Acute Spinal Injury After Centrifuge Training in Asymptomatic Fighter Pilots

Kyung-Wook Kang; Young Ho Shin; Seungcheol Kang

INTRODUCTION: Many countries have hypergravity training centers using centrifuges for pilots to cope with a high gravity (G) environment. The high G training carries potential risk for the development of spinal injury. However, no studies evaluated the influence of centrifuge training on the spines of asymptomatic fighter pilots on a large scale.

METHODS: Study subjects were 991 male fighter pilots with high G training at one institution. Subject variables included information about physical characteristics, flight hours of pilots prior to the training, and G force exposure related factors during training. The two dependent variables were whether the pilots developed acute spinal injury after training and the severity of the injury (major/minor).

RESULTS: The incidence of acute spinal injury after high G training was 2.3% (23 of 991 subjects). There were 19 subjects who developed minor injury and 4 subjects who developed a herniated intervertebral disc, which is considered a major injury. In multivariate analysis, only the magnitude of G force during training was significantly related to the development of acute spinal injury. However, there was no significant factor related to the severity of the injury.

DISCUSSION: These results suggest that high G training could cause negative effects on fighter pilots' spines. The magnitude of G force during training seemed to be the most significant factor affecting the occurrence of acute spinal injury.

KEYWORDS: pilot training, acute spinal injury, high G force, centrifuge.

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Pilots of military high performance aircraft are frequently exposed to high physical stress on the spinal column. Many factors are known to contribute to spinal columnar overload. Among them, high gravity (G) is the most important element.[15,24,25] Both the magnitude of the G force and the high G onset rate to high peak G are known as causes of spinal column stress.

Many countries have high G training centers using centrifuges for pilots to learn how to cope with a high G environment. The training system reproduces a similar environment as a real fighter aircraft. The trainee maintains a face-front position identical to a pilot's general flying position and checks the level of induced G force from the monitor. This position can fatigue the posterior neck extensor muscles.[4,20,22] The lumbar spine is kept straight by an upright seated position which is maintained during the training because the harness restraint limits extra motion of the trunk.[20] Thus, most elements of high G force are directly transmitted to the longitudinal axis of the spinal column. Furthermore, the anti-G straining maneuver, which is performed by pilots to maintain peripheral venous return and prevent loss of consciousness, could aggravate axial force to the lumbar spine.[22] Although centrifuge training is valuable in maintaining and enhancing a fighter pilot's ability to endure high G force, it carries the potential risk of developing spinal injury.[2,16,17]

To date, many studies have reported spinal abnormalities of fighter pilots. Most have reported cases of high G force related acute injuries[6,18,24] or the cumulative effect of repetitive high G exposure on the spine.[3,10,14] To our knowledge, no studies have

From the Department of Neurology, Chonnam National University, Gwangju, Republic of Korea; the Department of Orthopaedic Surgery, Aerospace Medical Center, Republic of Korea Air Force (ROKAF), Republic of Korea; and the Department of Orthopaedic Surgery, Asan Medical Center, University of Ulsan College of Medicine, Seoul, Republic of Korea.

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Address correspondence to: Young Ho Shin, M.D., Department of Orthopaedic Surgery, Aerospace Medical Center, Republic of Korea Air Force, PO Box 335, Ssangsu-ri, Namil-myeon, Cheongwon-gun, 363-849 Chungbuk, Republic of Korea; 123sinyh@gmail.com.

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evaluated the influence of high G training on the spines of asymptomatic fighter pilots on a large scale. The purpose of our study was to assess the incidence of acute spinal injury in fighter pilots after high G training and to evaluate the clinical significance of those lesions. Also, analysis was performed to reveal the related factors for the occurrence and severity of an acute spinal injury.

METHODS

Subjects

It is mandatory for all fighter pilots of the Republic of Korea Airforce (ROKAF) to have high G training every 3 yr and a routine health check-up at our institute every 2 yr. Between July 2012 and October 2013, 1016 fighter pilots had high G training at one institution. Before the training, the health status of all subjects was checked by survey. At the time of training, no subjects had any symptoms related to spinal abnormality, including neck pain, back pain, radiating pain to the extremities, or neurological abnormality at an extremity. Eight subjects were excluded because of the history of herniated intervertebral disc (HIVD) at the cervical or lumbar spine. Of the remaining 1008, 17 were female pilots and were excluded from the analysis due to their small population size. A total of 991 subjects were enrolled in the final analysis. All subjects were retrospectively evaluated and documented using training records and medical records. The study was approved by the institutional review board of the Aerospace Medical Center of the ROKAF (ASMC-14-IRB-006).

Subject Variables

Subject variables consisted of three categories: 1) physical characteristics including body size; 2) exposure to high G force prior to the training; and 3) G force exposure related factors during training. Physical characteristics included age, height, weight, and body mass index (BMI). Age, height, and weight were obtained from training records. BMI was calculated using height and weight data. The mean age of the enrolled pilots was 29.5 ± 5.2 yr (range 20–49 yr), mean height was 175.0 ± 4.8 cm (range 160–193 cm), mean weight was 72.8 ± 8.1 kg (range 47–109 kg), and the mean BMI was 23.8 ± 2.2 $kg \cdot m^{-2}$ (range 17.7–31.4 $kg \cdot m^{-2}$).

Previous exposure to high G force was defined as flight hours of each individual before training.[12] Total flight hours, excluding the early training hours, were used for the analysis. The data was acquired from the pilot flight database of the Airforce Medical Information System of the ROKAF. Mean flight experience of the subjects prior to the training was 658.8 ± 642.6 h (range 32–3600 h).

The G force exposure related factors are determined depending on the type of main aircraft. The detailed training protocol of each type of aircraft is described in **Table I**. The magnitude of G force is a continuous variable. However, our training protocol was performed in three fixed forces: 7.3 G, 8 G, and 9 G. Therefore, we also presented the exposed G force as a categorical form. As the difference between the three designated G force variables is not consistent, we divided our data into two categories by the average value of the subjects' G force exposure during training: 8.2 ± 0.7 G (range 7.3–9 G); 7.3 G/8 G and 9 G. Both continuous and binary categorical forms were viewed as subject variables for the statistical analysis. There were 314 subjects (31.7% of 991 subjects) trained with 7.3 G, 293 subjects (29.6% of 991 subjects) with 8 G, and 384 subjects (38.7% of 991 subjects) with 9 G. Among the 314 subjects who were trained with 7.3 G, 115 subjects were assigned to the F-4 as the main aircraft, 148 subjects to the F-5, 21 subjects to the KA-1, 27 subjects to the KT-1, and 3 subjects to the T-59. Among the 293 subjects who were trained with 8 G, 259 subjects were assigned to the T-50 as the main aircraft and 34 subjects to the TA-50. Among the 384 subjects who were trained with 9 G, 112 subjects were assigned to the F-15 as the main aircraft and 272 subjects to the F-16.

All subjects wore a standard five-bladder G suit and did not wear a helmet. They leaned back on the seat, but were not allowed to rest their head against the seat. They were required to maintain a face-front position and checked the level of induced G force from the monitor. Also, they were required to perform anti-G straining maneuvers during training. Basically, each individual was assigned a single episode in the centrifuge. However, trainees who experienced loss of consciousness during the training were required to repeat the high G training within 30 d whenever they desired. For these trainees, we only used the results from the final run of the centrifuge for the analysis. There were 943 subjects (95.2% of 991 subjects) who completed the training protocol in a single attempt. On the second attempt, 35 subjects (3.5% of 991 subjects) completed the training and 13 subjects (1.3% of 991 subjects) completed the training with more than three attempts. Because every episode of training is independent and the time gap between repeated G exposures is different among each subject, the number of centrifuge runs was not considered a subject variable.

Determination of Acute Spinal Injury

In our study, an acute spinal injury was defined as an acute cervical or lumbar injury which developed certain symptoms within 24 h after high G training. Patients who visited our outpatient clinic with typical symptoms related to spinal abnormality, including neck pain, back pain, radiating pain to an extremity, or neurological abnormality at an extremity were

Table I. ROKAF Protocol for High G Force Training According to the Type of Assigned Aircraft.

TYPE OF AIRCRAFT	PEAK G LEVEL	ACCELERATION RATE TO PEAK	DECELERATION RATE TO BASE	PEAK G LEVEL SUSTAINED TIME	TOTAL HIGH G EXPOSURE TIME
F-15, F-16	9 G	$6\ G \cdot s^{-1}$	$3\ G \cdot s^{-1}$	15 s	18.99 s
T-50, TA-50, FA-50	8 G	$6\ G \cdot s^{-1}$	$3\ G \cdot s^{-1}$	15 s	18.49 s
F-4, F-5, KT-1, T-59	7.3 G	$3\ G \cdot s^{-1}$	$2\ G \cdot s^{-1}$	20 s	25.25 s

physically examined to check main symptoms and tenderness points. A simple X-ray was routinely taken to rule out bony abnormalities or to detect spinal curvature changes. Patients with neck or back pain only with paraspinal muscle or interspinous process ligament tenderness without any abnormal lesions on X-ray were considered acute cervical or lumbar sprain patients. Patients with neck or back pain only without any tenderness points or any abnormal lesion on X-ray received conservative management under the diagnosis of acute soft tissue injury. This was confirmed as the final diagnosis if improvement occurred after conservative management. If not, magnetic resonance imaging (MRI) was done to evaluate disc and bone status. Patients with newly developed radiating pain to extremities or neurological changes at the extremities after training underwent MRI at the acute stage. If the MRI finding was compatible with the symptoms, the patients were considered to have a newly developed HIVD. If not, the herniated disc on MRI was considered an old lesion and an acute soft tissue injury was considered the cause of the symptoms.

Various types of injury could occur, from soft tissue injury to HIVD or fracture. These acute spinal injuries were divided by their location and severity: cervical/lumbar and major/minor. A minor injury was defined as acute soft tissue injury only involving the paraspinal muscles and ligaments. A major injury was defined as acute hard tissue injury, including acute HIVD and vertebral fractures of the vertebral body, transverse process, and spinous process.[3,24]

Statistical Analysis

Associations between subject variables and development of acute spinal injury after training were analyzed by univariate analysis using binary logistic regression analysis. In the acute spinal injury patients, associations between injury severity and subject variables were analyzed by univariate analysis using binary logistic regression analysis. Statistical significance was accepted for $P < 0.05$. To eliminate confounders among the variables, multivariate analysis was respectively done with all variables which were used in the univariate analysis.

RESULTS

Of 991 asymptomatic male fighter pilots, 23 subjects (2.3% of 991 subjects) presented with acute spinal injury after high G training. The results of univariate analysis using binary logistic regression for variables associated with the development of acute spinal injury are shown in **Table II**. For these variables, the magnitude of G force exposure during training (odds ratio 3.727, 95% confidence interval 1.519–9.144, $P = 0.004$) was statistically significant on multivariate analysis (binary logistic regression, forward conditional method).

Of 23 acute spinal injury patients, 14 patients (60.9% of 23 patients) had cervical spinal injury and 9 patients (39.1% of 23 patients) had lumbar spinal injury. In terms of injury severity, 19 patients (82.6% of 23 patients) had minor injury: 13 cervical and 6 lumbar soft tissue injury. The other 4 patients (17.4% of 23 patients) had major injury: 1 patient with cervical HIVD and 3 patients with lumbar HIVD. The results of univariate analysis using binary logistic regression for variables associated with the injury severity (minor injury vs. major injury) are shown in **Table III**. Of these variables, no variable including flight hours prior to training (odds ratio 1.002, 95% confidence interval 1.000–1.004, $P = 0.073$) was statistically significant on multivariate analysis (binary logistic regression, forward conditional method).

Table II. Results of Univariate Analysis Using Binary Logistic Regression for Variables Associated with the Development of Acute Spinal Injury.

VARIABLES	B(SLOPE)*	*P*-VALUE	ODDS RATIO (95% CI†)
Patient age (yr)	0.029	0.452	1.030 (0.954–1.112)
BMI ($kg \cdot m^{-2}$)	−0.084	0.408	0.919 (0.753–1.122)
Flight hours prior to training (h)	0.000	0.353	1.000 (1.000–1.001)
Magnitude of trained G force	0.881	0.009‡	2.413 (1.249–4.663)
Magnitude of trained G force: 7.3 G/8 G vs. 9 G**	1.316	0.004	3.727 (1.519–9.144)

* In the binary form 'characteristic α vs. β', 'slope' is positive if characteristic β is more positively related to the dependent variable than characteristic α, and vice versa.
† CI = confidence interval.
‡ Excluded from multivariate analysis because its *P*-value was higher than that of its binary form.
** Also revealed to be significant in multivariate analysis.

The one cervical HIVD patient had disc protrusion at the C5-6 level. All three lumbar HIVD patients had disc herniation with annulus fibrosus tear at the L5-S1 level. One of them had disc sequestration along the posterior surface of the S1 vertebral body (**Fig. 1**). He was treated by operation (open discectomy L5-S1) and was not able to fly for 19 mo. Excluding this patient, good results were achieved after conservative management for the other three HIVD patients (two lumbar and one cervical) along with a flight stoppage period lasting from 2 wk to 3 mo. All of these flight stoppages were determined by aeromedical decisions.

DISCUSSION

Previous studies revealed a high rate of spinal abnormalities in aviators exposed to high G forces. Most studies collected information on dependent variables, including subjects' physical

Table III. Results of Univariate Analysis Using Binary Logistic Regression for Variables Associated with the Injury Severity (Minor Injury vs. Major Injury).

VARIABLES	B(SLOPE)*	*P*-VALUE	ODDS RATIO (95% CI†)
Patient age (yr)	0.231	0.113	1.260 (0.947–1.678)
BMI ($kg \cdot m^{-2}$)	0.195	0.487	1.215 (0.701–2.106)
Flight hours prior to training (h)	0.002	0.073	1.000 (1.000–1.004)
Magnitude of G force during training	0.553	0.572	1.739 (0.255–11.873)
Magnitude of G force during training: 7.3 G/8 G vs. 9 G	0.325	0.796‡	1.385 (0.118–16.227)

* In the binary form 'characteristic α vs. β', 'slope' is positive if characteristic β is more positively related to the dependent variable than characteristic α, and vice versa.
† CI = confidence interval.
‡ Excluded from multivariate analysis because its *P*-value was higher than that of its original form.

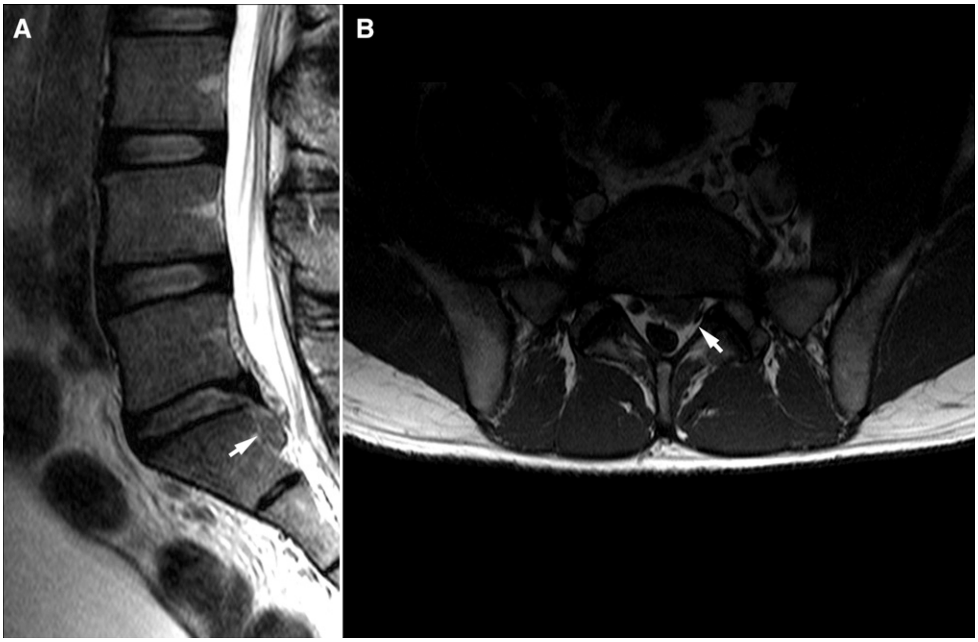

Fig. 1. MRI result of a 33-yr-old man on the day of 8-G training. A) T2-weighted sagittal MRI, and B) T1-weighted axial MRI. The herniated disc was sequestrated along the posterior surface of the S1 vertebral body (A) and the S1 nerve root was compressed (arrow).

characteristics, G force related characteristics, and the flight environment to find the contributing factors for the development of spinal abnormalities.[4,14,15] Based on these studies, flight hours, frequency of high G force exposure, magnitude of G force, and flight environment have been suggested as important contributing factors to the development of spinal injuries.[6,12,14] However, these studies had inevitable limitations in the aspect of data collection, especially for G force-related characteristics. Except for newly developed aircraft, most of the aircraft did not have an apparatus to continuously record induced G force. Therefore, data such as G exposure time, frequency of high G force exposure, and magnitude of G forces for specific flight situations are extremely dependent on the pilots' statements. As pilots are not able to exactly remember all the details, it is difficult to collect accurate information for analysis. As a result, such data is subjective and extremely dependent on the pilots' statements.[2,4] We designed this study to overcome these limitations and evaluate the accurate influence of high G force on the spine. We unified the flight environment by using the same training facility. Also, we could achieve the chosen G force using the designated protocol for all candidates.

In 991 subjects, the incidence of acute spinal injury after high G training was 2.3% and the development rate of HIVD was 0.4%. Some subjects with mild symptoms may not have visited our outpatient clinic after the training due to personal schedules or concerns about aeromedical decisions. Thus, the incidence may have been higher than our result of 2.3%. In a recent survey of households in the United States, the 3-mo prevalence of back and/or neck pain was 31%.[23] In addition, the lifetime prevalence for spinal disorders associated with lumbar radiculopathy is thought to be between 4% and 6% in the general population.[5] Though the study results are not directly comparable with our study, considering the frequency of pilots being exposed to high G force, 2.3% of incidence after high G training is deemed to be higher than the results of the periodic analysis on the general population. This result is compatible with previous studies that revealed the negative effect of high G force on pilots` spines.[11,16,21] Also, the incidence rate of HIVD was higher than the previous study, which reported an average annual incidence rate of HIVD in U.S. Army aviators as approximately 1 per 1000 aviator-years per year.[18] We think that the following two factors contribute to the high HIVD incidence in our study. First, in addition to the different study design and data collection methods between the two studies, the average G force load was much higher in our study. Second, all training procedures in our institute were observed by a duty flight surgeon and all pilots were queried about any abnormal signs or symptoms in need of medical attention. Some subjects with abnormal symptoms or signs were transferred to our clinic for further evaluation. This systematic controlled procedure was one contributing factor for detecting spinal injury.

In a training situation, the flight environment is consistent among all subjects. The neck position is kept forward front without extra motion and the aircraft does not have any other force of direction other than the G_z force. The G force load is predictable as it is induced when the subject pulls the control stick. The effect of known risk factors on acute spinal injury, such as neck position, motion during flight, and abruptness of G force, could be ignored in this training simulation.[6,7,13] Although these risk factors did not directly contribute to the results, 21 subjects had acute spinal injuries, including major spinal problems, in our study. Furthermore, the magnitude of G force exposure during training was positively related to the development of acute spinal injury. Therefore, we showed that the high magnitude of G force itself is essential in the occurrence of an acute spinal injury.

For data analysis, two stepwise analyses were performed. First, we compared the injured group with the uninjured group. Second, we compared the major injury group with the minor injury group within the injury group. The reason for this was that the number of patients in the injury subgroups was quite small to be compared with the uninjured group. In multivariate analysis between subgroups, all variables including flight hours prior to training were not significantly related to the injury severity. This result somewhat varies from previous studies. There is no consensus on the relationship between biological age and the development of spinal degenerative changes. Also, increased flight hours or repeated exposure to high G force might cause repeated minor acute spinal injuries, which could cause premature spinal degenerative changes.[3,8,9] This degenerative process makes the spine a more vulnerable structure for major injury when exposed to a high G force. Vanderbeek et al. reported an increased susceptibility to a major injury with increasing age in U.S. Air Force pilots.[24] Petren-Mallmin et al. analyzed spinal MRI scans of subjects and revealed that older and more experienced pilots had more disc and vertebral body degenerative changes than younger and more inexperienced pilots.[20] However, in our study, subject age and flight hours prior to training were not associated with injury severity. Yet we cannot simply conclude that age and previous exposure to high G force do not affect the severity of injury through our study result. The analysis was performed with the subgroup of 23 subjects, which is a very small number in absolute value to show a statistically meaningful result. If the study period was to be extended and the population of trainees was increased, the number in the injury group would be greater in absolute value, which might accompany a different result. Additional study is required.

Our study had several limitations which need to be considered. First, we examined only aviators who trained with high G force, preventing comparison with aviators who trained with low G force. Second, although the pilots with a history of major spine abnormalities were excluded from the analysis and we confirmed that all subjects were free of spine-related symptoms by performing a survey prior to training, we did not check the pretraining spinal status of all subjects with objective tools, such as a more detailed questionnaire or images. A further study is required to compensate for this weakness. Third, for minor injury patients, the symptom severity was not checked at the outpatient clinic and the symptom-related flight stoppage period was not examined. This could be another limitation of our study.

In conclusion, acute spinal injury occurred in 23 (2.3%) of 991 subjects, including 4 HIVD patients after a single episode of high G force training. Among many variables, the level of G force loading for training is significantly related to the development of acute spinal injury. Other characteristics, such as body size, age, and previous flight hours are assumed to have much less effect on injury development. Concerning injury severity, the number of flight hours was higher in the major injury group than the minor injury group, but was not statistically meaningful.

Regular high G training is necessary for maintaining pilots' ability to cope with the flight environment. However, the training itself has potential risk for the development of acute spinal injury, which may weaken the military power of a flight unit.[2,16,17] Therefore, it is necessary to closely examine the spinal conditions of each pilot before and after the training, especially for the high G training group. Also, the training protocol, such as high G exposure time and level of peak G, needs to be reviewed for its appropriateness. Additionally, methods to reduce G-associated spinal injury, such as pre-training neck stretching and muscle strengthening exercise, need to be informed before high G training.[1,3,19]

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Authors and affiliations: Kyung-Wook Kang, M.D., Department of Neurology, Chonnam National University, Gwangju, Republic of Korea; Young Ho Shin, M.D., Department of Orthopaedic Surgery, Aerospace Medical Center, Republic of Korea Air Force, Cheongwon-gun, Chungbuk, Republic of Korea; and Seungcheol Kang, M.D., Department of Orthopaedic Surgery, Asan Medical Center, University of Ulsan College of Medicine, Seoul, Republic of Korea.

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