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Original research

The effect of helmet mass and aircraft acceleration on cervical spine loads during typical fast jet aircraft pilot head motions

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ABSTRACT

Objectives: Gravitational Force (Gz), head motion, and helmet mass are associated with neck pain in high performance aircraft pilots. Few studies have quantified neck kinetics (intersegmental neck moments) during aerial combat manoeuvres.
Design: Cross-sectional.
Methods: We quantified net joint moments between the skull and C1, and C6–7 during typical flight related headchecks using the Musculoskeletal Model for the Analysis of Spinal Injuries (MASI). We measured the influence of pilot-specific helmets and Gz on joint moments. Nineteen fighter pilots performed four head checks (check6 left, check6 right, extension hold and extension scan) under two helmet conditions. Motion data were transferred to OpenSim where joint moments were calculated at 1G to 9G. Net joint moments were compared across helmet conditions, Gz and headchecks.
Results: The Joint Helmet Mounted Cueing System (JHMCS) resulted in higher moments at each segment- by a factor of 1.25 per unit of Gz, at C1, and by a factor of 1.08 per unit of Gz for C7. ExtensionScan and Check6Left were associated with the highest peak (96.13 Nm and 92.56 Nm). ExtensionScan and ExtensionHold accrued the highest mean cumulative loads at C7 at 9Gz (607.35 Nm.*sec*/motion, 362.99 Nm.sec/motion respectively). Asymmetries were observed between the Left and Right Check6 motions. High variability was evident between and within pilots.
Conclusions: The MASI model has been successfully applied to quantify intersegmental neck joint moments for typical headchecks that are performed during combat flight manoeuvres. In future, data derived from this model may inform conditioning, rehabilitative and preventative interventions to reduce neck pain in fast jet pilots.

Practical implications

- Occupationally significant neck pain is twice as prevalent in fast jet pilots as in the general community.
- More capable aircraft, higher G-Force, helmet type, head posture and increased helmet mounted mass are the most likely contributors to total neck workload.
- This study has calculated dynamic neck moments applied to cervical segments in 19 trained pilots performing 4 common headcheck motions and accounting for the effects of G-force and helmet design.
- Mean, peak and cumulative net joint moments have now been defined.
- Individual differences and movement asymmetries suggest individual workload modelling is required for more accurate workload assessment and to inform risk mitigation strategy.

1. Background

Fast jet aircrew (FJA) operate high performance aircraft while exposed to high and rapidly applied gravitational accelerations.[1] The highest and most frequent accelerations result in compressive forces directed through the z axis (Gz). Pilots manoeuvre their aircraft to execute offensive and defensive combat engagements while maintaining awareness of targets in the surrounding airspace.[2] To achieve this, FJA will "headcheck" by turning their head, neck and trunk into extreme ranges of motion (ROM) to scan the airspace (Supplementary Fig. 1). Headchecks involving neck rotation and/or extension have been associated with neck pain and injury.[3] Performing headchecks under high Gz

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with helmets and helmet-mounted equipment increases cervical stress[4] and likely contributes to neck pain.[5]

The prevalence of neck pain in the FJA population varies across published literature.[6] Some studies report figures as high as 89.1 %. This is concerning given the 5.9 % to 22 % global point prevalence of neck pain in the general population.[7] It costs $15.2 million to train an F/A-18 Hornet pilot in Australia and $72,000/h of flight[8] The consequences of neck pain for FJA, including debilitation, time loss from flight duties,[5] and termination of career[9] are strategic causes for concern.

In elite sport, load monitoring has become standard practice, as evidence has demonstrated the risks of high acute and/or chronic workloads on the musculoskeletal system[10] and benefits achieved by tracking and adjusting workloads for individuals as they approach known thresholds.[11] FJA routinely log flight hours, however time of flight has been shown to be unrelated to neck pain complaints.[12] It is likely that better understanding of the intensity, frequency, type and duration of head motion over the duration of flight will be more enlightening.

Authors have investigated muscular responses to the effects of helmets and helmet mounted masses,[13] Gz[14] and headchecks.[15] Much of this research has used surface electromyography (SEMG) to examine muscle activity as a surrogate measure of load.[1] However, the accuracy of SEMG is affected by factors like skin conductivity, electrode placement and cross-talk between electrodes.[16] Since SEMG measures muscle activation, muscle and joint forces can only be inferred from this data.[17] It also assumes that muscle overload is a primary source of complaint, potentially ignoring the contributions from overstrained or compressed joint-related structures.

Biomechanical characteristics of neck pain in FJA must be explored to develop more informed risk management.[9] Computerised musculoskeletal modelling is a tool used to simulate human movement. It facilitates the investigation of anatomical loading not normally examinable without invasive procedures.[18] The Musculoskeletal Model for the Analysis of Spinal Injuries (MASI)[19] is a graphical biomechanical model developed to enable the calculation of muscle lengths, forces and moments.[20] The MASI is composed of 35 rigid anatomical structures, 34 joints, 19 cervical muscle groups and 23 torque actuators to simulate muscle actions in the lower and upper body.[19] It can be applied to specific anatomical regions, and has been previously scaled for healthy rugby players to investigate neck loading during rugby scrums.[19] Validation of the MASI has been completed by comparing modelled kinematics, joint moments and neuromuscular activations of the neck with in vivo data collected from healthy individuals and rugby players.[21] Although data collected using force, torque and position transducers provide direct information about real time dynamic movement, the MASI allows for a near identical approach to first person data collection while allowing for the manipulation of equivalent forces and conditions in a controlled and safe environment.

There have been limited applications of musculoskeletal modelling to investigate neck pain for FJA. Studies have used biomechanical models to explore how pilot-specific helmets affect joint moments in the neck.[22] Some models have analysed the isolated effects produced by different helmets,[22] check6 movements[23] and aircraft ejection on neck forces. However, no previous studies have simultaneously compared joint moments in the neck while incorporating the combined effects of helmet type, headcheck type and changing Gz.

This study aimed to quantify neck joint moments between the occiput (C0) and C1, and C6-C7 during typical pilot headchecks. By simulating different levels of external force (Gz) and helmet+head mass, we aimed to determine the net joint moments, peak and cumulative moments per headcheck and the intersegmental moments around each axis.

2. Method

Prior to testing, analysis of two ten-minute videos from rearward facing cockpit cameras involving two pilots was conducted to determine typical head motions associated with basic flight manoeuvres. An average of 176 head rotations away from the head-up display were observed. Headchecks were categorised into four common motions; rotation of the head to look over the left shoulder toward the aircraft tail (Check6L) –; rotation of the head to look over the right shoulder toward the aircraft tail (Check6R) –; looking directly up through the rear of the cockpit (ExtHold)–; looking directly up through the rear of the cockpit with additional rotation of the head left and/or right (ExtScan) (Supplementary Fig. 1).

Ethical approval was granted by the Joint Health Command Low-Risk Ethics Panel (project number 18-005) and the University of Canberra Committee for Ethics in Human Research, (project 20180285). All participants provided prior written informed consent.

Nineteen pilots were recruited via briefings and distribution of participant information organised by the Air Combat Group at Williamtown, New South Wales. Individuals were eligible for inclusion if they were fit to fly and willing volunteers. The proportions of participants from each gender and age groups are not reported to maintain participant anonymity. Each participant had 28 retro-reflective markers measuring 14 mm in diameter fixed to key landmarks on the shoulder, helmet and neck according to established protocols.[19] They then performed several common headchecks in an F/A-18A Hornet ejection seat while secured with an adjustable harness. Pilots were asked to perform headchecks in their habitual way for a non-random sequence of basic flight manoeuvres. Duration and range of headchecks were not constrained to maintain external validity. Trajectory data was collected using a 12-camera T160 Series Vicon motion analysis system (Oxford Metrics, UK) sampling at 250 Hz and filtered using a low-pass fourth order Butterworth filter with a cut-off frequency of 12 Hz, determined after a residual analysis.[2419]

The MASI model allows for motion (flexion-extension, axial rotation and lateral bending) of each intervertebral joint between the skull and T1 to be calculated as a percentage of total movement between the head and trunk. This allows both the upper cervical spine (skull to C2) and lower cervical spine (C2-T1) to be modelled as six degrees of freedom mechanical linkage systems.[20] The MASI model has been developed by Cazzola et al. and validated against healthy individuals.[19,20] Subject-specific models for each participant were attained by scaling each subject's anthropometry.[19] Kinematic measures were determined using an inverse kinematic approach where the sum of the squares of the differences between experimental marker trajectories and virtual markers in the model was minimised.[25] Kinematic constraints were disabled prior to a standardised inverse dynamic approach being used to compute joint moments.[19] It is important to acknowledge that the model was used as a torque driven model without individual muscle forces being calculated, it is not clear how this influences the accuracy of estimated neck moments, however this was outside the scope of this current research. Both modelling processes were repeated for all movements after extra mass was added to the head to simulate differing levels of Gz (2,3,4,5,6,7,7.5,8,9G). The base mass of the head was modelled at 3.8 kg while all Joint Helmet Mounted Cueing System (JHMCS) and HGU-55/P (55P) helmets were modelled at 1.82 and 1.21 kg respectively and again added to the mass of the head. Centre of mass and moment of inertia information were taken from published data,[26] with the centre of mass for both the 55P and JHMCS being more anterior and superior then a non-helmeted condition. The JHMCS was also more anterior and superior in comparison to the 55P condition.[26]

Joint moments about each axis for C1, and C7 were exported, and summed to calculate net joint moments, similar to the approach seen when defining the support moment for the lower limb.[24] Cumulative joint moments were the product of mean Nm per second x motion duration.

z

All data was de-identified and descriptive analyses were conducted in Statistical Package for Social Sciences (SPSS) version 27. Statistical Parametric Maps (SPMs) were created using the open-source package SPM1d (version M.0.4.8, https://spm1d.org) in Matlab (version

R2022a, https://au.mathworks.com/products/matlab) to determine the difference in net joint moments between helmet conditions for each manoeuvre (using a paired *t*-test, SPM {t}). Significance was accepted when $p < 0.05$. Data processing and visualisation for the SPM analysis were performed using R (version 4.1.2, https://cran.r-project.org) in RStudio (version 2022.02.0, https://www.rstudio.com).

3. Results

Nineteen participants completed 75 trials with a 55P helmet, and ten participants completed 40 trials performing the headchecks with a JHMCS helmet. Nine participants changed helmets and completed trials under both helmet conditions in a randomised order. The total dataset included 115 motion files.

For every unit increase in Gz a linear increase in moments at all segments was observed (C1 net moment = 0.94Gz + 0.07, C7 net moment = 0.70Gz + 0.29). At C1 the net joint moment had increased by a factor of 8.61 from 1Gz to 9Gz. At C7 the net joint moment had increased by a factor of 6.63 from 1Gz to 9Gz (Fig. 1).

The JHMCS helmet was modelled 50.4 % heavier than the 55P and resulted in higher mean and peak moments at both segments. JHMCS was found to increase joint moments at C1 by a factor of 1.25 compared to at C1 under the 55P, while at C7, the JHMCS was found to increase joint moments by a factor of 1.08 compared to C7 under the 55P (Supplementary Table 2). SPM analysis showed that the JHMCS resulted in significantly higher flexion/extension moments in the ExtHold at C1, at the end of the motion at C7, and in the net joint moments at C1 (Fig. 2).

Ninety-five percent of data maintained narrow upper and lower bounds, however peak moment values varied by between 2.1 and 8.2 times the mean across individuals. The average proportion of Gz applied to C7 ranged from 25 % to 76 % between participants. The motions associated with the highest proportion of joint moments at C7 were the Check6R and ExtScan. Within these motions, peak values were as high as 96 Nm at the C7 segment. Joint moments associated with the neutral position are also reported in Supplementary Table 1. The neutral position was defined as head flexion or extension <15 degrees, head lateral flexion <15 degrees, and head rotation less than ten degrees.

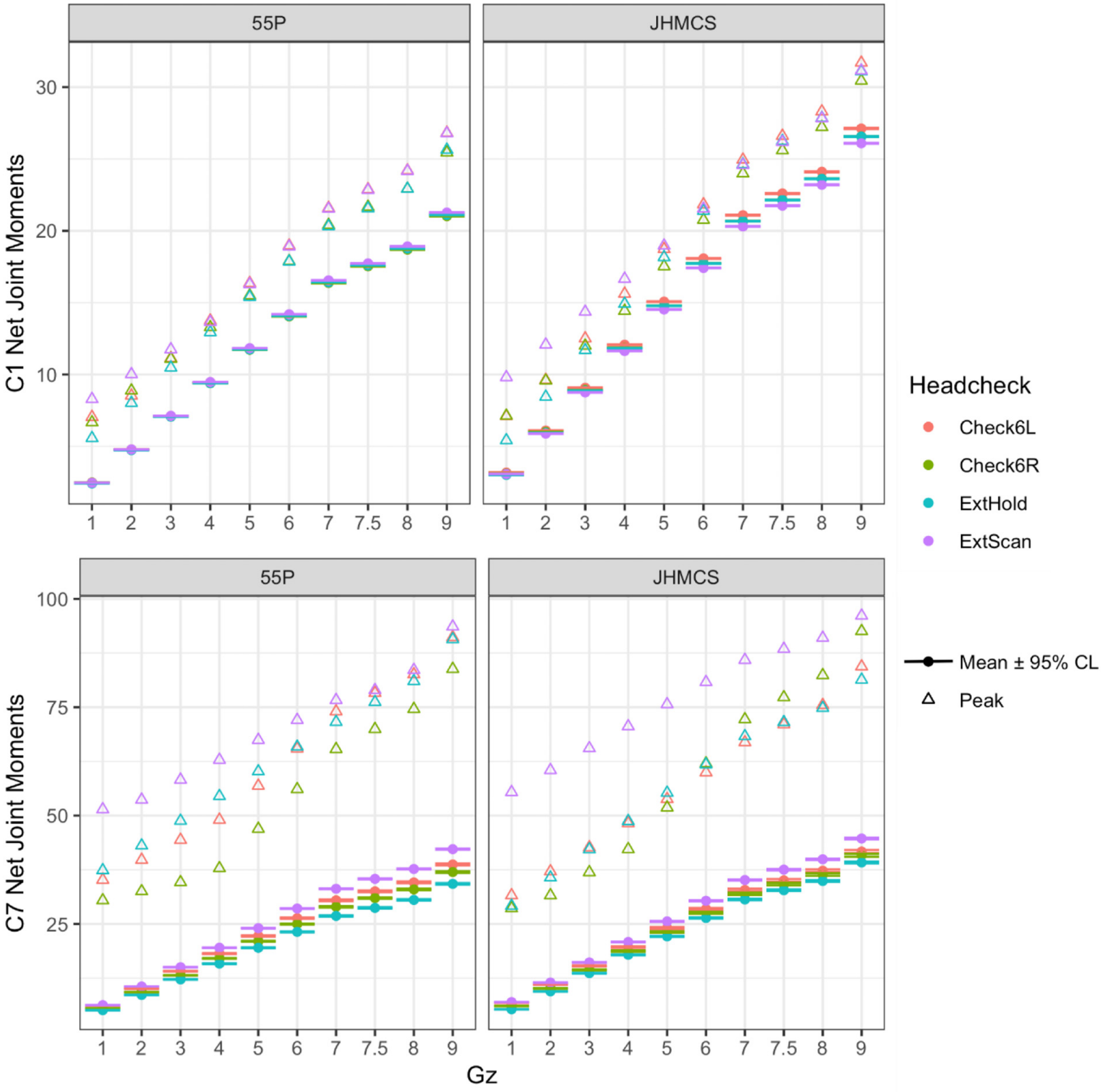

Fig. 1. Mean and Peak and confidence intervals for Net Joint Moments (Nm) by Gz, at C1 and C7, and for each helmet, and headcheck.

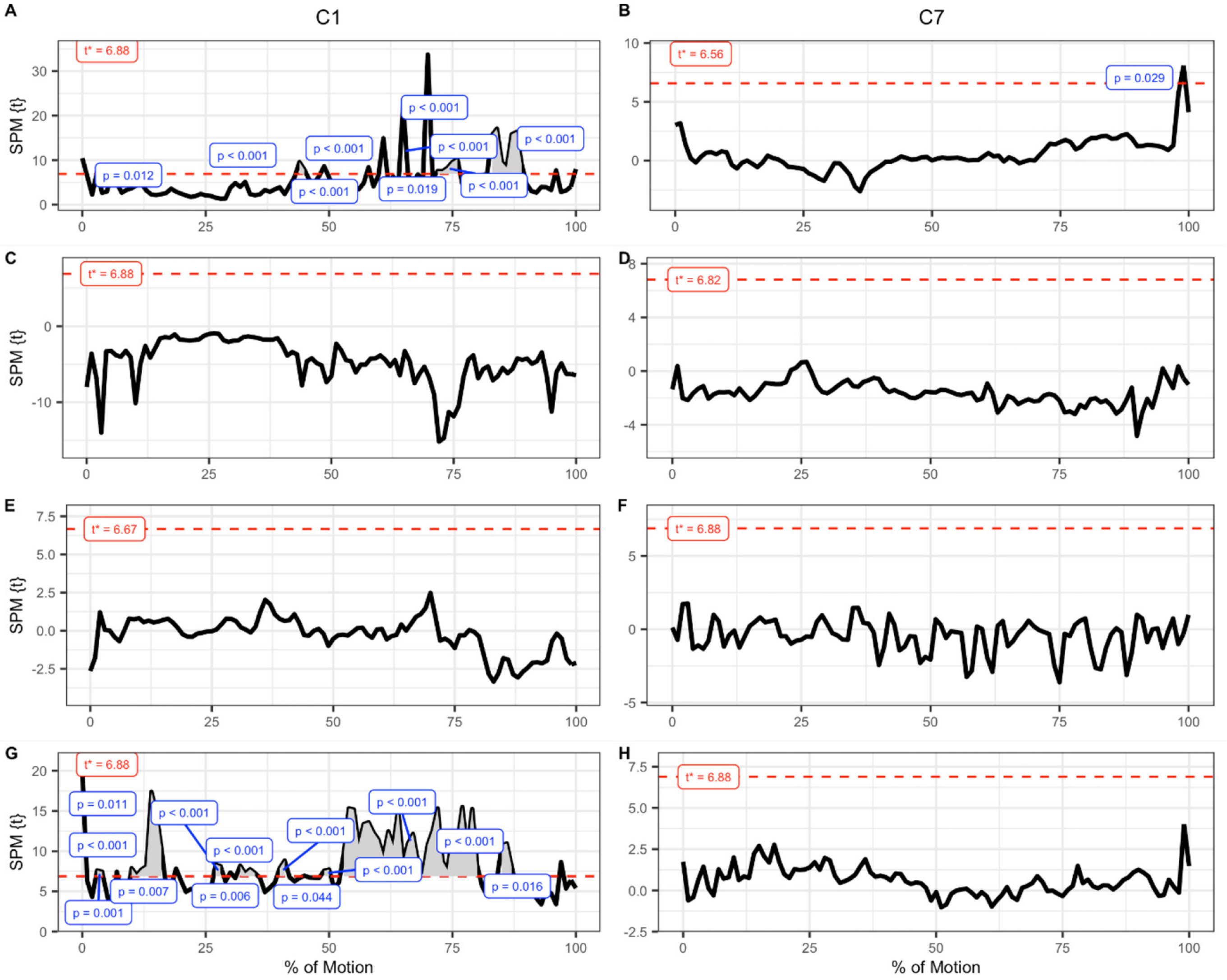

Fig. 2. An example of the Statistical Parametric Mapping (SPM {t}) analysis showing significant differences between helmet conditions during the ExtHold at 3Gz. The subfigures are: A and B = Flexion/Extension at C1 and C7, respectively; C and D = Lateral Flexion at C1 and C7, respectively; E and F = Rotation at C1 and C7, respectively; G and H = Net Joint Moments at C1 and C7, respectively. t* refers to the t critical value. The JHMCS resulted in significantly higher flexion/extension moments in the ExtHold at C1, at the end of the motion at C7, and in the net joint moments at C1.

Large variance was observed between and within participants for all motions (Fig. 3). Headcheck motions took on average 7.15 s to complete (range 1.91–23.36 s), with the extension scan motion average time more than double the Check6L motion (12.4 s versus 4.5 s respectively).

Univariate ANOVA showed significant differences in duration were observed between each participant and each motion type ($F_{1,19} = 6.48$, $p < 0.01$ Check6L; 5.4, $p < 0.01$ Check6R; 7.31, $p < 0.01$ ExtHold; 10.52, $p < 0.01$ ExtScan) indicating performances are highly individualised. Individuals also varied the duration of hold between their own trials of the same motion, with only two out of nine participants with repeated trials in each helmet showing consistency in duration of motion.

Cumulative net moments per motion per *sec*ond differed significantly between participants ($F_{1,19} = 2.71$, $p < 0.01$). There was more variance in the net cumulative moments calculated for ExtScan and ExtHold motions. Mean values for cumulative net moments in Nm per sec, for each motion, for each level of Gz ranged from 34.69 Nm.sec/headcheck (Check6L at 1Gz in 55P) to 607.35 Nm.sec/headcheck (ExtScan at 9Gz in JHMCS) (Supplementary Table 2).

Interestingly there was a tendency for participants to laterally flex more to the right at both C1 and C7 in a roughly 2:1 ratio (right:left) in all motions. There was asymmetry in the ratio of Flexion:Extension associated with Check6R (1:1) versus Check6L(5:1). ExtScan and ExtHold motions where both characterised by the highest proportion of extension moments (31 % at C7).

4. Discussion

Net joint moments (mean, peak and cumulative) at C0-C1, and C6-C7 for typical headchecks performed during combat flight manoeuvres were quantified across ten levels of Gz and two helmet types. The model used (MASI) behaved predictably demonstrating a linear increase in segmental moments with increasing Gz, an increase in moments produced at each cervical segment with the heavier helmet, and an increase in moments at vertebral segments further from the centre of mass. Our experimental design intentionally avoided an imitation approach to headcheck technique to maintain external validity. Instead, pilots were asked to perform headchecks in their own habitual way. Individuality is apparent in the large variance between participants, and technique variation is evidenced by the differences within participants. Duration of hold and moments (mean, peak and cumulative) all differed between trials. This variation is in keeping with studies of humans performing repeated tasks.[27] In our initial task analysis we observed 176

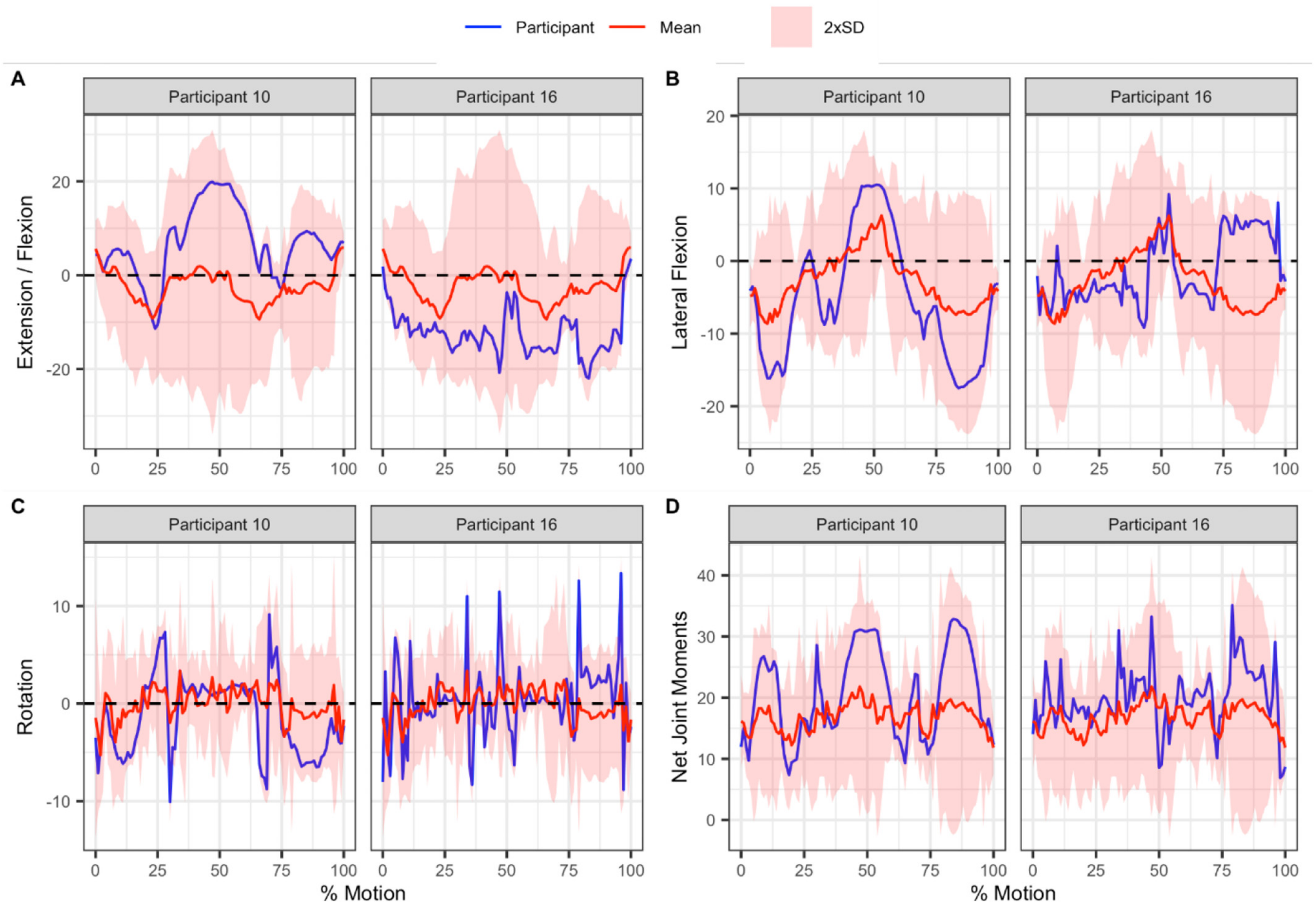

Fig. 3. Normalised mean curves and 2 standard deviations (shading 2xSD) visualising individual participant differences in moments (Nm) about C7 under JHMCS at 3Gz during the ExtensionScan. Subfigures: A = Flexion/Extension; B = Lateral Flexion; C = Rotation; D = Net joint moments.

rotations of the head in just ten minutes of flight, in two pilots. Our results suggest it is therefore unlikely that accurate estimates of workload could be made by simply counting head rotations in pilots, as the forces applied to the cervical spine are not consistent, even within the same pilot. If future studies aim to examine neck workload in pilots during flight, then individual monitoring must occur for accurate assessments of workload to be made. Preliminary data from our trial of real-time flight monitoring (11 sorties involving seven pilots) demonstrates that peak and cumulative workloads can vary by a factor of four times between pilots performing the same flight profiles.[28]

Asymmetry of motion was also noted. Check6L should result in similar net joint moments and displacements as Check6R; however Check6L involved more flexion and higher net joint moment. In reviewing motion data and analysis of the directional moment traces, the explanation for this appears to relate to the torso and shoulder position. Our participants placed their hands as if on the controls of an F-18, resulting in a left arm forward position of their trunk. As the left shoulder was brought forward in this posture, Check6L tended to result in more flexion to look “around” the shoulder. This increases confidence in the model. It also raises questions about how asymmetry of motion may relate to asymmetric symptoms in injured pilots, and how cockpit designs may influence neck loads.

Helmet configurations changed moment intensity and distribution in the cervical spine. Our results indicate that a more forward centre of mass (JHMCS) created increased net moments and changes in the planes that this occurred at each cervical spine segment. As new helmets and helmet-mounted masses are deployed, modelling of neck workloads will need to account for these changes. The OpenSim software underpinning our model allows for inertial parameters related to the distribution of helmet mass to be adjusted for new helmets.

There are limitations in the application of a laboratory-based model to real flight. Our model does not account for neck force modification that occurs as the helmet is supported by the canopy or headrest of the seat. Pilots commonly use cockpit structures to assist in holding a position for a high Gz turn. The collection of in-situ kinematics during flight using inertial sensors and three-dimensional cockpit mapping would enable adjustments to be made to real-time workload models, accounting for gravity changes and when the head is supported by the canopy or seat, creating a more ecologically valid approach. Laboratory based approaches do not account for additional external forces applied by harnesses and life-support attachments, or for gravitational forces that are not acting in the vertical direction of the vertebrae that may occur when the aircraft undergoes specific manoeuvres.

The current modelling approach was that of a torque driven model that did not account for individual muscle forces or joint reaction forces. While the model and approach used has the capacity to do this, and while specific muscle force data would be interesting, practical applications of such analysis is limited. For this reason, understanding how increased gravities influence kinematics is currently not known. Net joint moments are more functionally relevant and applicable to clinicians and end-users, as modification of muscular force inputs in the form of neck strength training or technique alteration would not require understanding of individual muscle tendon forces, but rather would focus on the resultant neck moments. Another limitation is the unknown contribution of lower spinal segments to the variance seen in cervical net joint moment calculations. Future research should endeavour to explore these limitations.

Knowing the intensity, frequency, duration and type of head motions that pilots perform is vital to understand conditioning parameters. Neck strengthening has been considered important in preventing neck pain in aircrew.[29,30] This study now provides parameters for exercise prescription which have not previously been available. The next important step is to understand the relationship between operationally significant neck pain complaints and neck workloads. This is now possible through application of our approach, if combined with long term neck injury surveillance. If risk thresholds are associated with workload thresholds, then risk management strategies can be applied through workload monitoring in the same way as in elite sport.[10] Training periodisation, technique modification and helmet design could all be informed by this approach.

5. Conclusion

The MASI model has been successfully applied to quantify joint moments at Occiput-C1, and C6-C7 for typical headchecks performed during combat flight manoeuvres. The effect of the heavier JHMCs helmet was both an increase in the net joint moment at each segment but also proportionally greater increase at C1. The effect of Gz was a predictably linear increase in the moment at each segment, but more advanced techniques are needed to understand the influence of gravity on kinematics. The ExtScan and Check6L headchecks were associated with the highest peak and cumulative net moment. Unexpectedly there were asymmetries observed between the Left and Right check 6 motions. High variability within and between pilots was observed for duration, peak and cumulative net joint moments. Individual monitoring of the intensity, frequency, duration and type of head motions that aircrew perform is needed to understand injury, conditioning parameters, and to inform risk management.

Declaration of Interest Statement

This study was completed through collaboration between the University of Canberra and the Royal Australian Air Force at Williamtown, New South Wales. The Royal Australian Air Force provided funding for the study to be completed. No conflicts of interest.

Confirmation of Ethical Compliance

Ethical approval was granted by the Joint Health Command Low-Risk Ethics Panelproject number 18–005 and the University of Canberra Committee for Ethics in Human Research, approved project 20,180,285. All participants provided written informed consent prior to procedures.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsams.2022.07.007.

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