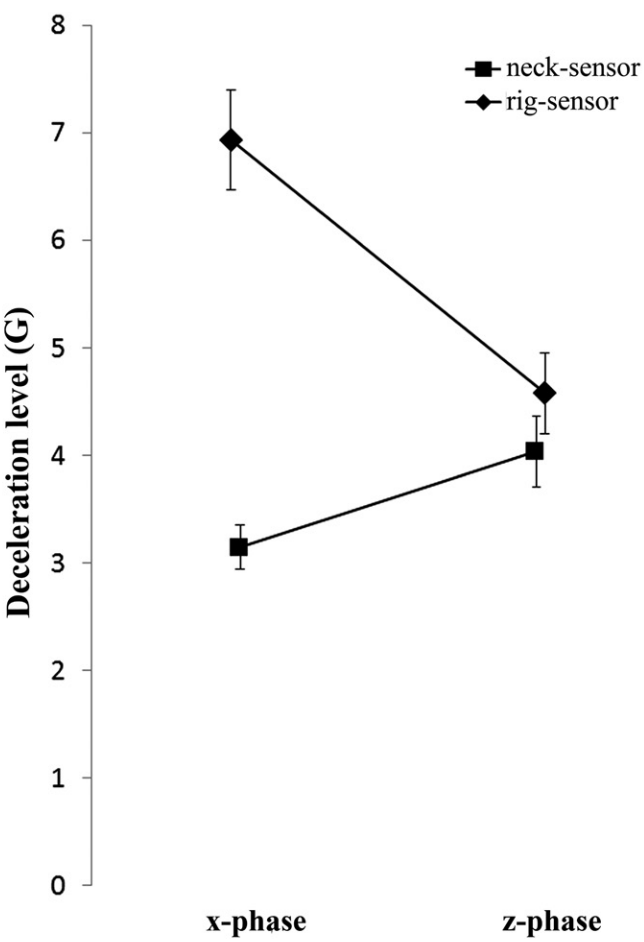

Fig. 3. Deceleration maximum for the neck- and rig-sensor. Deceleration level is shown on the y-axis and POS phase on the x-axis.

While POS-deceleration data from ram-air parachutes is presently absent in the literature, canopy drag-forces have been studied extensively.[24,25] Mathematical models have been presented and validated by experimental data acquired from load cells integrated in the risers of the skydiving equipment.[25] POS drag-force curves are somewhat similar in shape to our $\boldsymbol{a}_z$ from the neck-sensor, but not $\boldsymbol{a}_x$ or a.[25] This indicates that forces which affect the skydiver during rotational kinematics are not recorded by riser load cells, which risk underestimating skydiver deceleration and implications on neck load during the x-phase. The resulting neck load would be the sum of external torque (product of inertia of the head and lever arm down to C7/T1) and internal torque (product of the counteracting neck extensor muscle force and internal lever arms, added to the solidity of passive structures).[11] Rapid onset deceleration in $-\boldsymbol{a}_x$ will, due to long moment arms and a swift rise in head momentum, generate a large external torque for the neck extensor muscles to counteract in order to maintain a neutral head position. High neck flexion torque induced by POS is evident in a study of head-borne mass effect on neck bending moment measured with load cells built into the cervical spine of a modified hybrid III manikin.[20] This is strengthened by measurements of supra-maximal neck extensor muscle activity during POS (compared to prejump maximum isometric contractions) previously described by the authors of the present work.[18] Approximations of total neck load during POS could be made from future in vivo measurements if head acceleration and quality kinematic measures were added to our setup. Compared to previous POS research done in the physical sciences, the current study is an important methodological development toward describing human exposure and response to POS. The results are a vital stepping stone for future biomechanical researchers, who should investigate neck load and associated injury risk during POS.

The high $jerk_{max}$ and $jerk_{avg}$ decelerations found during the x-phase can be directly attributed to the initial rapid rise of $-\boldsymbol{a}_x$ deceleration. As the lines attached to the harness at shoulder level stretch from increasing canopy drag, the skydiver is rotated backward from a horizontal belly-to-earth position to an upright feet-down body position in about half a second (0.58 s). Though no previous study has described deceleration jerks during POS, sled tests representing low-velocity car crashes have been performed with acceleration pulses somewhat similar to x-phase decelerations, albeit with acceleration vectors directed mainly in $\boldsymbol{a}_y$ or $+\boldsymbol{a}_x$.[13,15,35]

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Table II. ANOVA Main Effects for Accelerometer and Phase Comparisons Presented Along with Post Hoc Effects and Effect Sizes Calculated with Cohen's d.

DEPENDENT VARIABLE	MAIN/INTERACTION EFFECTS	*F*	*P*	SENSOR	POST HOC EFFECTS PHASE	COMPARISON	*P*	EFFECT SIZE
a_{max}	Sensor*Phase	65.5	**<0.001**	Neck		x-phase < z-phase	**<0.001**	**0.32**
				Rig		x-phase > z-phase	**<0.001**	**3.01**
					x-phase	Neck < Rig	**<0.001**	**5.54**
					z-phase	Neck Rig	0.065	0.74
$Jerk_{max}$	Sensor*Phase	7.6	**0.009**	Neck		x-phase > z-phase	**<0.001**	**2.01**
				Rig		x-phase > z-phase	**<0.001**	**3.98**
					x-phase	Neck < Rig	**<0.001**	**3.35**
					z-phase	Neck < Rig	**<0.001**	**2.25**
$Jerk_{avg}$	Sensor	287.9	**<0.001**		x-phase	Neck < Rig	**<0.001**	**3.80**

Dependent variables are deceleration maximum (a_{max}), maximum ($jerk_{max}$), and initial average ($jerk_{avg}$) jerk. Bold numbers indicate statistical significance.

Acceleration pulses ($+a_x$ and $+a_y$) of 25–37 $G \cdot s^{-1}$ reaching 0.5–1 G were used on human volunteers, and reportedly produced increased vertical head acceleration[13] and floppy head kinematics with eyes closed,[35] related to high jerk levels. It is known that with the head outside of the neutral position during exposure to acceleration, internal forces in the facet joints of the cervical spine, as well as the muscle force required to protect the neck, have been shown to rapidly increase,[3,30] raising the risk of soft tissue injury. If the external force exceeds the maximum isometric force producible by the muscle, lengthening muscle contractions will occur, which is associated with soft tissue injuries and muscle strain.[28] A study using sled-tests with $+a_x$ perturbations found acceleration pulses of 58–170 $G \cdot s^{-1}$ reaching 2.1–3.6 G (figures similar to x-phase deceleration), which caused lengthening neck muscle contractions and minor neck pain symptoms for 20 out of 48 participants.[1] A different acceleration direction makes the comparison to the x-phase values somewhat thin because of differing injury mechanics and tissue tolerances. However, several lengthening contractions of neck extensors were evident in our video data, along with supramaximal neck extensor muscle activity, as previously mentioned.[18] Further, some skydivers entered the z-phase with the neck still flexed, causing continuous flexion torque strain on the neck from a_z deceleration lasting up to 2.9 s. When exposed to such POS deceleration hundreds of times per year, soft tissue injuries and cumulative microtraumas to the cervical structures seem highly possible. Skew and/or hard openings, abnormal timing from deployment to line snatch (caused by external factors related to equipment or packing), or intrinsic factors like mental fatigue or lack of concentration could make it difficult for the skydiver to anticipate POS onset and maintain a neutral head position during the x-phase and into the z-phase. The amount of abnormal openings experienced by the skydiver can be expected to increase with the number of skydives. It can thus be speculated whether such accumulation alone, and/or that of normal openings, can explain the established relationship between many skydives and neck pain.

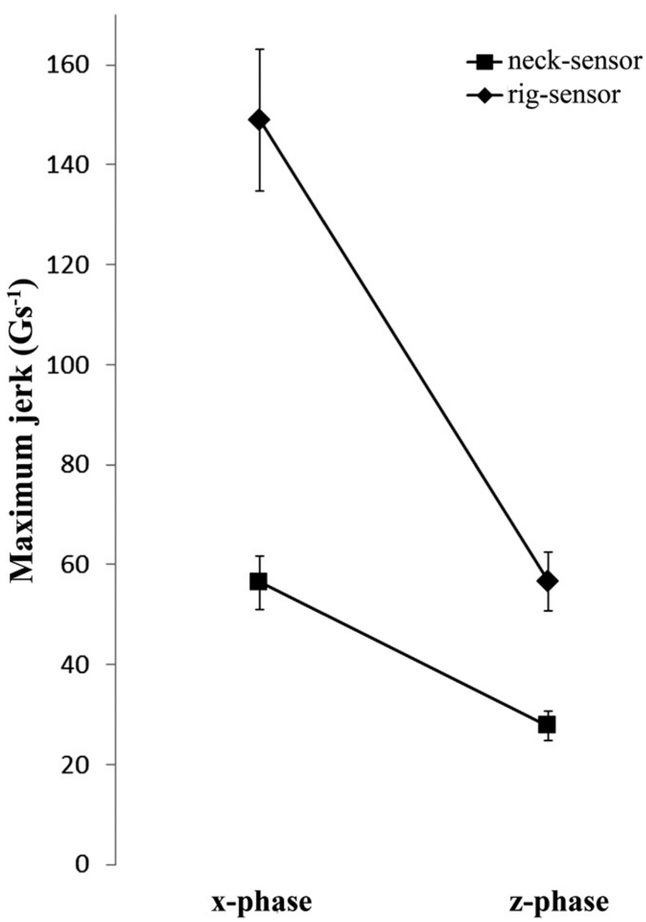

Fig. 4. Maximum deceleration onset rates (jerk) representing a 0.1-s temporal window. Deceleration level is shown on the y-axis and POS phase on the x-axis.

By adapting a more vertical body position before parachute deployment, the skydiver could potentially limit $-a_x$ deceleration, shorten the external lever arms, and decrease force requirements for neck extensor musculature. A factor known to affect POS is falling speed before and at line stretch.[25] Thus, another suggested strategy to lower POS deceleration is to decrease the sink rate of the skydiver, i.e., manually "putting on the brakes" by exposing maximal body area against the airflow well in time before parachute deployment. This would lower the amount of kinetic energy decelerating the skydiver during POS. Future research should investigate the effects of such interventions on deceleration magnitude and jerk, with the addition of head acceleration and kinematics to enable calculations of neck loads and risk of injury.

In summary, parachute type and packing were not standardized, and the rig-sensor was fastened on the harness, two factors which likely increased variance in the data set. Head acceleration and kinematics were not measured, preventing approximations of actual neck load during POS. Two distinct phases during skydiving POS were observed: the initial x-phase and the following z-phase. Given its implications on neck biomechanics, the high

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jerk in $-\boldsymbol{a}_x$ during the x-phase may be important in development of future neck pain preventive strategies. Accelerometer values obtained from the human neck vs. from the equipment rig differed greatly during the x-phase, suggesting an accelerometer placement on the human rather than the equipment as preferable to obtain valid measurements of biomechanical load.

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Authors and affiliations: Kristofer Gladh, RPT, M.Sc., Riccardo Lo Martire, RPT, M.Sc., Björn O. Äng, PT, Ph.D., and Jenny Nilsson, PT, M.Sc., Department of Neurobiology, Care Sciences and Society, Division of Physiotherapy, Karolinska Institutet, Huddinge, Sweden, and Peter Lindholm, M.D., Ph.D., Department of Physiology and Pharmacology, Karolinska Institutet, Solna, Stockholm, Sweden.

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