G Tolerance During Open- vs. Closed-Loop G-Time Control

Mikael Grönkvist; Britta Levin; Ola Eiken

BACKGROUND: $+G_z$ tolerance is traditionally determined in centrifuges with open-loop G control, i.e., the centrifuge is under operator control (open loop), and thus the test subject is unable to influence the G_z load. In modern centrifuges, however, the subject is commonly able to continuously control the G_z load (closed loop). It is a widespread opinion among fighter pilots that $+G_z$ tolerance is higher under closed- than open-loop G control. The aims were to investigate whether $+G_z$ tolerance is higher in closed- than open-loop G control, and whether it is possible to use closed-loop G control during precise determination of $+G_z$ tolerance.

METHODS: Relaxed $+G_z$ tolerance was determined in eight men during rapid G_z-onset rate (ROR) under three conditions: 1) OL-VFB, open loop with visual feedback; 2) OL-NFB, open loop with no visual feedback; and 3) CL, closed loop. Straining $+G_z$ tolerance was determined in 10 men during ROR in OL and CL conditions.

RESULTS: Relaxed $+G_z$ tolerance did not differ between CL (3.66 G_z), OL-VFB (3.70 G_z) and OL-NFB (3.64 G_z). Straining $+G_z$ tolerance was similar in the CL (8.5 G_z) and OL (8.6 G_z) conditions. In the CL condition, the G_z load varied substantially and was on average lower than in the OL conditions, at any stipulated G-time profile.

DISCUSSION: There is no systematic difference in relaxed or straining $+G_z$ tolerance as determined in closed- vs. open-loop G-controlled systems. During closed-loop control, precision and reproducibility are too low to recommend it for accurate determination of relaxed G tolerance.

KEYWORDS: Dynamic flight simulator, fighter jet aircraft, headward acceleration, human-use centrifuge, $+G_z$ tolerance, target chase.

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It is essential for a pilot flying high-performance aircraft to be aware of his/her capacity to withstand high gravitoinertial (G) load in the head-to-foot direction ($+G_z$-level tolerance), not only while performing anti-G straining maneuvers but also in the relaxed state (for reviews see Banks et al., Green, and Newman).[1,5,7] In addition, determination of relaxed $+G_z$ tolerance constitutes a salient feature during development and testing of anti-G equipment.[2,3,9] Traditionally, relaxed $+G_z$ tolerance is determined in “open-loop-controlled” (OL) human-use centrifuges, in which the G-time profile is controlled by a centrifuge operator or automatically through a preprogrammed profile; viz. the pilot/test subject cannot influence the G load. Modern centrifuges, however, commonly have G-control functions permitting the test subject to continuously control the $+G_z$ load (closed-loop control; CL).

It is a widespread opinion among fighter pilots that the $+G_z$ tolerance is considerably lower during OL G control in a centrifuge than while flying, i.e., than under CL G control conditions. Even though it appears that experimental studies confirming this notion are scarce, it could be assumed that the coordination of the anti-G straining maneuver is facilitated if the pilot controls the G load, hence suggesting that straining $+G_z$ tolerance might be higher under conditions of CL G control. Furthermore, it cannot be ruled out that apprehension-induced autonomic up-regulation of arterial pressure might result in improved relaxed $+G_z$ tolerance in closed- compared to open-loop G-controlled situations. From a practical viewpoint, it is of interest to establish any systematic difference in open- vs. closed-loop straining, as well as relaxed $+G_z$ tolerance.

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In addition, the reproducibility and precision of the G-time profiles may be critical, for instance in conjunction with testing of anti-G equipment. Thus, it is conceivable that the test-retest reliability of the G-time stimulus profiles is substantially lower under CL than OL G control.

Accordingly, the primary aim of the present study was to investigate whether +G_z tolerance differs in a systematic manner when determined during CL vs. OL G control. The secondary aim was to investigate if the precision and reproducibility of the G-time profiles are sufficiently high during CL G control to permit determination of +G_z tolerance in conjunction with testing of anti-G equipment. Three series of experiments were conducted, with series one and three focusing on relaxed +G_z tolerance and its test-retest reliability, and series two on straining +G_z tolerance.

METHODS

Subjects

Three series of experiments were conducted. Altogether 22 healthy men participated as test subjects, $N = 8$ in series 1, $N = 10$ in series 2, and $N = 12$ in series 3. Of the subjects in series 2, three also participated in series 1 and five in series 3, but no subject took part in all three series. The subjects′ average (range) age was 31 (23–43) years. There were 11 active fighter pilots and the remaining subjects were recruited from a pool of subjects who had undertaken extensive G-training in the centrifuge, and hence were also well accustomed to G-tolerance end-point symptoms. Each subject gave his written, informed consent prior to participating and knew that he was free to withdraw from the study at any time. The study protocol and experimental procedures conformed to the declaration of Helsinki and were approved by the Regional Ethics Committee in Linköping, Sweden.

Equipment

The series 1 and 2 experiments were performed in a 9.1-m radius human-use centrifuge (Dynamic Flight Simulator, DFS; Wyle Laboratories, El Segundo, CA), at the Swedish Defense Materiel Administration in Linköping, Sweden. Series 3 was performed in a 7.25-m radius centrifuge (ASEA, Sweden) at the Royal Institute of Technology (KTH), Stockholm. It has a swing-out gondola and a maximum G-onset rate of $5\ G_z \cdot s^{-1}$.

In series 1 and 3, the subject was wearing a cotton flight coverall but no anti-G garments. In series 2, the subject was equipped with an extended coverage anti-G suit (AGS) that had been modified to allow separate inflation of the abdominal and leg parts of the bladder. Since we anticipated that the vast majority of the subjects would sustain the maximum allowed G load, +9 G_z, if wearing the full coverage AGS while straining, only the leg bladders were connected to the regulator (Eros F-5341, Eros, Plaisir Cedex, France), thus reducing the AGS protection by +1 G_z.[4] We reasoned that this might increase the chance to discriminate between the OL and CL conditions as regards straining +G_z-tolerance. As in the aircraft, pressurization of the AGS commenced at +2 G_z, with pressure increasing linearly with increasing +G_z load to a maximum of 67 kPa (500 mmHg) at +9 G_z; at loads $\leq$ +2 G_z, the suit was supplied by a ready pressure of 1.3 kPa.

The KTH centrifuge has a tangentially pivoted gondola and is equipped with a mock-up of the Gripen 39 seat, with back support reclining 28° from the vertical. The DFS gondola was furnished with a SAAB 39 Gripen cockpit mock-up environment containing a Gripen seat. The mock-up was also equipped with three computer screens subtending a visual field of 100° horizontally and 30° vertically. In the present experiments, the out-the-window (OTW) scenery consisted of hilly terrain, always with a readily identifiable horizon. The central screen has a head-up display function, which, in the present experiments, did not contain any information of the G load.

The DFS has two operational modes, open (OL) and closed loop (CL). In the OL mode, the centrifuge operator selects a preset computer-derived G-time profile; the test subject initiates and terminates the profile by pulling and releasing, respectively, the spring-loaded stick. The OTW presentation is coordinated with the +G_z load and displays a tilted horizon corresponding with a coordinated left turn. To reduce motion artifacts, an onset of +G_z is accompanied with a momentary pitch down motion of the gondola. As this rapid gondola movement may be perceived as uncomfortable, the +G_z-onset is allowed a minimum time of 1 s for acceleration between any two +G_z-levels. For instance, with an idle of 1.55 G_z, acceleration to 2.5 G_z will give an average onset slightly below 1 s. In the CL mode, the subject continuously controls the +G_z load by maneuvering the control stick as in the real aircraft. In the present experiments, a DFS functionality referred to as the "G-stick function" was used. Here, the task was to chase a target cue (aircraft symbol) displayed in the OTW by adjusting the pulling force applied to the stick, and hence the +G_z load. Lateral movements of the control stick or changes to throttle position have no effect on the simulation.

A "G-stick" sequence starts with the target cue entering a coordinated left turn, i.e., with a bank angle corresponding to the stipulated +G_z level. The subject's task is to chase the target by applying a sufficient +G_z load increment. The head-up display shows a square that is to be centered over the target symbol. This occurs when the subject attains the stipulated +G_z load ($\pm$ 0.1 G_z), and is confirmed by a color change of the square from red to green. The sequence ends by the target cue reassuming level flight, after which the subject releases his pull on the stick and the DFS gondola reassumes idle speed.

Heart rate (HR) was monitored continuously from a 5-lead precordial electrocardiographic recording, using a cardiometer (Gould 6600 ECG/Biotach module, Valley View, OH). Mean arterial pressure (MAP) was measured continuously using a volume-clamp method (Portapres®, TNO, Amsterdam, The Netherlands), with the pressure cuff placed around the mid-phalanx of the third or fourth finger on the left hand, and the reference transducer taped to the temple at the vertical level of the eyes. Before each experiment, systolic and diastolic arterial pressure values obtained with the volume-clamp technique were compared, and found to agree well, with those obtained from the right brachial artery using a standard sphygmomanometric method.

The $+G_z$ load was measured by an analog accelerometer positioned behind the seat at a vertical level approximately corresponding to the subject's heart. All signals were transmitted via slip rings and recorded on a computer via a 16-channel AD-conversion board (DAS-1602; Keithley Metabyte, Cleveland, OH). Data acquisition and analyses were performed using custom-made software (TestPoint, Capital Equipment Corp., Bedford, NH).

In series 1, electromyographic activity (EMG) was monitored continuously in the right vastus lateralis and rectus abdominis muscles, using a Bagnoli-4 EMG system in combination with EMG-works computer software (DelSys Inc, Boston, MA). Bipolar surface electrodes, positioned over the midportion of the muscles, detected the EMG signals. The subject performed maximal voluntary isometric contractions (attempted knee extension at 0° knee angle and hip flexion at 90° hip angle) prior to the experiment, and the EMG recordings obtained during these maneuvers were then used as references for the EMG values obtained during the experiments. The subject was instructed to sit relaxed and breathe quietly throughout the experiment. If the root-mean-square EMG activity in either of the muscles increased from baseline during a G-time profile by $> 15\%$ of maximal voluntary contraction, data was not accepted for further analysis. EMG values were used solely as data inclusion/exclusion criteria and were not further analyzed.

In all three series, peripheral and foveal visions during the G exposures were rated using a light bar comprising a central red and two green lights, positioned at a 60° angle in relation to the subjects' eyes. Impairment of foveal and peripheral vision was assessed using a 4-point scale (clear, dim, gray, light loss).[2] Following each G exposure, the subject rated his peripheral and central vision during the preceding exposure. The subject was instructed to terminate the G exposure by releasing the stick or hand grip once one or both of the peripheral lights were no longer visible (light loss) or once the central light was gray/white.

The subject was continuously monitored via a closed-circuit video system and was able to communicate with the experimenter by means of a two-way intercom system.

Procedures

Series 1. Each experiment commenced with instrumentation of the subject, who thereafter was trained in the G-stick task with the centrifuge parked (1 g). In addition, the subject was familiarized with the OL and CL conditions, i.e., with the centrifuge gondola rotating (increased $+G_z$ load). Thereafter his $+G_z$ tolerance was investigated in three conditions:

1.) OL-VFB, open loop visual feedback: The subject initiated the onset of $+G_z$ load, which remained constant at the preset G plateau. A left turn was displayed on the computer screens.
2.) OL-NFB, open loop no visual feedback: The subject initiated the onset of $+G_z$ load, which remained constant at the preset G plateau. The computer screens were turned off.
3.) CL, closed loop: The G-time profile was executed with the G-stick function, i.e., the subject controlled the onset rate, level, and duration of the $+G_z$ load. A target executing a coordinated left turn was displayed on the computer screens.

The subject was instructed to refrain from performing anti-G straining maneuvers and to remain as relaxed as possible throughout each G exposure.

In all three conditions, high-G exposure commenced from the centrifuge idle speed (1.55 G_z). In both of the OL conditions, $+G_z$ load was increased from 1.55 G_z to the preset plateau and then maintained during 15 s (plateau phase) and thereafter reduced to 1.55 G_z. The subject was able to terminate the G-time profile prematurely by releasing the stick. In the CL condition, the subject was, as mentioned, able to control the G level and G-onset at all times. Any correctly performed G-stick sequence resulted in a G-time profile corresponding to that of the OL conditions, i.e., a rapid G onset followed by a 15-s G plateau at the targeted $+G_z$-load. During the G-stick sequence the subjects had a visual cue of $\pm$ 0.1 G_z from the target $+G_z$-load.

In each condition, the $+G_z$ load of the plateau phase was increased in steps of 0.25 G_z until the subject reported visual impairment. The increments were, however, not applied in a successive manner but randomized for three groups of G-levels (i.e., 2–3 G_z; 3–4 G_z; 4–5 G_z). To reduce the risk of fatigue, any subject possessing high relaxed G-tolerance was not exposed to all low G levels, the choice of initial $+G_z$-load being determined from previous $+G_z$ tolerance tests. An example of used order of exposure for the "3–4 G_z group" is: 3.5; 3.0; 3.75; 3.25 G_z. The subject was thus not aware of the current and succeeding G-time profile. For each subject, the randomization order varied between conditions. In all conditions, each sequence was repeated so that the subject was exposed to every $+G_z$ load twice in all conditions. The order of the conditions was alternated among subjects in a counter-balanced manner.

Series 2. An experiment commenced with instrumentation of the subject, who thereafter was trained in the G-stick task with the centrifuge parked (1 g), and in the OL and CL conditions with the centrifuge gondola rotating (increased $+G_z$ load). Thereafter his $+G_z$ tolerance was investigated in two conditions:

1.) OL, open loop: The subject initiated the onset of $+G_z$ load, which remained constant at the preset G plateau. A left turn was displayed on the computer screens.
2.) CL, closed loop: The G-time profile was executed with the G-stick function, i.e., the subject controlled the onset rate, level, and duration of the $+G_z$ load. A target executing a coordinated left turn was displayed on the computer screens.

The subject was instructed to perform anti-G straining maneuvers of sufficient vigor to counteract G-induced impairment of vision.

In both conditions, high-G exposure commenced from 1.55 G_z. In the OL condition, the +G_z load was increased from 1.55 G_z to the preset plateau and then maintained during 15 s (plateau phase) and thereafter reduced to 1.55 G_z. The subject was initiating the G-profile by pulling the stick toward him and was thus able to terminate the G-time profile prematurely by releasing the stick. In the CL condition, the subject was able to control the G level and G-onset at all times. Any correctly performed G-stick sequence resulted in a G-time profile corresponding to that of the OL conditions, i.e., a rapid G onset followed by a 15-s G plateau. As in series 1, the subject got a visual cue of $\pm$0.1 G_z from the target +G_z load.

In each condition, the +G_z load of the plateau phase commenced between 5 and 6 G_z, and was increased in steps of 0.5 G_z until the subject reported visual impairment. The increments were applied in a successive manner, as a safety precaution to minimize the risk of severe G induced loss of consciousness. The order of the two conditions was alternated among subjects in a counter-balanced manner.

Series 3. After instrumentation, the subject was seated in the gondola, and his G-level tolerance was determined in two conditions:

1.) OL-OI, Open-loop: The operator initiated the G-time profile.
2.) OL-SI, Open-loop: The subject initiated the G-time profile by pulling the stick toward him.

In both conditions the computer screen was turned off. As in series 1, the subject was instructed to refrain from performing anti-G straining maneuvers and to remain as relaxed as possible throughout each G exposure. For each G-exposure, the centrifuge was accelerated from an idle G load of 1.4 G_z with a rapid G onset (5 $G_z \cdot s^{-1}$), to a preset G plateau level, where it remained constant for 15 s and was then followed by a deceleration by 0.2 $G_z \cdot s^{-1}$ to 1.4 G_z. In both conditions, the +G_z load of the plateau phase was increased in steps of 0.25 G_z until the subject reported visual impairment. The order of the two conditions was balanced among the subjects. +G_z tolerance was determined twice in each condition.

Analyses

The statistical significance of intercondition differences was evaluated by Student's *t*-test or repeated measures analysis of variance and, if significant, followed by a Tukey HSD post hoc test (Statistica Statsoft, Tulsa, OK). *P*-values < 0.05 were regarded as statistically significant. In series 1, virtually all tests were performed between 2.75–4.00 G_z, thus data are only presented for those G-levels. Values are reported as mean $\pm$ SD unless otherwise stated.

RESULTS

Series 1

The G-onset rate varied considerably in the CL condition (**Table I**), and was on average lower (0.87 $\pm$ 0.23 $G_z \cdot s^{-1}$) than in the OL conditions (1.23 $\pm$ 0.21 $G_z \cdot s^{-1}$) ($F(2,14)=22.9$, $P <$ 0.001). In the CL condition G-onset phase, both G overshoots (exceeding the stipulated plateau value by up to 25%) and slow responses (in some instance with a G onset rate of 0.28 $G_z \cdot s^{-1}$) were observed (**Fig. 1**). During the G-plateau phase, the G force was commonly slightly lower in the CL than OL conditions (Table I), with an average (SD) difference of -0.08 (0.08) G_z in the CL compared to the stipulated G-level [$F(5,10)=6.19$, $P = 0.007$]. After correcting for this discrepancy in +G_z-load, the +G_z tolerance (average of the two determinations in each condition) was similar in CL (3.66 $\pm$ 0.42 G_z), OL-VFB (3.70 $\pm$ 0.31 G_z), and OL-NFB (3.64 $\pm$ 0.19 G_z) [$F(2,14)=0.19$, $P = 0.83$].

There was no difference in +G_z tolerance between the first and second determination, neither when comparing all tests regardless of condition 3.68 $\pm$ 0.37 G_z in the first test and 3.65 $\pm$ 0.31 G_z in the second test [$F(1,7)=0.13$, $P = 0.73$], nor in any of the individual conditions: CL = 3.69 $\pm$ 0.48 G_z in the first vs. 3.62 $\pm$ 0.41 G_z in the second determination [$F(1,7)=0.55$, $P = 0.48$]; OL-VBF = 3.72 $\pm$ 0.36 G_z vs. 3.69 $\pm$ 0.35 G_z [$F(1,7)=0.07$, $P = 0.80$]; and OL-NFB = 3.62 $\pm$ 0.29 G_z vs. 3.65 $\pm$ 0.18 G_z [$F(1,7)=0.08$, $P = 0.78$].

Before G-onset, MAP was similar in CL (72 $\pm$ 16 mmHg), OL-VFB (74 $\pm$ 14 mmHg), and OL-NFB (73 $\pm$ 13 mmHg), [$F(2,14)=0.32$; $P = 0.73$], as shown in **Fig. 2A**); whereas HR was somewhat higher in OL-NFB (89 $\pm$ 16 beats $\cdot$ min^{-1}) than in CL (85 $\pm$ 16 beats $\cdot$ min^{-1}) and OL-VFB (86 $\pm$ 15 beats $\cdot$ min^{-1}), [$F(2,12) = 6.99$; $P = 0.010$], as shown in **Fig. 2B**. At the G-tolerance level, MAP was similar in the three conditions (CL (27 $\pm$ 22 mmHg), OL-VFB (31 $\pm$ 17 mmHg) and OL-NFB (30+18 mmHg), [$F(2,12) = 0.90$, $P = 0.43$; Fig. 2A]; whereas HR was somewhat lower in the CL condition (CL (101 $\pm$ 17 beats $\cdot$ min^{-1}) than in OL-VFB (107 $\pm$ 19 beats $\cdot$ min^{-1}) and OL-NFB (107 $\pm$ 18 beats $\cdot$ min^{-1}), [$F(2,12) = 6.53$, $P = 0.012$; Fig. 2B].

Series 2

The G onset rate varied considerably in the CL condition (**Table II**), and was on average lower (2.5 $\pm$ 0.90 $G_z \cdot s^{-1}$) than in the OL condition (3.0 $\pm$ 0.25 $G_z \cdot s^{-1}$), [$F(1,49)=13.2$, $P < 0.001$]). During the G-plateau phase, the G force was commonly slightly lower in the CL than OL conditions, with an average (SD) difference of -0.14 (0.23) G_z in the CL compared to the stipulated +G_z-level [$F(1, 49)=13.2$, $P < 0.001$] with an increasing difference at higher +G_z-loads [$F(6,49)=2.3$; $P = 0.045$]. After correcting for this discrepancy in G-load, the G tolerance (average of the two determinations in each condition) was similar in CL (8.5 $\pm$ 0.61 G_z), and OL (8.6 $\pm$ 0.74Gz), $P = 0.31$.

At the G-tolerance plateau (i.e., the highest 15-s G plateau that was completed), MAP and HR appeared to be lower in the CL (54 $\pm$ 30 mmHg; 126 $\pm$ 11 beats $\cdot$ min^{-1}) than OL (74 $\pm$ 31 mmHg; 131 $\pm$ 16 beats $\cdot$ min^{-1}) condition, but the differences were not significant, $P = 0.20$ and $P = 0.090$, respectively.

Table I. Average (Range) G Plateau and G Onset Rate Values in Series 1 in the Closed Loop (CL) and Open Loop (OL) Conditions at Six Stipulated G Plateaus. $N = 8$.

Series 1: relaxed	2.75 G_z	3.00 G_z	3.25 G_z	3.50 G_z	3.75 G_z	4.00 G_z
G-plateau CL ($+G_z$)	**2.73**	**2.93**	**3.19**	**3.46**	**3.60**	**3.88**
	(2.66-2.78)	(2.74-3.03)	(3.10-3.33)	(3.41-3.58)	(3.44-3.70)	(3.81-3.91)
Onset CL ($G_z \cdot s^{-1}$)	**0.77**	**0.75**	**0.86**	**0.91**	**0.99**	**0.94**
	(0.52-1.19)	(0.59-0.89)	(0.67-1.12)	(0.54-1.20)	(0.58-1.19)	(0.67-1.31)
Onset OL ($G_z \cdot s^{-1}$)	**0.98**	**1.05**	**1.22**	**1.30**	**1.39**	**1.47**

Series 3

There was a slight difference in $+G_z$ tolerance between the first (OL-OI 3.35 ± 0.51 G_z; OL-SI 3.31 ± 0.47 G_z) and second determination (OL-OI 3.13 ± 0.51 G_z; OL-SI 3.13 ± 0.36 G_z), irrespective of condition [$F(1,11) = 8.21$; $P = 0.015$], but no difference in the averaged $+G_z$-tolerance between the OL-OI (3.24 ± 0.49 G_z) and OL-SI conditions (3.22 ± 0.38 G_z), [$F(1,11) = 0.124$; $P = 0.73$].

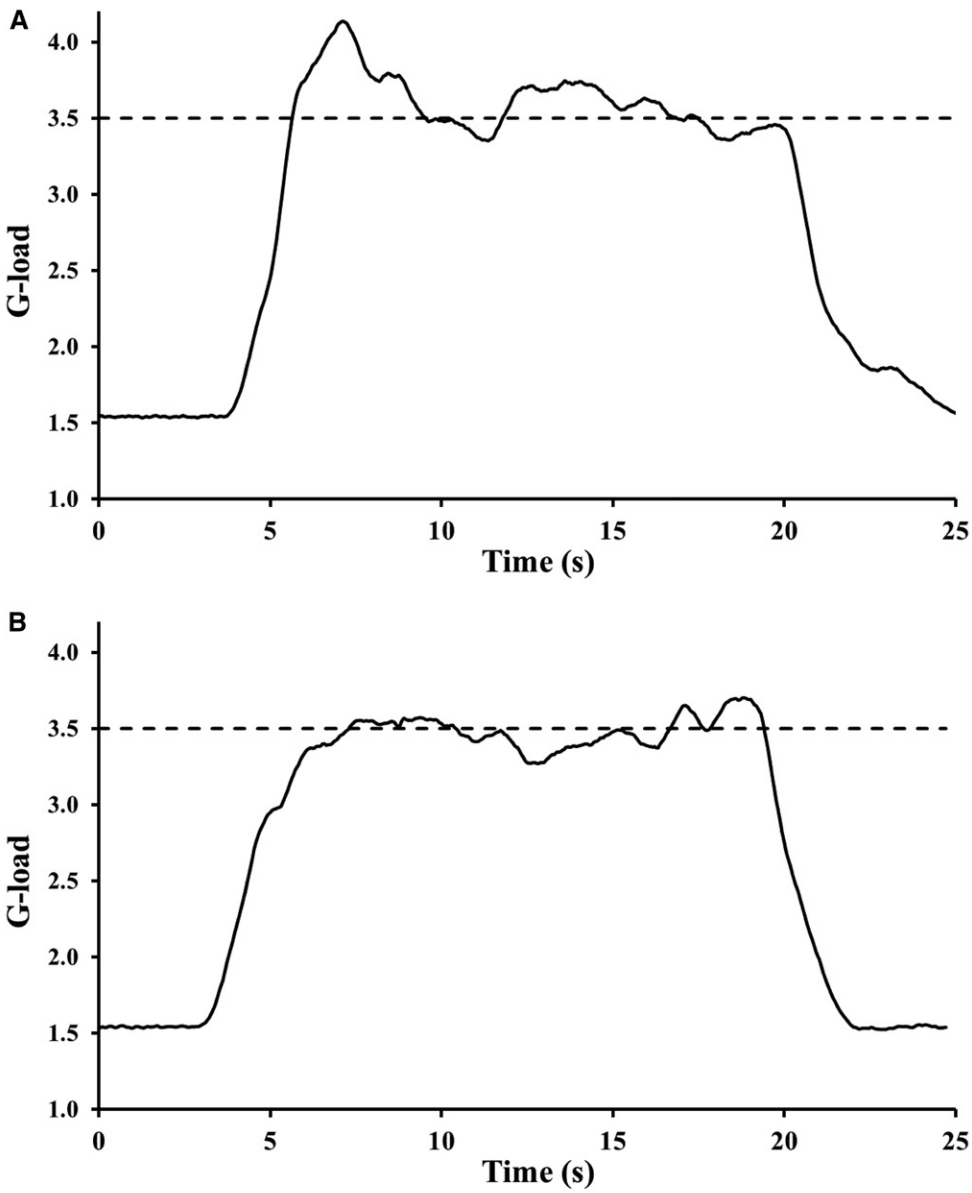

Fig. 1. G_z profile during the closed-loop condition in series 1 for two test subjects in conjunction with a stipulated G load of 3.5 G_z, with the upper graph (A) showing a rapid G onset with an overshot of more than 25% and the lower graph (B) a slow G onset (≈0.5 $G_z \cdot s^{-1}$).

DISCUSSION

Present results demonstrated that relaxed G tolerance was similar whether the $+G_z$ load was controlled by the test subject or the centrifuge operator, and regardless of whether or not the subject was given visual feedback of the G-time profile. Also, straining $+G_z$ tolerance was similar during open- and closed-loop G-time control.

These findings do not support the common notion among fighter pilots that $+G_z$ tolerance is considerably higher when actively flying an aircraft than when in its back seat, and, in particular, than when exposed to $+G_z$ loads in an open-loop G-controlled centrifuge. Our study does not allow us to discern the reason behind the discrepancy between this notion and present results. Conceivably, pilots tend to overestimate the severity of the $+G_z$ conditions in flight. Thus, the onset rate and/or the duration of any given $+G_z$ exposure may typically be lower and shorter, respectively, in a flight situation than during centrifuge testing designed to reflect "worst-case conditions." Moreover, it cannot be ruled out that in flight, more pronounced apprehension-induced increments in arterial pressure might improve relaxed $+G_z$ tolerance. As evident in series one, from baseline measures of HR and arterial pressure in the three conditions, present apprehension effects on autonomic vascular control were, however, not prominent and did not vary substantially between conditions. Notably, present results do not contradict that in flight a back-seat pilot, who is taken "off guard" and hence does not perform a proper straining maneuver, may exhibit low G tolerance during a rapid-onset high-G profile. Finally, given that the present G-tolerance determinations relied on perception of visual symptoms and that pilots, as mentioned, typically presume higher G tolerance

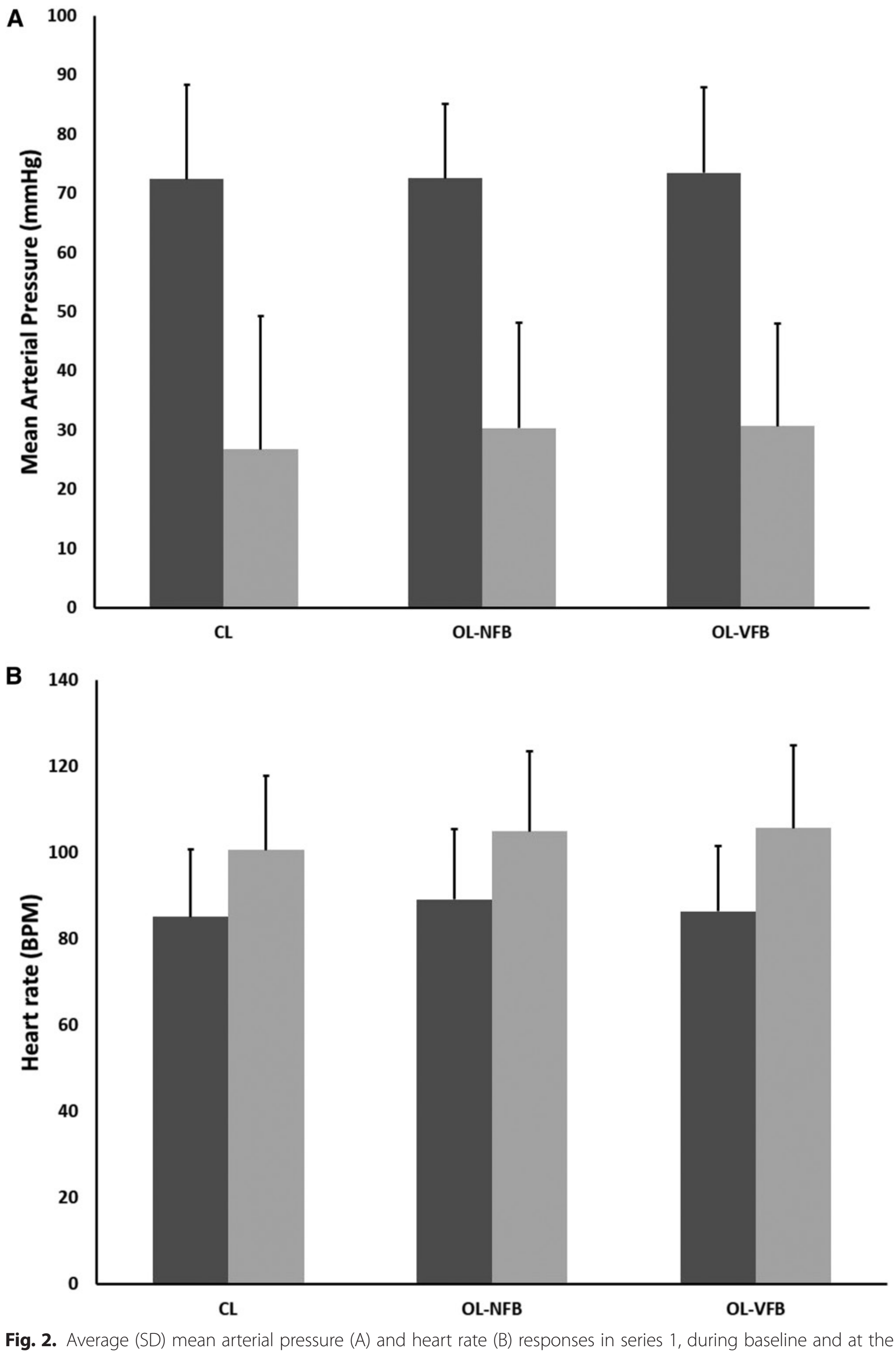

Fig. 2. Average (SD) mean arterial pressure (A) and heart rate (B) responses in series 1, during baseline and at the G-tolerance level for the three conditions: closed loop (CL), open loop no visual feedback (OL-NFB), and open loop visual feedback (OL-VFB). $N = 8$. Dark grey: baseline; lighter grey: G-tolerance level.

in closed-loop conditions, we cannot rule out a subject-bias effect on G-tolerance in the present study, even though the subjects were blinded as regards the $+G_z$ levels during the tests and even though no difference in G tolerance between OL and CL conditions was noted.

Both during the relaxed and straining $+G_z$ tolerance tests, the G-onset rates and G plateaus in the CL conditions were, on average, less than the stipulated values. Throughout the G-time profiles the G precision was substantially lower in the CL than OL conditions. Possible explanations for the low G-level precision in the CL conditions include inadequate feed-back presentation of G level to the subject, with an acceptance feedback G-level during the target chase of $\pm 0.1\ G_z$ and that the subjects, consciously or subconsciously, avoided high $+G_z$ loads; notably, during relaxed $+G_z$ tolerance testing, the discrepancy between stipulated and real $+G_z$ load increased with the G level. In addition, several subjects commented that especially at high $+G_z$ loads approaching the tolerance level, it was hard to maintain the G level while concomitantly observing symptoms of visual impairment. In this connection, it should be pointed out that in the present OL experiments, the "G-stick functionality" was employed, which substantially limits the complexity of the task compared to when employing the CL "target-chase functionality," in which the pilot also needs to control the roll-position and the thrust. Presumably, the G-time precision is even lower in the target-chase than in the G-stick functionality. Regardless of what mechanisms may have contributed to the low G precision in the CL condition, it must be concluded that a G-level variability exceeding the test-retest $+G_z$ tolerance variation is commonly not acceptable, i.e., that it is possible to distinguish biological variation from measurement inaccuracy. For instance, a high reliability is of essence during development and testing of G-protective garments;[9] on occasions, the G-onset rate did in fact not reach the threshold for being defined as rapid onset rate (i.e., $< 1.0\ G_z \cdot s^{-1}$; Fig. 1B). Obviously, high G-time precision is warranted also in pilot selection procedures.

The observation that, regardless of condition, relaxed $+G_z$ tolerance was either similar (series 1 and 2) or slightly reduced

Table II. Average (Range) G_z Plateau and G_z Onset Rate Values in Series 2 in the Closed Loop (CL) and Open Loop (OL) Conditions at Seven Stipulated G_z Plateaus. $N = 10$.

Series 2: straining	6.00 G_z	6.50 G_z	7.00 G_z	7.50 G_z	8.00 G_z	8.50 G_z	9.00 G_z
G-plateau CL (+G_z)	**5.95** (5.58-6.44)	**6.38** (5.98-6.61)	**6.82** (5.95-7.32)	**7.27** (6.03-7.88)	**7.85** (7.75-8.00)	**8.34** (8.24-8.41)	**8.90** (8.72-9.00)
Onset CL ($G_z \cdot s^{-1}$)	**2.67** (1.31-4.35)	**3.02** (1.77-4.38)	**2.32** (0.46-3.28)	**2.45** (1.05-4.04)	**2.41** (1.73-3.40)	**2.31** (1.50-3.32)	**2.25** (1.72-3.59)
Onset OL ($G_z \cdot s^{-1}$)	**2.56**	**2.79**	**2.97**	**3.11**	**3.16**	**3.21**	**3.30**

(series 3) over time in the test and retest situation, is in line with previous tests performed in our laboratory[3,4] and the findings by Stevenson et al.,[8] who showed that +G_z tolerance did not change in a systematic manner during repeated gradual onset-rate +G_z tolerance determinations separated by 2-min periods of rest. Thus, despite that resting arterial pressure tended to increase after the first determination, the change was insufficient to improve +G_z tolerance.[8] Lalande and Buick,[6] by contrast, found that the rapid onset-rate G-level tolerance improved in response to acutely repeated +G_z exposures.

In conclusion, neither relaxed nor straining +G_z tolerance differed as determined under closed-loop vs. open-loop control. During closed-loop control, the precision and repeatability, with respect to stipulated G-load, were not sufficient to permit determination of G-tolerance in conditions requiring high G-time reliability, such as in conjunction with testing of anti-G equipment.

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