Head Movements and Neck Muscle Activity During Air Combat Maneuvering

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BACKGROUND: The aim of the study was to determine the characteristics of cervical muscle activity in different head movements when using helmet mounted display in air combat maneuvering.

METHODS: Cervical EMG was measured with eight F/A-18 pilots using the Joint Helmet Mounted Cueing System (JHMCS) during air combat maneuvering. In-flight G_z acceleration and continuous head position were recorded. Muscular activity was compared between head movements in isolation and combined with torso movement. In addition, the effect of the direction of head movements and the use of head support of the ejection seat on muscle activity was determined.

RESULTS: Muscular loading increased in the cervical flexors and extensors when using the torso during targeting beyond the field of vision in the neutral sitting posture; the difference was significant in the flexors, but activity levels were higher in the extensors. Cervical muscles are loaded to a lesser extent if the head is kept in a stable position during G_z loading. Muscular activity in the neck muscles was higher when the pilot was moving the head out of neutral posture rather than toward neutral posture. The use of the headrest as a support decreased muscle activity in the extensors, but resulted in higher activity in the flexor muscles.

DISCUSSION: All analyzed conditions were significantly affected by an increase in G_z. An increase of muscle activity with torso movements is considered as a positive factor as it reflects maintained muscular support for the cervical spine. Presented results may be helpful when specific conditioning programs and cockpit ergonomics are developed for fighter pilots.

KEYWORDS: +Gz, EMG, workload, cockpit ergonomics.

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Fighter pilots' spinal structures, especially in the cervical area, are exposed to high inertial forces due to air combat maneuvering (ACM). Modern helmet mounted devices with weapons targeting technology have changed cockpit ergonomics. Increased mass of the helmet system and its shifted center of gravity are parallel to an increased need to move the head during targeting, which subjects a fighter pilot's neck to a higher risk for injury. Awkward head postures, especially during the highest G_z forces, have increased as tactical use of the Joint Helmet Mounted Cueing System (JHMCS) forces pilots to use the full range of motion of the head to effectively use aircraft weapon systems off boresight. Besides technological and operational advantages, the use of the JHMCS has been reported to increase the harmful effects of G_z loading on the cervical spine and muscles.[2,10,16]

These new challenges have created a need for better cockpit ergonomics. During training pilots are encouraged to use the headrest on the ejection seat or other cockpit structures as a head support during high G_z loading. Additional strategies such as combining torso movements with head movements are used to avoid the maximal range of motion in the cervical spine, especially during high-angle rotations to the rear of the aircraft.

Cervical musculature strength levels apparently vary with head-neck position and the direction of movement. Extension force or torque is greater than flexion force and the neck rotator muscles have the least isometric force-generating capacity among the functional neck muscle groups.[4] Neck extensor strength is decreased from the flexion to extension position in the lower cervical spine. Force production toward the neutral

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posture is reported to be highest both in the sagittal and horizontal planes.[7] Similarly, maximal neck rotation strength is achieved when the head and neck are at the highest prerotation angles.[19] The highest strength values are not reached in the neutral position, but while turning the head in the opposite direction from the prerotated position. So under G_z forces cervical muscles are working more efficiently at any bended head posture when turning the head back toward the neutral posture than turning the head away from the neutral posture.

In questionnaires, pilots have reported the use of the ejection seat headrest or canopy as a strategy to diminish cervical G_z loading. Reports show that pilots can reduce cervical loads by wedging or bracing the head against aircraft structures prior to the application of $+G_z$.[12] As a result, the total mass of the head and helmet system is not maintained by the neck structures, but is partially carried by the structures the head is supported against. In a study by Green and Brown,[5] the activity of the neck erector spinae was halved when the canopy was used as a support.

To achieve higher angles of line of sight more easily, combined torso movement has potential benefit in the operational setting if it leads to more accurate and quicker performance when tracking targets. However, there is a lack of documented studies investigating the effect of G_z forces on muscle activity and movement accuracy in these conditions.

The aim of this study was to determine the characteristics of cervical muscle activity during 1 vs. 2 ACM to provide knowledge for appropriate and effective countermeasures. An earlier article presented a general overview of neuromuscular activity in the cervical area when using JHMCS helmets.[15] This paper will focus on muscular activity during cervical movements, and how torso rotation and use of the ejection seat headrest support effect cervical loading during different G_z levels.

METHODS

Subjects

Acting as test subjects were 13 Finnish Air Force F/A-18 pilots. Their mean age was 30 yr (range 27–35). Their mean height was 180 cm (SD $\pm$ 4 cm), weight 78 kg ($\pm$ 5 kg), and body mass index (BMI) 24 $\pm$ 1 kg $\cdot$ m^{-2}. They all were men as there were no female subjects available to attend the study. The subjects had no flight limitations in their flying status and they did not report any current musculoskeletal symptoms before test flights. They all used the JHMCS (Vision Systems international, San Jose, CA, USA) on a regular basis. Out of 13 test flight recordings, 5 were excluded from the study due to technical problems in the EMG recordings (3 flights) or with test flight instruments (2 flights).

The subjects were informed of the details of the experimental protocol. The Finnish Defense Forces Medical Research Register, the Finnish Air Force Headquarters, which granted a Research License, and the Ethical Committee of the Central Finland Hospital District, approved this study.

Equipment

The test flights were flown in dedicated F/A-18D Hornet aircraft equipped with test flight instrumentation collecting acceleration of the aircraft in the x, y, and z directions, attitude in pitch, roll, and yaw, and the rates of changes of these variables. The helmet's elevation (flexion or extension angle), azimuth (rotation angle), lateral bending, and the rate of head movements in these planes were also collected as a function of flight time. Each pilot's maximal range of movements in rotation, extension, and flexion were measured during JHMCS calibration before flight. The line of sight of the helmet was used to determine head postures and movements. This was done when strapped in the cockpit with full flight gear on just prior to the start of the sortie.

During the sorties EMG activity of the right and left sternocleidomastoid (SCM) and cervical erector spinae (CES) was measured using bipolar surface electrodes. Muscle activity was determined using a portable eight-channel EMG device (ME6000P, Mega Electronics Ltd., Kuopio, Finland). Bipolar EMG recordings were obtained using pregelled surface electrodes (Medicotest M-OO-S, Olstykke, Denmark) placed longitudinally on muscles with a distance of 2 cm between their measurement surfaces. Ground electrodes were placed on inactive tissues. Electrodes were placed according to the SENIAM guidelines.[8] EMG signals from the skin above working muscles were acquired at a sample rate of 1000 Hz. The measured signal was preamplified 2000 times, and the signal band between 20 and 500 Hz was full-wave rectified and averaged with a 100-ms time constant. EMG level and muscle activity were determined as a percentage of maximal voluntary contraction (%MVC). Measured in-flight EMG was compared with EMG recorded during maximal voluntary contraction (MVC) performed prior to the walk to the aircraft. MVC efforts were performed by test subjects in a seated posture while wearing their flight suit without life vest and helmet. Subjects performed three 5-s maximal voluntary isometric contractions. Test MVC of SCM and CES were measured during isometric flexion and extension, respectively. The peak activity of each muscle was then used as an MVC value.

Procedure

The data was collected during an air combat sortie, one fighter against two ships within visual range. The test subject flew the solo aircraft against two others; this setting was chosen in order to provide as many head movements as possible. The test flight consisted from three to six encounters depending on operational factors. All encounters were recorded from starting point to an end, when a pilot terminated the encounter. All encounters started beyond visual range and pilots were briefed to start them with similar set-ups so that the beginning of maneuvering would be identical. The fight then developed to a within visual range dogfight, freely within the tactical situation, and without any limiting factors in terms of study settings. The transit flights and time between encounters were excluded from more detailed analysis.

All recorded data via JHMCS helmet system was linearly interpolated to a 0.02-s time frame during post-processing. Similarly, EMG data was linearly interpolated to the same 0.02-s time frame. EMG and JHMCS data had different time sources and those two data sources needed to be synchronized. The 0.02-s time frame helped to achieve more accurate synchronization. Time synchronization was determined by comparing JHMCS sensor position values and rates and EMG activity during JHMCS calibration.

During posture analysis contra- and ipsilateral SCM and CES were separated. When the pilot was looking to the right, the right-side SCM and CES were defined as ipsilateral muscles and the left-side muscles as contralateral. When the pilot was looking to left, opposite muscles were defined to ipsi- and contralateral, respectively. Thus, later in the text ipsi- or contralateral terms include data from both the right and left muscles; the side is dependent on the direction of rotation at the moment. The aim of this approach was not to lose the comparable data between agonist-antagonist or bilateral muscle group activations regardless of direction of rotation.

Naturally, rotation angles beyond 90° cannot be achieved without rotation also from the thoracic spine, but head movements were considered as isolated if the helmet was not moved forward (with torso flexion) and remained in contact with the ejection seat headrest. The helmet's contact with the headrest was calibrated during helmet calibration before takeoff. If the helmet was determined to move forward from its neutral position, the head movements were considered to be performed with torso movement. Additionally, the effect of direction of the head movement on muscle loading was studied. The resultant vector of head movement during flexion-rotation or extension-rotation combination postures at all test points was determined and the direction of the resultant vector was regarded as out of neutral or toward neutral sitting posture.

The effect of head support strategy on cervical muscle loading was analyzed with head position as a separate factor and with interaction of different G_z levels. G_z was categorized as low ($\leq +4\ G_z$) or high ($> +4\ G_z$) for the analysis of variances.

Statistical Analysis

Descriptive statistics, means with 95% confidence intervals (CI95%), are used as descriptive parameters. Means with standard deviation (SD) are presented when ANOVA is performed. All changes in head postures during test flights were considered as separate test points; subsequently some 156,000 postures were analyzed in all.

Measured outcome (EMG) was a continuous parameter and considered normally distributed. A mixed (random + fixed) model of ANOVA was used to study the effect of given factors on muscle activity. Model structures are described below with their respective findings. The level of statistical significance was set at $P < 0.05$. Primarily combined effect of factors was considered. When an effect of an individual factor is presented, it is then stated.

The study setting did not allow use of controls during test flights. Control measurements would have needed similar flights with a legacy helmet without head postures data or flying with JHMCS off. Both options would cause different data to be collected as well as a lack of available information for pilots that would lead to different cervical loading due to different tactical flying.

RESULTS

Mixed effect ANOVA was used to examine the effect of torso movements in combination with head movements on cervical muscle activity. The study design was as follows: subjects were considered random factors as there was an intrasubject dependency on measured test points; head movements (helmet movement recorded as in isolation or with torso movement) and different G_z levels were considered fixed factors. The head movements with torso movement increased the muscle activity both in the SCM and CES compared to head movements in isolation. The increase was greater in the CES, but statistically significant in the SCM. This increase of EMG activity in the SCM was statistically significant when movement patterns were analyzed separately. When the interaction of acceleration levels was included with head movement in the analysis, the increase of muscle activity was more significant and was seen also in the CES. Higher G_z levels load more contralateral muscles in relation to rotation direction. More detailed results with rotation side differences included are presented in **Table I**.

Mixed effect ANOVA was used to examine whether direction of head movement away or toward the neutral position influenced cervical muscle activity. In this study, subjects were considered random factors as there was an intrasubject dependency on measured test points; direction of head movements (helmet movement recorded as toward or away from neutral position) and different G_z levels were considered fixed factors. In post hoc evaluations, Levene's test with Bonferroni indicated that fixed factors effects varied significantly from the main effects. However, only ANOVA results (P, F) are presented as post hoc analysis did not raise any specific difference between factors individually or in their interaction. The mean SCM activity during head movements out of neutral was 53.8% (CI 95% 52.8–54.7% MVC), toward neutral head position 44.2% MVC (CI 95% 43.4–45.0% MVC), and when the head was maintained stable mean SCM activity was 24.7% MVC (CI 95% 24.5–24.8% MVC). Respectively, the values for CES activity were 57.0% MVC (CI 95% 56.1–57.9% MVC), 50.8% MVC (CI 95% 50.0–51.6% MVC), and 37.1% MVC (CI 95% 36.9–37.3% MVC). Both muscle groups had higher activity when the head was moved away from the neutral posture. The head in a stable condition resulted in lower EMG activity compared to both direction of movement in the SCM and CES during lower acceleration levels. During higher G_z ($> 4\ G_z$) this difference diminished in the SCM and disappeared in the CES (**Fig. 1**). Significant differences were identified in both muscles between G levels (SCM: $F = 5.450$, df $= 6$, $P = 0.006$; CES: $F = 4.830$, df $= 6$, $P = 0.009$) and direction of

Table I. The Comparison of Cervical Muscle Activity (in %MVC) Between Head Movements in Isolation and with Torso Movements During Different G_z Levels.

	SCM		CES	
	CONTRALATERAL	IPSILATERAL	CONTRALATERAL	IPSILATERAL
	MEAN (SD)	MEAN (SD)	MEAN (SD)	MEAN (SD)
Head movements				
$> 4\ G_z$				
in isolation	50.0 (40.3)	38.8 (29.8)	57.8 (45.6)	55.5 (46.9)
with torso	57.5 (37.5)	42.7 (34.1)	64.8 (43.1)	65.7 (48.2)
$\leqslant 4\ G_z$				
in isolation	26.6. (30.2)	24.9 (30.3)	38.8 (42.5)	39.6 (41.9)
with torso	36.4 (33.3)	33.6 (35.9)	46.5 (43.2)	47.8 (44.8)
P_{torso}	0.019	0.020	0.629	0.329
F_{df}	$F_{8,57124} = 5.511$	$F_{8,57018} = 5.410$	$F_{7,51860} = 0.755$	$F_{7,50555} = 1.460$
$P_{torso+Gz}$	<0.001	0.011	0.026	<0.001
F_{df}	$F_{8,57124} = 5.488$	$F_{8,57018} = 2.613$	$F_{7,51860} = 2.395$	$F_{7,50555} = 6.838$

Head movements and different G_z levels were considered as fixed factors. First the effect of head movement pattern was analyzed as a separate factor (P_{torso}) then in combination with G_z ($P_{torso+Gz}$). Muscles are presented as ipsi- or contralateral, depending on the direction of cervical rotation. SCM = sternocleidomastoids; CES = cervical erector spinae; %MVC = muscle activity as a percent of maximal voluntary contraction; SD = standard deviation; P_{torso} = *P*-value of torso movement as a separate factor; $P_{torso+Gz}$ = *P*-value of torso movement in combination with G_z.

head movement (SCM: $F = 8.874$, df $= 14$, $P < 0.001$; CES: $F = 33.658$, df $= 2$, $P < 0.001$), and in interaction of these variables (SCM: $F = 9.642$, df $= 12$, $P < 0.001$; CES: $F = 13.357$, df $= 12$, $P < 0.001$).

Mixed effect ANOVA was used to examine whether cervical muscle activity varied when the pilot used or did not use the headrest as a support. In this study, subjects were considered random factors as there is an intrasubject dependency on measured test points; head position (supported against headrest, helmet placement without contact to headrest) and different G_z levels were considered fixed factors. Conditions where the upper body moved, like torso flexion, and when the helmet was located away from "over-the-seat-to-sit" were excluded from this analysis. When pilots used the headrest of the ejection seat as a support, muscle activity decreased in both in the cervical flexors (SCM) and in the extensors (CES): 2.7% (CI 95% 0.6–4.8) and 10.2% (CI 95% 8.1–12.3), respectively. The difference was statistically significant only in the extensor muscles. When the effect of G_z loading was included in the analysis, the changes in muscle activity were statistically significant in both muscle groups but in different ways. Muscular activity was diminished in the CES with use of head support, but increased in the SCM for higher G_z levels. More detailed results with rotation side differences included are presented in **Table II**.

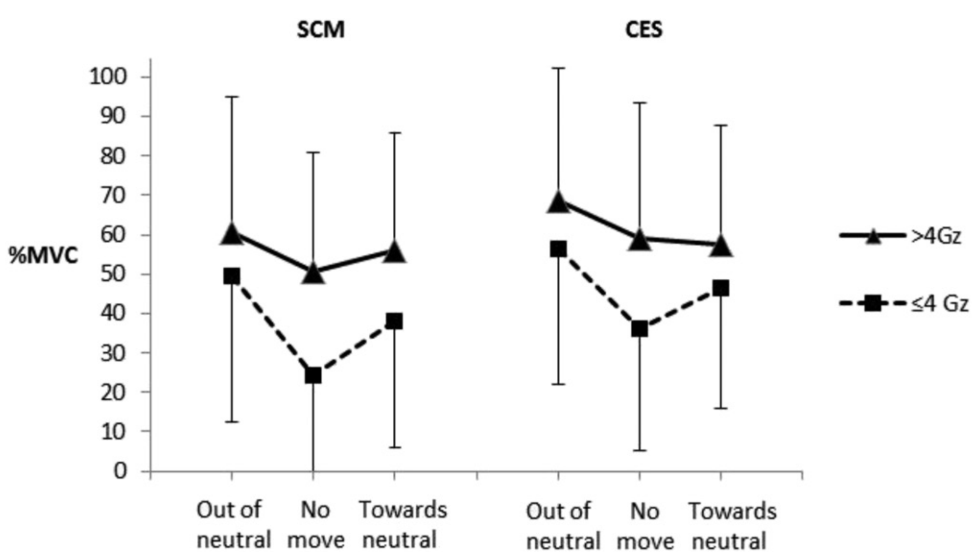

Fig. 1. Mean muscular activity in SCM and CES in order of direction of head movement. All head postures without movement were placed into the No move category. The resultant vector of flexion-extension and rotation movements indicated when the move was out of neutral or toward neutral. SCM = sternocleidomastoids; CES = cervical erector spinae; %MVC = muscle activity as a percent of maximal voluntary contraction. Error bars indicate standard deviation.

DISCUSSION

The comparison of cervical muscular activity between head movements in isolation and with torso movements indicated higher muscular loading both in the SCM and CES when using the torso during targeting. The results of this study are paradoxical to the goal of enhanced cockpit ergonomic actions to diminish cervical loading. In an earlier paper[15] we reported that pilots' cervical muscles force production capacity is exceeded during awkward postures of the head and higher G_z. EMG activity is diminished as the muscle fails to support the head during axial loading. Thus, the result must be considered as a positive sign, as higher muscular activity means maintained force-producing capacity with muscular support. We hypothesized that higher EMG activity, at least in the SCM, indicates a maintained muscular support, preventing higher load bearing by the spinal column. Thus the lower the force transmitted via the spinal column and intervertebral discs, the lower the risk of load-induced premature disc degeneration. This is adverse to the cumulative injury model where a lack of muscular capacity and support results in intervertebral

Table II. The Effect of the Use of Head Support on Cervical Muscle Activity During Different G_z Loading Levels.

	SCM			CES		
	NEUTRAL*	CONTRALATERAL†	IPSILATERAL†	NEUTRAL*	CONTRALATERAL†	IPSILATERAL†
	MEAN (SD)	MEAN (SD)	MEAN (SD)	MEAN (SD)	MEAN (SD)	MEAN (SD)
Head supported to seat						
$> 4\ G_z$						
Yes	40.5 (30.9)	74.4 (42.8)	56.9 (44.5)	52.2 (33.0)	54.4 (37.7)	45.8 (41.5)
No	38.5 (24.2)	62.2 (43.6)	44.5 (33.2)	50.4 (33.6)	68.3 (45.8)	65.7 (48.8)
$\leq 4\ G_z$						
Yes	16.0 (20.3)	52.3 (41.2)	50.4 (46.6)	28.3 (26.3)	52.8 (40.1)	55.4 (47.5)
No	16.4 (18.2)	46.2 (35.9)	43.0 (40.5)	30.3 (29.3)	57.2 (42.4)	53.8 (46.1)
P_{head}	0.679	0.102	0.547	0.015	0.531	0.029
F_{df}	$F_{6,79704} = 0.697$	$F_{7,17131} = 2.758$	$F_{7,16550} = 0.912$	$F_{6,79704} = 8.914$	$F_{7,15615} = 0.935$	$F_{7,15756} = 6.936$
$P_{head+Gz}$	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F_{df}	$F_{6,79704} = 6.518$	$F_{7,17131} = 10.195$	$F_{7,16550} = 7.488$	$F_{6,79704} = 7.285$	$F_{7,15615} = 8.107$	$F_{7,15756} = 4.378$

Head support use and different G_z levels were considered as fixed factors. First the effect of using head support was analyzed as a separate factor (P_{head}) and then in combination with G_z ($P_{head+Gz}$). Muscles are presented as ipsi- or contralateral, depending on the direction of cervical rotation.
SCM = sternocleidomastoids; CES = cervical erector spinae; Mean = %MVC, muscle activity as a percent of maximal voluntary contraction; SD = standard deviation; P_{head} = *P*-value of head support used as a separate factor; $P_{head+Gz}$ = *P*-value of head position in combination with G_z.
* Head in a sagittally normal position, no rotation (includes both left and right side muscles); † head during any rotation in posture.

disc and spinal degenerative changes.[1,3] This suggested theory must be tested with further investigations. Use of torso movements like rotation and/or flexion from the lumbar spine may diminish the need for range of movement in cervical rotation when targeting at high angles. This study was not able to determine how much the isolated cervical rotation could change when a pilot is performing the rotation movement with or without combined torso flexion and rotation movement. Thuresson[17] reported increased muscle activity during ipsilateral rotated positions with head and torso flexion than in most other positions among helicopter pilots. Fighter pilots try to avoid flexion positions, at least during high G_z, thus results between different airframes are not directly comparable. However, a similar pattern of supportive muscle column activation is seen. It is the ipsilateral cervical extensor that bears the axial load in a combined rotation + flexion posture and, respectively, the contralateral extensor in combined rotation + extension posture, which is more common during ACM. Thus we recommend future studies in which recognized risky postures are followed up pilot by pilot and flight by flight to evaluate the long-term effects of different cockpit ergonomics on pilots' cervical disorders,[14,18] and to determine the most effective preventive actions.

When the direction of head movement was analyzed, EMG was higher during out of neutral direction head movement. This was seen both in the SCM and CES; G_z loading did not change this pattern, but made it more evident. The results are in line with presented reports in +1 G_z conditions.[7,13,19] Also, some studies have considered head movements in the high G_z environment,[5,6,11] but those results are not quite comparable to the movement analysis of the present study as the EMG values other studies have presented were recorded during different conditions, e.g., only in stable head positions.

Muscular activity was naturally highest when muscles were performing movement in addition to bearing the axial loading of G_z forces (Fig. 1). SCM activity increases more during higher G_z loading ($>$ +4 G_z). CES activity is relatively high already at $\leq$ +4 G_z. This may be due to more head down (flexion) time with instruments and more head movements when a pilot is observing the situation outside the cockpit. When there is higher G_z loading, the CES activates more for support and stabilizes the head in different postures as well as during conditions where the head is stable. There is great deviation in presented muscular activity in both muscles and G_z levels, as the figures presented include the muscle activity in both left and right muscles in all head postures during flight. However, the main finding in Fig. 1 is the difference between head movements and stable conditions. The question lies in the line between the bars, as a pilot using JHMCS need to move and aim the lock symbol over the target and maintain it there: what is the pilots' ability to cue the weapon during awkward postures during high G_z? Head-aiming is reported to be deteriorated when G_z loading is increased.[9] The question cannot be answered with these results, but it does warrant further studies.

The use of the ejection seat headrest as a support decreased muscle activity in the extensor muscles (CES). During higher G_z loading ($>$ +4 G_z) the SCMs were loaded more than in conditions where the head was without support. This pattern of activation was seen predominantly on the side toward where rotation is performed. As rotation movement is mainly executed by the contralateral SCM, this ipsilateral muscle activation is considered to occur in order to support axial loading frontally when the occiput or temporal part of the helmet is supported against the headrest. All measured muscles are activated for support during axial loading. Nevertheless, independently, the significance of G_z was most important over any other studied variables.

In this study the effect of supporting the head to reduce extensor muscle activity was lower than Green and Brown reported.[5] This may be explained by different study methods and test points. The situations when the pilot may have supported the head on the canopy or other cockpit structures could not be identified in this study setting. Green and Brown[5] reported EMG activity levels during particular moments chosen from a cockpit video, but in this study the figures are means from all test points where particular head positions took place. Also, the different helmet systems used themselves may have influenced the findings in these studies. Additionally, conditions such as head postures with support vary between the studies. Since the head position and posture analysis is based on recorded position in a coordinate system made by JHMCS during its calibration, there may also have been some collecting bias between interpreted data and actual conditions (e.g., was the head actually in contact with the headrest or not). Thus conclusions for the benefits of different head support strategies cannot be made. It can be considered that supporting the head during high G_z is beneficial in terms of muscular activity, and the more the head is away from neutral position, the more advantage is achieved, at least in some activated muscles.

When pilots' cervical muscles are subjected to maximal performance there is also the risk of acute muscle and ligamentous injuries. Therefore, pilots' muscular fitness and muscle control must be trained as highly as possible. The combined effect of high G_z and head position and movement variables had statistically the most significant outcome on all muscle groups studied. This indicates the importance of the acceleration effect on pilots' cervical loading. Thus, the more G_z, the more vigilantly countermeasures must be performed.

The present results should be helpful when occupationally specific conditioning programs are developed for fighter pilots. The results of this study should also be taken into consideration when pilots' cockpit ergonomics are developed and optimal targeting strategies are trained in terms of diminishing the cervical loading due to G_z forces.

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