+Gz Exposure and Flight Duty Limitations

Roope Sovelius; Tuomas Honkanen; Marjo Janhunen; Maunu Mäntylä; Heini Huhtala; Tuomo Leino

BACKGROUND: High $+G_z$ exposure is known to cause spinal problems in fighter pilots, but the amount of tolerable cumulative $+G_z$ exposure or its intensity is not known. The aims of this study were to assess possible breaking points during a flight career and to evaluate possible determinants affecting pilots' spines.

METHODS: Survival analysis was performed on the population who started their jet training in 1995–2015. The endpoint was permanent flight duty restriction due to spinal disorder. Then the quantified G_z exposure and possible confounding factors were compared between those pilots with permanent flying restriction and their matched controls. Cumulative G_z exposure was measured sortie by sortie with fatigue index (FI) recordings. FI is determined by the number of times certain levels of G_z are exceeded during the sorties.

RESULTS: The linear trend of the survival curve indicates an annual 0.86% drop out rate due to spinal problems among the fighter pilot population. A conditional logistic regression did not find any difference in the FI between cases and controls (OR 0.96, 95%CI 0.87–1.06). No statistical difference was found for flight hours, a sum of intensive flying periods, fitness tests, or with nicotine product use. Additionally, a maximum $+G_z$ limitation without airframe restriction was assessed and is presented as a useful tool to manage loading and developed symptoms.

DISCUSSION: No particular breaking point during follow-up or individual factor was found for G_z induced spinal disorders. The results of the study outline the multifactorial nature of the problem. Thus, multifactorial countermeasures are also needed to protect pilots' health.

KEYWORDS: case-control, military pilots, musculoskeletal disorder, dose-dependent, acceleration.

Sovelius R, Honkanen T, Janhunen M, Mäntylä M, Huhtala H, Leino T. +G_z *exposure and flight duty limitations*. Aerosp Med Hum Perform. 2022; 93(4):390–395.

Flight-induced neck or back pain among modern fighter pilots is a common and persistent problem.[7,8,13] Acute pain periods may lead to more permanent symptoms and degenerative changes in spinal structures.[1,2] The prevalence rate of spinal disorders among fighter pilots has been found to range from 25–95% depending on the length of the surveyed period. This also has operational impacts and has raised different concerns besides health issues. Decreased operational performance was found in 38% of fighter pilots in Australian and Japanese studies.[12,16]

There are both aeromedical and administrative needs to restricting and diminishing occupational loading in the case of persistent flight-related symptoms. Conventionally fighter pilots have been grounded permanently, transferred to transport aircraft, or waivered for limited maximum $+G_z$ sorties with fighters.

Despite numerous epidemiological studies, there is need for studies on the dose-dependent relationship between $+G_z$ exposure and spinal disorders. It has been shown that the cumulative G exposure has more effect on neck pain than the peak G exposure.[11] Honkanen et al.[10] studied the quantity of G_z exposure, but did not find a correlation between $+G_z$ exposure in early flying careers and spinal injury-induced flight duty limitations. Yet this study is the only one reporting the measured individual quantity of $+G_z$ exposure, not the exposure by flight hours or aircraft type flown.

From the Centre for Military Medicine, Finnish Defence Forces, Helsinki, Finland; the Test Flight Centre, Finnish Air Force, Pirkkala, Finland; the University of Tampere, Tampere, Finland; and the National Defence University Finland, Helsinki, Finland.

This manuscript was received for review in April 2021. It was accepted for publication in December 2021.

Address correspondence to: Roope Sovelius, P.O. Box 50, FI-00301 Helsinki, Finland; roope.sovelius@mil.fi.

DOI: https://doi.org/10.3357/AMHP.5915.2022

The objective of this study is threefold. First, to analyze the career-long incidence of permanent flight duty limitations to determine possible higher risk phases during a flight career. Secondly, to compare cumulative $+G_z$ loading between pilots with neck or back problems and their matched controls to determine the dose dependency of $+G_z$ exposure and permanent spinal symptoms. And thirdly, to evaluate the effect of maximum $+G_z$ limitation on cumulative loading dose of $+G_z$ after a limitation is set. The aim of this study was to increase knowledge of confounding factors for spine loading in high $+G_z$ environments.

METHODS

Subjects

This study is a register-based follow-up research. The data was collected from the Finnish Air Force's (FINAF's) registers, flight database, and annual aeromedical examinations. The study was approved by the Finnish Defense Force review board of research permits.

The first part of the study, survival analysis, was determined over cohort, including all FINAF pilots who started jet training between the years 1995 and 2015. In the beginning of the training, they all met the aeromedical requirements for aircrew of high-performance aircraft (HPA) and were asymptomatic in terms of spinal disorders. Individuals with symptomatic findings in baseline spinal MRI screening before enrolment to fighter pilot training had been disqualified.

In the second part of the study, a case-control study, the subjects were collected from the same cohort as presented above. The selection criteria for the subjects are presented in **Fig. 1**. Cases were included if they had any flight duty limitation due to spinal issues. Pilots with inflammatory spinal diseases were excluded, as their symptoms were not considered $+G_z$ loading induced, as were those with less flying experience than 100 h in HPA, as their $+G_z$ exposure was considered too low to cause cumulative loading effects on the spine. Cases were subclassified by the affected anatomical part of the spine (cervical or lumbar). Two controls were selected for each case. Controls were matched on annual cohort (± 1 yr) and curriculum of flying career thereafter with the cases. The follow-up time of the controls was matched with their cases.

At the beginning of the case-control study, subjects' mean age was 23 yr (range 21–25 yr), height 179 cm (range 169–191 cm), weight 75 kg (range 61–96 kg), and BMI 23.5 (range 19.6–27.8). During the follow-up, subjects accumulated an average of 1122 flight hours (range 182–2305 h) in high performance jets (BAE Hawk, F/A-18 C/D). Demographic information of cases and controls is presented in more detail in **Table I**. There was no difference in demographics between groups. All subjects were men.

Subjects' nicotine product use was categorized as ever/never. Respectively, 39.3% and 41.4% of cases and controls were nicotine users. These figures are relatively high and possibly overestimate the prevalence of nicotine use among the study population, especially toward the end of the follow-up period. If pilots answered yes to regular use of nicotine products in any annual aeromedical examination, he was considered a user. The rationale behind this categorization was to not miss any nicotine effect on spinal degeneration during follow-up.

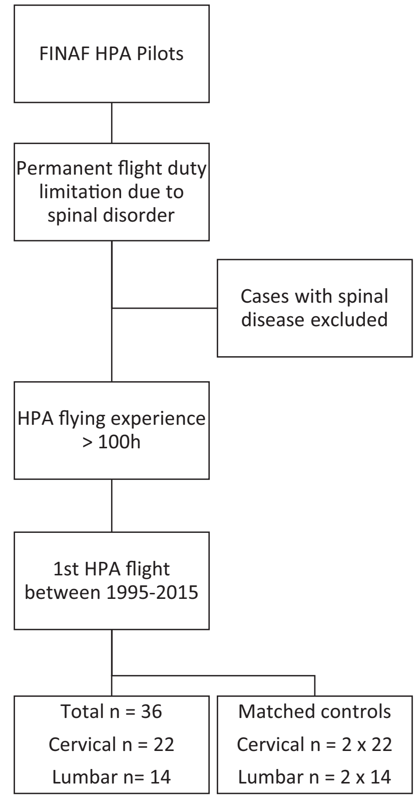

Fig. 1. Selection criteria for this case–control study.

The subjects' annual fit-to-fly exercise test results were collected and they were classified into four fitness groups based on their follow-up period averaged results. The exercise test is a maximal bicycle ergometer test with work rate increments of 50 W per 2-min stages. The test result is determined by the last minute workload divided by the subject's weight and 3.4 W/kg is the required minimum level for fighter pilots in FINAF. Classifications for this study were based on the levels reached up to 3.5 W/kg, 4.0 W/kg, 4.5 W/kg, or above.

Table I. Demographic Comparison Between Case and Control Groups (Mean ± SD).

	CASE	CONTROL	*P*-VALUE
Age (yr)	22.4 ± 1.0	22.5 ± 1.0	0.618
Follow-up time (yr)	10.4 ± 4.8	10.2 ± 4.8	0.853
Flight hours (h)	1009.0 ± 451.1	1002 ± 525.6	0.951
Height (cm)	177.9 ± 5.0	180 ± 5.2	0.072
Body mass (kg)	77.3 ± 6.6	77.0 ± 7.5	0.851
BMI (kg · m^{-2})	24.1 ± 1.9	23.9 ± 2.0	0.495
Nicotine users	39.3%	41.4%	0.522

Procedure

Fighter pilots cumulative $+G_z$ loading is determined using the Fatigue Index (FI) sortie by sortie. FI is obtained from FINAF flight data recordings and is presented in more detail in our previous study.[10] Since 1995, $+G_z$ loads of FINAF jet aircraft BAE Hawks and F/A-18C/D Hornets have been recorded into a database where aircrew can also be identified sortie by sortie. FI is determined by the number of times the levels of +0.25, +2.5, +3.5, +4.5, +5.5, +7.0, and +8.0 G_z are exceeded during the sorties or, respectively, levels lower than −0.5 and −1.5 G_z are reached. The FI values from each sortie were then given a figure representing the amount of $+G_z$ exposure during that particular sortie. This is calculated using the following equation:

$$FI = (5.17584 * m2 - 0.4053 * m + 771.2636) * 10^{-7} * (95/957 * G_1 + 33.0343 * G_2 + 0.3467 * G_3 + 1.065 * G_4 + 19.177 * G_5 + 69.8557 * G_6 + 204/8637 * G_7 + 450.418 * G_8 + 393/5057 * G_9)$$

Where m = mass of aircraft and G_i = level of $+G_z$ exceeded or $-G_z$ passed during the sortie: $G_1 = -1.5\ G_z$, $G_2 = -0.5\ G_z$, $G_3 = 0.25\ G_z$, $G_4 = 2.5\ G_z$, $G_5 = 3.5\ G_z$, $G_6 = 4.5\ G_z$, $G_7 = 5.5\ G_z$, $G_8 = 7.0\ G_z$, and $G_9 = 8.0\ G_z$. Cumulative exposure for G_z is then determined per 1000 flight hours.

Statistical Analysis

The survival analysis was performed using the Kaplan-Meier method. Cervical and lumbar cases were analyzed separately and combined. The endpoint for events in the survival analysis of the follow-up was the date when a fighter pilot was given a permanent flying limitation (permanent grounding, restricted to no HPA, or waivered with certain max $+G_z$ limitation in HPA due to spinal degeneration).

In the case-control study, subjects' demographic characteristics were analyzed through means with range or with standard deviation (± SD). Pair-wise *t*-test was used for a comparison of the demographics between the groups. Conditional fixed-effects logistic regression analyses were used to calculate odds ratios (OR) with 95% confidence intervals (CI) between groups with cumulative G_z loading (cumulative FI) as an independent variable. The grouping of matched cases and controls was maintained in this conditional logistic regression analysis. The cumulative FI was adjusted for potential confounders such as flight hours, flight intensity, physical fitness, anthropometry, and nicotine product use. A more strenuous flight intensity was determined as the sum of conditions when two high FI sorties were flown consecutively with a poor recuperation time. A high FI threshold for a flight was set as 0.013 as this is in line with the suggested maximum annual exposure of 13 FI/1000 flight hours. Time periods of a maximum of 48 h and 24 h were used

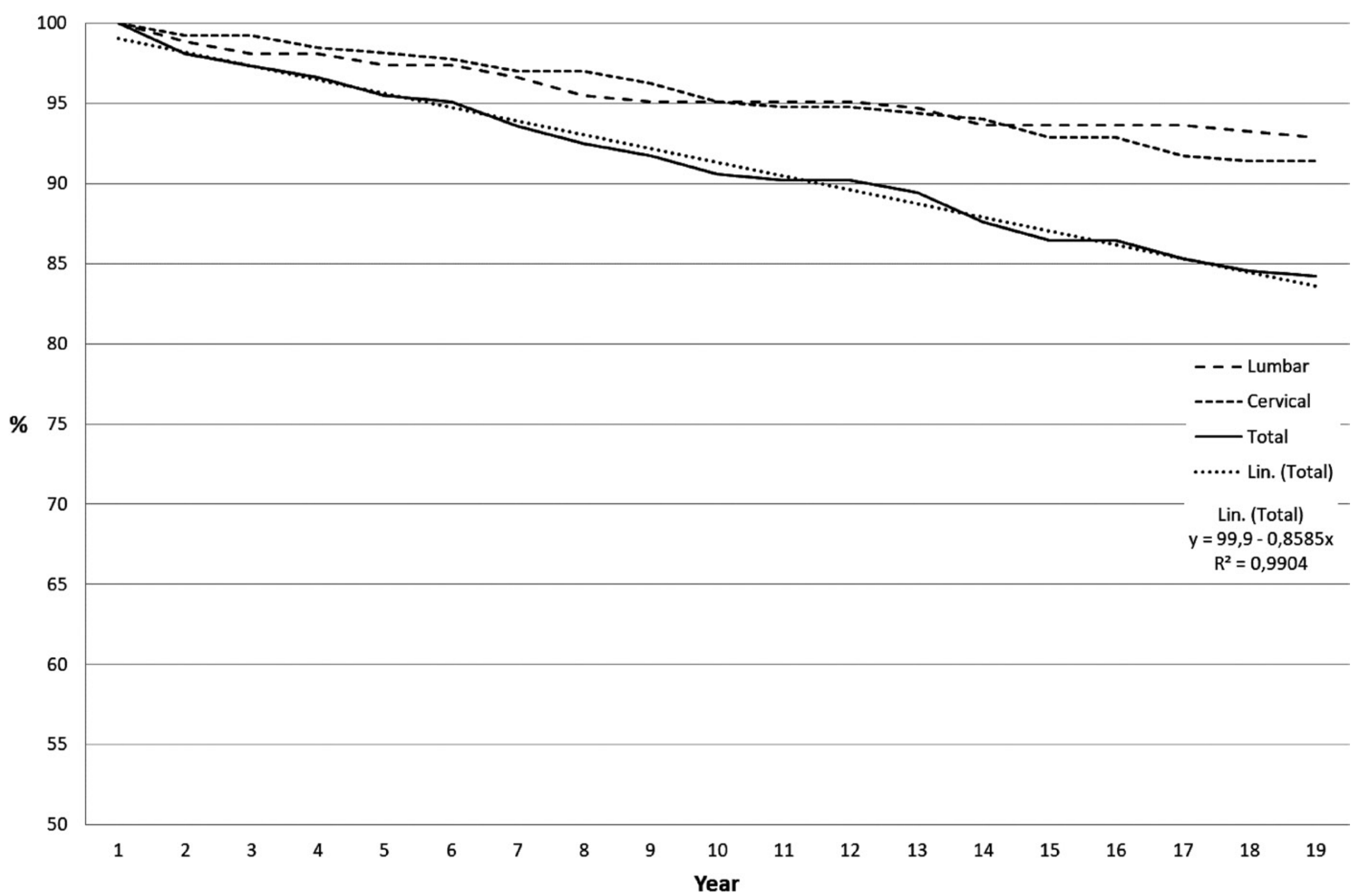

Fig. 2. Kaplan-Meier survival among the jet pilot population with permanent flight limitation due to spinal disorder as an endpoint. Cervical and lumbar cases are presented separately and combined (Total).

as it is shown in the literature that muscular recuperation after strenuous loading may take 24–72 h.

RESULTS

Kaplan-Meier analysis showed a linear trend of prevalence in the flight duty limitations (**Fig. 2**). The slope of the survival curve indicates a −0.86% drop out rate annually among the pilot population. No steep curves or otherwise different trends could be seen either for cervical or lumbar degeneration throughout the flying career. Mean follow-up time was 12.3 yr (range 2–20). In total, 118,323 sorties flown were counted in analyses. Due to sensitive information, other descriptive statistics about the analyzed cohort are not given.

There was no difference in cumulative loading (FI) between cases and controls during the follow-up period (OR 0.96, 95% CI 0.87–1.06). In addition, their accumulated HPA flight hours were equal (OR 1.00, 95%CI 0.998–1.002, $P = 0.453$).

As there was no difference in $+G_z$ exposure between groups, intensity of the logged flights was checked for an explanation for the flight-induced spinal disorders. Possible insufficient recuperation time after particularly strenuous flights was determined as a sum of conditions when two flights with FI more than 0.013 took place consecutively in less than 48 h or 24 h. Odds ratios were respectively the same (0.99, 95%CI 0.98–1.00, $P = 0.226$; and 0.99, 95%CI 0.98–1.00, $P = 0.226$). Thus, there was no difference between groups in the flight intensity over the follow-up period.

Maximal anaerobic exercise test results were not different between groups. The odds ratio was 0.59 (95%CI 0.15–2.24, $P = 0.440$). Similarly, nicotine use was not significant in either group (OR 0.67, 95%CI 0.25–1.78, $P = 0.426$). Moreover, there was no statistical difference between the groups in the cumulative FI with presented independent variables when cervical and lumbar cases were determined separately.

The effect of $+G_z$ limitation on a pilot's exposure is presented in **Fig. 3**. The presented data includes all levels of $+G_z$ limitations varying from max $+4\ G_z$ to max $+6\ G_z$. The mean annual FI/1000 h before and after setting the max $+G_z$ limitation was, respectively, 1.237 and 0.204. Possible self-administration of G_z loading or temporary flight limitations due to musculoskeletal symptoms before a permanent flight limitation were not able to be excluded from FI values. Still, cutting the top of the loading reduced the quantity of $+G_z$ loading to one-fifth what it was before the limitation.

DISCUSSION

The prevalence of flight duty limitations did not show any steep steps during the follow-up period. This indicates that there is no particular training phase significantly more than any other which would cause permanent spinal disorders during the pilots' careers. Alternatively, it more probably indicates the loading effect of $+G_z$ exposure evens out over time, in terms of developing degenerative changes in the spine. Cervical structures are subjected to a high amount of strain due to awkward head positions

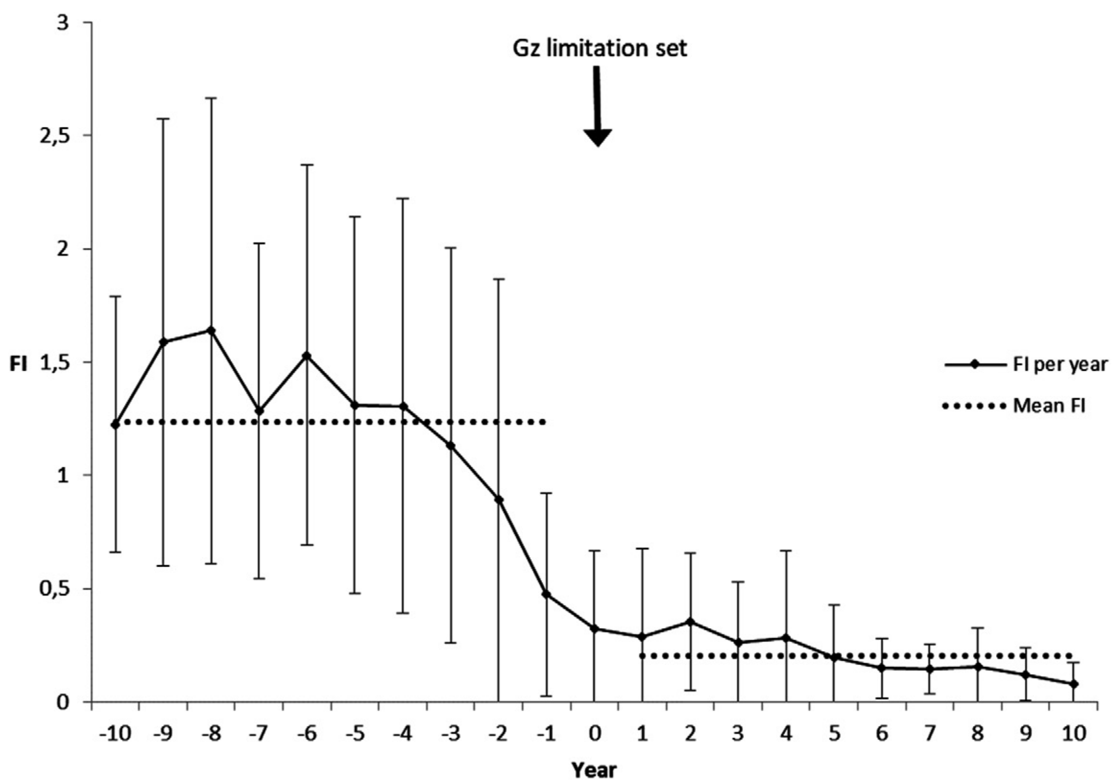

Fig. 3. The effect of G_z limitation on spinal loading exposure. Annual FI/1000 h (mean ± SD) is presented before and after G_z limitation. Dotted lines represent mean FI/1000 h over the years before or after G_z limitation set at year 0.

during high $+G_z$[22] and, thus, the cervical spine is prone to high risk of occupation-induced health problems. Alternatively, the lumbar part of the spine also takes more load during high $+G_z$ and vertebras and lumbar intervertebral discs are exposed to higher loading as there is more body weight to bear.[15] However, both parts of the spine seem to fatigue in the same manner. The linear trend in the prevalence of flight duty limitations warrants career-long countermeasures against $+G_z$ exposure. There is not any particular time frame when supportive actions should be executed. Persons enrolling in a fighter pilot program must be prepared for the physical demands of their occupation before they are exposed to it. All-level countermeasures are widely presented, e.g., Coakwell's review article[4] and more recently in the NATO HFM-252 Aircrew Neck Pain report.[6]

Additionally, it may be hypothesized that the nature of the linear trend of spinal disorders covers different conditions: in the beginning of a career symptoms may be due to higher intensity of loading that result in more muscular-based symptoms, during midcareer it may be more due to premature degeneration of the spine by cumulative $+G_z$ exposure, and toward the end of a career the effect of aging is taking a role in spinal degeneration and its symptoms. In the meta-analysis of Shiri,[20] G_z exposure was associated with neck pain, but showed no differences in the prevalence of radiological disc degeneration between fighter pilots and controls. This possibly outlines the hypothesized trend of acute pain, appearing more slowly in radiological findings and then the aging effect confounding the outcome. However, the present study's data is not able to give scientific evidence for this hypothesis. The research methods used would need to at least include repeated survey data and controlled spinal imaging in addition.

The linear slope of the trend line of the survival curve during follow-up was −0.86. If an operative unit of fighters is, e.g., a flight of 4 aircraft, and armed forces have 100 fighter pilots, the current dropout rate shown here gives a loss of a flight after 4 yr and a loss of two flights after 8 to 9 yr from the beginning of HPA training. If the armed forces have 500 fighter pilots, the loss is a man power of 5 and 10 flights, respectively (20 or 40 pilots), just due to spinal disorders. Readers may consider the operative relevance of these figures by applying this trend to the number of fighter pilots in their armed forces.

There was no difference in the cumulative $+G_z$ exposure between cases and controls. Those pilots who have permanent musculoskeletal disorders have not flown more strenuously than the others. This result indicates, at least within this study population, that cumulative $+G_z$ exposure is very similar among fighter pilots due to their similar training syllabus. There have been changes and variation in flight training syllabuses over the years, but annual cohorts are flown with very similar level of cumulative loading. There may be different national curriculums in fighter pilot training and operative careers in other nations, and thus the results of this study may not be adaptable as a whole to other nations' systems.

The present study is register-based and available independent factors were used in the analyses. The fighter pilots' annual maximal bicycle ergometry test was chosen to describe their fitness level. This was considered to reflect the overall fitness of pilots, although it measures the aerobic capacity more than muscular fitness. The subjects' annual military fitness test battery includes a basic muscular endurance test (i.e., push-ups, sit-ups, standing long jump), but unfortunately, this data was not available for the present study due to a different registering system. General strength test outcomes have been reported to be associated with outcomes of fighter pilots' musculoskeletal pathologies.[9,18] The aerobic fitness test result does not seem to have an effect on neck or back disorders. Suggested pilot-specific tests and conditioning programs are warranted to enhance pilot performance to the required level and to evaluate their working condition.[21] These pilot-specific test values should be used as independent variables in future follow-up studies that are suggested below.

The $+G_z$ forces are regarded as a causative or aggravating factor, of which effects can be reduced by limiting the pilot's exposure to high $+G_z$ forces. Maximum $+G_z$ limitation without airframe restrictions is commonly used in FINAF with spinal disorders and it is adjusted individually to achieve a flight envelope where the pilot remains asymptomatic. Fig. 3 highlights the waiver with any max G_z limitation as a useful tool to manage $+G_z$ strain for symptomatic pilots. It has made it possible to continue to fly HPAs even 10 yr after earlier existing symptoms when $+G_z$ loading has been adjusted to the level that pilots remain asymptomatic. Their health is not compromised as their symptoms have diminished, but their experience and airmanship are in use in the squadrons. That these trained pilots have been able to continue in some active flying duties means the effort to flight train them is used more optimally.

The presented FI method is based on a formula for metallurgic considerations not physiological ones. Based on the literature, amplified axial loading on the human spine is considered to have more linear effect on spinal structures than presented in the FI formula.[5,19] Still, some weighting factors have been suggested with some other studies.[3,17] The rationale to use a complicated metallurgic formula in this study was that it is a value that has been followed up since the first subjects started their jet flight training and it has been adopted to use for pilots' follow-up as well. The suggested maximum for follow-up on pilots' annual exposure is 13 FI/1000 flight hours. This figure comes from specific values for structural fatigue follow-up of a fighter aircraft (unpublished observation: Air Force Command Finland, order CK9720; July 7, 2014), not from human spine loading physiology. Nevertheless, this 13 FI/1000 h is not a constant maximum that a pilot must not exceed. This system was introduced to increase pilots' and squadron leaders' awareness about who may be at risk due to intensive loading, and to be a tool for smart scheduling in order to manage occupational loading.

The FI method more carefully takes into consideration the sortie by sortie $+G_z$ loading spectrum than previous methods. Therefore, it is considered to be a more precise tool to determine fighter pilots' $+G_z$ loading than just flight hours or flown aircraft type as in previous studies.[7,14] However, based on the results of this study, it is not precise enough. The limitation of

FI is that it indicates just thresholds of certain $+G_z$ levels. It does not count the time of exposure.

The present study could not find any particular breaking points in the survival analysis nor was any particular independent factor causing fighter pilots' spinal disorders discovered. It must be concluded that the issue is a multifactorial, long-term phenomena. Thus, multifactorial, long-term countermeasures and follow-up are needed to prevent negative health effects and compromised operative performance.

ACKNOWLEDGMENTS

Financial Disclosure Statement: This study was supported by a grant from the Centre for Military Medicine, Finnish Defence Forces. The authors have no competing interests to declare.

Authors and Affiliations: Roope Sovelius, Ph.D., Tuomas Honkanen, Ph.D., and Marjo Janhunen, M.Sc., Centre for Military Medicine, Finnish Defence Forces, Helsinki, Finland; Maunu Mäntylä, M.Sc., Test Flight Centre, Finnish Air Force, Pirkkala, Finland; Heini Huhtala, M.Sc., University of Tampere, Tampere, Finland; and Tuomo Leino, Ph.D., National Defence University Finland, Helsinki, Finland.

REFERENCES

1. Adams MA, Freeman BJ, Morrison HP, Nelson IW, Dolan P. Mechanical initiation of intervertebral disc degeneration. Spine. 2000; 25(13):1625–1636.
2. Burton R. Cervical spinal injury from repeated exposures to sustained acceleration. Neuilly-sur-Seine Cedex (France): NATO RTO; 1999. Report No. AC/323(HFM)TP/9.
3. Callaghan JP, Salewytsch AJ, Andrews DM. An evaluation of predictive methods for estimating cumulative spinal loading. Ergonomics. 2001; 44(9):825–837.
4. Coakwell MR, Bloswick DS, Moser R Jr. High-risk head and neck movements at high G and interventions to reduce associated neck injury. Aviat Space Environ Med. 2004; 75(1):68–80.
5. Cripton PA, Dumas GA, Nolte LP. A minimally disruptive technique for measuring intervertebral disc pressure in vitro: application to the cervical spine. J Biomech. 2001; 34(4):545–549.
6. Farrell PSE. Aircrew neck pain prevention and management. Neuilly-sur-Seine Cedex (France): NATO STO; 2020. Report No. TR-HFM-252.
7. Grossman A, Nakdimon I, Chapnik L, Levy Y. Back symptoms in aviators flying different aircraft. Aviat Space Environ Med. 2012; 83(7):702–705.
8. Hermes ED, Webb TS, Wells TS. Aircraft type and other risk factors for spinal disorders: data from 19,673 military cockpit aircrew. Aviat Space Environ Med. 2010; 81(9):850–856.
9. Honkanen T, Mantysaari M, Avela J, Kyrolainen H, Leino T. Assessment of muscular fitness as a predictor of flight duty limitation. Mil Med. 2018; 183(11–12):e693–e698.
10. Honkanen T, Sovelius R, Mantysaari M, Kyrolainen H, Avela J, Leino TK. +Gz exposure and spinal injury-induced flight duty limitations. Aerosp Med Hum Perform. 2018; 89(6):552–556.
11. Kang S, Hwang S, Lee ET, Yang S, Park J. Measuring the cumulative effect of G force on aviator neck pain. Aviat Space Environ Med. 2011; 82(11):1042–1048.
12. Kikukawa A, Tachibana S, Yagura S. G-related musculoskeletal spine symptoms in Japan Air Self Defense Force F-15 pilots. Aviat Space Environ Med. 1995; 66(3):269–272.
13. Lange B, Torp-Svendsen J, Toft P. Neck pain among fighter pilots after the introduction of the JHMCS helmet and NVG in their environment. Aviat Space Environ Med. 2011; 82(5):559–563.
14. Lawson BK, Scott O, Egbulefu FJ, Ramos R, Jenne JW, Anderson ER. Demographic and occupational predictors of neck pain in pilots: analysis and multinational comparison. Aviat Space Environ Med. 2014; 85(12):1185–1189.
15. Nachemson A, Elfström G. Intravital dynamic pressure measurements in lumbar discs. A study of common movements, maneuvers and exercises. Scand J Rehabil Med Suppl. 1970; 1:1–40.
16. Newman DG. +Gz-induced neck injuries in Royal Australian Air Force fighter pilots. Aviat Space Environ Med. 1997; 68(6):520–524.
17. Parkinson RJ, Callaghan JP. Quantification of the relationship between load magnitude, rest duration and cumulative compressive tolerance of the spine: development of a weighting system for adjustment to a common injury exposure level. Theor Issues Ergon Sci. 2008; 9(3):255–268.
18. Rintala H, Hakkinen A, Siitonen S, Kyrolainen H. Relationships between physical fitness, demands of flight duty, and musculoskeletal symptoms among military pilots. Mil Med. 2015; 180(12):1233–1238.
19. Schultz A, Andersson G, Ortengren R, Haderspeck K, Nachemson A. Loads on the lumbar spine. Validation of a biomechanical analysis by measurements of intradiscal pressures and myoelectric signals. J Bone Joint Surg Am. 1982; 64(5):713–720.
20. Shiri R, Frilander H, Sainio M, Karvala K, Sovelius R, et al. Cervical and lumbar pain and radiological degeneration among fighter pilots: a systematic review and meta-analysis. Occup Environ Med. 2015; 72(2):145–150.
21. Slungaard E, Green NDC, Newham DJ, Harridge SDR. Content validity of level two of the Royal Air Force Aircrew Conditioning Programme. Aerosp Med Hum Perform. 2018; 89(10):896–904.
22. Sovelius R, Mantyla M, Heini H, Oksa J, Valtonen R, et al. Joint helmet-mounted cueing system and neck muscle activity during air combat maneuvering. Aerosp Med Hum Perform. 2019; 90(10):834–840.