Wearable Accelerometers in High Performance Jet Aircraft

G. Merrill Rice; Thomas B. VanBrunt; Dallas H. Snider; Robert E. Hoyt

INTRODUCTION: Wearable accelerometers have become ubiquitous in the fields of exercise physiology and ambulatory hospital settings. However, these devices have yet to be validated in extreme operational environments. The objective of this study was to correlate the gravitational forces (G forces) detected by wearable accelerometers with the G forces detected by high performance aircraft.

METHODS: We compared the in-flight G forces detected by the two commercially available portable accelerometers to the F/A-18 Carrier Aircraft Inertial Navigation System (CAINS-2) during 20 flights performed by the Navy's Flight Demonstration Squadron (Blue Angels). Postflight questionnaires were also used to assess the perception of distractibility during flight.

RESULTS: Of the 20 flights analyzed, 10 complete in-flight comparisons were made, accounting for 25,700 s of correlation between the CAINS-2 and the two tested accelerometers. Both accelerometers had strong correlations with that of the F/A-18 G_z axis, averaging $r = 0.92$ and $r = 0.93$, respectively, over 10 flights. Comparison of both portable accelerometer's average vector magnitude to each other yielded an average correlation of $r = 0.93$. Both accelerometers were found to be minimally distracting.

DISCUSSION: These results suggest the use of wearable accelerometers is a valid means of detecting G forces during high performance aircraft flight. Future studies using this surrogate method of detecting accelerative forces combined with physiological information may yield valuable in-flight normative data that heretofore has been technically difficult to obtain and hence holds the promise of opening the door for a new golden age of aeromedical research.

KEYWORDS: G forces, acceleration, in-flight physiology.

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Wireless wearable technologies, such as global positioning systems, accelerometers, and heart rate monitors, are fast becoming a standard with which investigators in the health sciences measure indices associated with human physical activity. Their application has been shown to be useful in a variety of situations ranging from monitoring performance in occupational and healthcare settings[3,9,15] to disease and vital sign monitoring[2,4,13] in ambulatory settings and emergency services. The utility of these devices has recently been demonstrated in simulated flight[6] and during high altitude parachute jumps,[5] but has yet to be studied and validated in high performance jet aircraft.

Modern day heads-up displays (HUDs) offer pilots information on dynamic G_z exposure; however, validation of wearable accelerometers would be useful for investigators and aviators. It would provide a readily available surrogate estimate of gravitational forces experienced during flight in all three axes and would eliminate the necessity of manually accessing the inertial navigation systems of aircraft postflight to obtain complete acceleration data. Moreover, many commercial accelerometers today are paired with physiological monitoring capabilities. Nonintrusive real-time physiological information on aviators during in-flight operations has been eluding aeromedical specialists since the inception of flight. In 2012, Steinkraus argued that certain preconditions must be met before the flying community would accept in-cockpit monitoring: "It must be dynamic, provide real-time information, and use valid, reliable, and practical

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technologies."[12] Recent technological advances have reduced the cumbersome nature of previous monitoring devices and now may be flown more practically without impeding or distracting flight operations. Whether these technologies are valid and reliable in extreme environments remains uncertain. The primary objective of this project was to determine if commercially available portable triaxial accelerometers accurately measure g-force exposures compared to the internal accelerometers within high performance aircraft.

METHODS

Subjects

Participants were six active duty F/A-18 pilots of the Naval Flight Demonstration squadron (aka Blue Angels) who were aeromedically cleared and gave informed consent to participate in the evaluation of portable accelerometers during high performance aircraft operations. The study protocols and procedures were approved by the Navy Medicine Operational Training Center's Scientific Ethical Review Committee under protocol number NMOTC2014.0005, and subsequently approved March 7, 2014 by higher level Institutional Review Board, Naval Medical Research Unit, Dayton, OH.

Equipment

The devices to be studied were commercially available, FDA cleared, portable triaxial accelerometers (**Fig. 1**). The first was an accelerometer within a physiological monitoring module called the Zephyr™ BioPatch™ (Zephyr Technology, Annapolis, MD; ACCEL 1) and the second was a standalone portable accelerometer called the ActiGraph™, (ActiGraph Corps, Pensacola, FL; ACCEL 2). Both accelerometers have been used and validated in ambulatory and clinical settings.[7,8,10] ACCEL 1 consisted of a BioModule and holder; the module was 2.8 cm in diameter by 0.7 cm and the holder was 8.8 cm × 4.8 cm × 0.8 mm and had a combined weight of 33 g. The ACCEL 1 had an acceleration sampling frequency of 100 Hz, a bandwidth of 50 Hz, and maximum range of G detection of ±16 G in any axis.[16] The power supply was an internal lithium cell, chargeable via USB prior to flight. Battery life while the radio is not transmitting is reported to be 35 h and has data storage of up to 20 d.[16] Although there is substantial evidence that wireless technology does not interrupt communication and navigations systems during the flight of commercial airliners,[11] we did not have the wireless function on during flight and data were downloaded following the flight. Data analysis for the ACCEL 1 was performed using proprietary data analysis software OmniSense™ (Annapolis, MD).[17]

The ACCEL 2's specifications were as follows; dimensions 4.6 cm × 3.3 cm × 1.5 cm, weight 19 g, acceleration sampling rate of 30-100 Hz, and an accelerative dynamic range of ±8 Gs in any axis. Power supply was an internal lithium cell, chargeable via USB prior to flight. The battery life was reported to be 25 d and had data storage of 120 d/2 GB. It communicated via USB and Bluetooth® Smart and used ActiLife Data Analysis Software (Pensacola, FL) to collate and interpret data.[1] Again, the Bluetooth feature for this device was not used during this protocol.

These two wearable accelerometers were correlated to the static Carrier Aircraft Inertial Navigation System-2 (CAINS-2) located within the F/A-18. The CAINS-2 dimensions were 18″

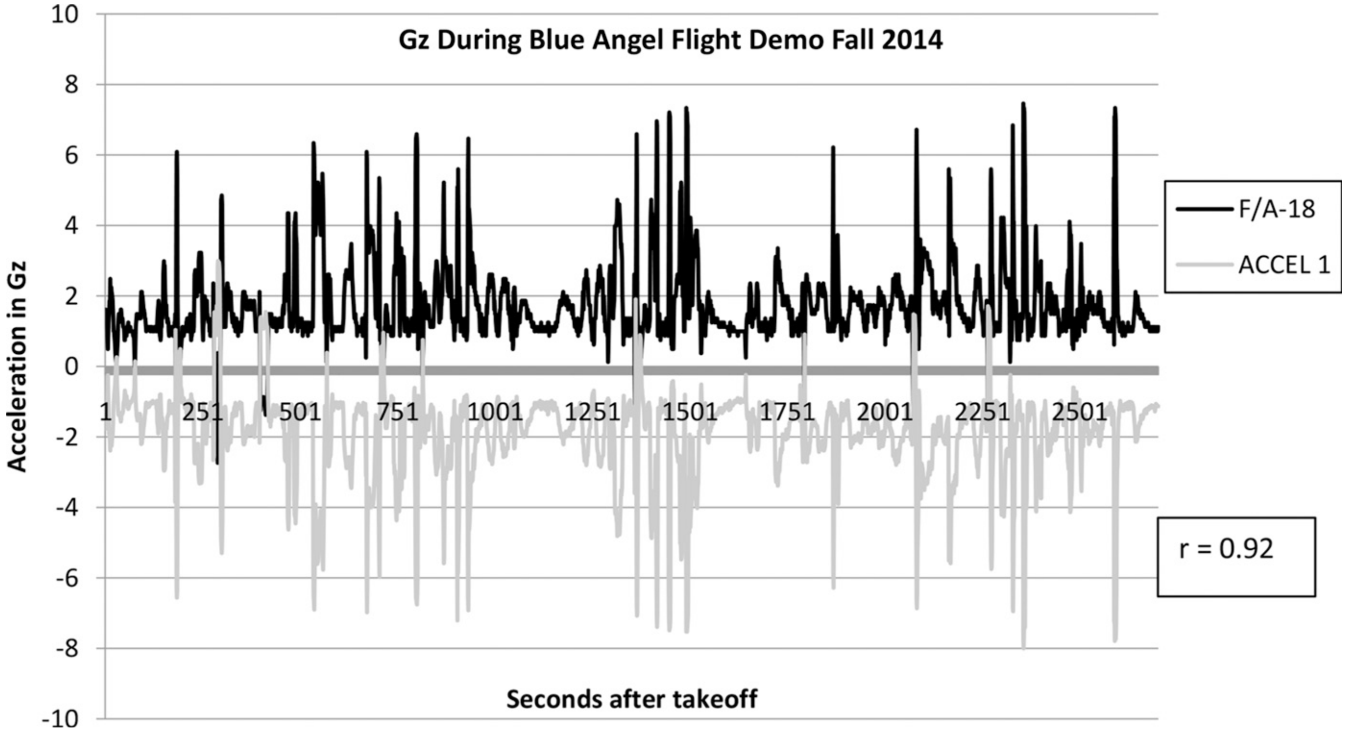

Fig. 1. Example flight comparing the detection of accelerative forces over time from the ACCEL 1 vs. the F/A-18 CAINS-2.

× 14.5″ × 12″ and was situated just aft of the cockpit, secured to the mounting envelope within the airframe. The accelerometer sampling rate was 65 Hz. Calibration of this device is achieved via a Kalman filter, a commonly used data fusion algorithm which estimates the gyro and acceleration bias during ground alignment and continues throughout flight through GPS.[14]

Procedures

Prior to each flight the ACCEL 1 was adhered to the pilot's bare chest via transdermal patch electrodes under their flight suit. The ACCEL 2 was worn in the most comfortable flight suit pocket of the aviator. Both the accelerometers were initialized and time stamped to Zulu (Greenwich Mean Time) by a co-investigator prior to flight and recovered postflight for data download and analysis. Following each flight, a co-investigator administered a postflight questionnaire (**Table I**) to access the comfort level of these devices during flight. To correlate the data perceived by the portable triaxial accelerometers with the static accelerometers found within the F/A-18's, following each flight profile our investigators received the CAINS-2 data card from the maintenance officer and downloaded the airspeed, the G forces in the G_z axis, altitude, and time stamp per the second that G_z occurred during the flight. Only data that were acquired with the aircraft altitude above 0 ft of altitude were analyzed and compared to the portable accelerometers.

Each accelerometer evaluated had sampling rates that were different. The F/A-18 CAINS-2 data output randomly selected an accelerative force from the 65-Hz sampling rate to report G_z in any given second. This report was obtained from the data card following each flight in an Excel data format. The wearable accelerometers reported data in comma separated value files. The ACCEL 1 reported acceleration data at 100 Hz and the ACCEL 2 reported data at 30 Hz. For accurate comparisons of G forces measured among the devices, the data from the wearable accelerometers had to be reduced to the lowest reported rate available, which was $G_z \cdot s^{-1}$ reported from the F/A-18 CAINS-2. To accomplish this task for each flight, data from both wearable accelerometers were uploaded from the comma separated value file to a SQL server database table using Microsoft's extract transform and load tool, SQL Server Integration Services. This tool reduced both portable accelerometer data sets to the average $G_z \cdot s^{-1}$, which could then be compared to the F/A-18 CAINS-2 data output.

Table I. Postflight Questionnaire.

1. On a scale of 0 to 10, 0 being not noticeable, 10 being extremely noticeable, how noticeable was the ACCEL 1 during flight?
2. On a scale of 0 to 10, 0 being not distracting, 10 being extremely distracting, how distracting was the ACCEL 1 during flight?
3. On a scale of 0 to 10, 0 being not noticeable, 10 being extremely noticeable, how noticeable was the ACCEL 2 during flight?
4. On a scale of 0 to 10, 0 being not distracting, 10 being extremely distracting, how distracting was the ACCEL 2 during flight?
5. How many times have you flown with the accelerometers? (please circle the appropriate number)
6. Is there anything you would improve about the accelerometer that you would like to convey?

To align data from the F/A-18's CAINS-2 with data from the portable accelerometers, we identified the first acceleration which occurred above 5 G_z for the aircraft and the wearable accelerometers. After aligning this first peak of both the wearable accelerometers to the F/A-18 CAINS-2 data, all subsequent accelerations in the G_z axis that took place during flight were correlated from takeoff to touchdown. Flight profiles flown were that of a typical air show and varied depending upon the cloud ceiling and weather conditions.

Only accelerations in the G_z axis were compared between the wearable accelerometers and the aircraft, as we were only given this acceleration force from the F/A-18 data card. Between the two accelerometers all three axes were compared by calculating the vector magnitude of G_x, G_y, and G_z using the equation:

$$VM = \sqrt{Gx^2 + Gy^2 + Gz^2}$$

Statistical Analysis

Sample size determination was determined by setting the Pearson Product Moment correlation coefficient at 0.9; with a power of 0.8 and alpha of 0.05, we determined a minimum of 6 s of sampling comparison between the portable accelerometers and the F/A-18's CAINS-2 would be sufficient to determine statistical significance. With each flight lasting an average of 42 min or 2520 s we would have more than enough power to determine statistical significance if it existed. To determine if one accelerometer correlated significantly more than the other compared to the aircraft's inertial navigation system, we used Fisher's Z transformation test, where if the value of z is more than 1.96, the difference is significant at the 5% level.

Following a given flight, each pilot was given a postflight questionnaire consisting of six questions, assessing how noticeable and distracting the wearable accelerometers were. Likert scores from 0, for not noticeable/distracting, and 10 for extremely noticeable/distracting were obtained for questions one through four. Standard *t*-tests were used to determine significant difference in Likert scores between the two accelerometers. The pilots were additionally asked how many times they had flown with the accelerometers and what improvements to the protocol could be made if they felt it were needed.

RESULTS

On 4 different flight days in the fall of 2014, we monitored 20 Naval Flight Demonstration Squadron (Blue Angel) practice flights. Of these 20 monitored flights, 10 complete data sets were acquired for comparison between the F/A-18's CAINS-2 and the commercially available wearable accelerometers. Of the 10 monitored flights that were excluded for comparison, only 1 flight was excluded as a result of incomplete data from the portable accelerometers. The other nine excluded flights were because of errant or incomplete data pulls from the F/A-18 data card.

Of the 10 complete flight comparisons, 5 flights were obtained from formation pilots and 5 flights were from solo pilots. Average flight time was 2570 s from takeoff to touch down. During all 10 flights both the ACCEL 1 and ACCEL 2 were highly correlative with the aircraft and with each other, with an average correlation for the ACCEL 1 of 0.92, and for the ACCEL 2 0.93 (**Table II**). On five flights the ACCEL 2 correlated significantly more than the ACCEL 1. On two flights the ACCEL 1 correlated significantly more than the ACCEL 2. On three flights there were no significant differences between either wearable accelerometer.

With regards to the postflight questionnaire, 20 postflight questionnaires were distributed with 17 postflight questionnaires returned (85%). Of the 17 responses, we obtained 5 each from the first 3 practice shows flown and 2 from the 4th practice show. During the first flight the average Likert scale for being noticed was 4.5 for the ACCEL 2 and 3.0 for the ACCEL 1 (zero being not noticed and 10 being extremely noticed; **Table III**). The average distractibility was 3.4 for ACCEL 2 and 2.0 for the ACCEL 1. The perception of being noticed or distracting dramatically decreased for the ACCEL 2 when aviators were advised to place ACCEL 2 in the most comfortable area of the flight suit in shows 2, 3, and 4. Subsequently, the overall perception of being "noticed" or "distractible" was less for the ACCEL 2 compared to the ACCEL 1, but did not achieve statistical difference due to the low number of comparisons.

DISCUSSION

In our study we found both wearable accelerometers to be highly correlative to the F/A-18 CAINS-2, with an average $r = > 0.9$. In fact, when these accelerometers were graphed against the CAINS-2 they appeared to be a mirror image of the accelerative forces detected by the F/A-18. (Fig. 1 and **Fig. 2**) These negative correlations were due to the aircraft's positive z-axis being opposite of the land-based portable accelerometers' positive z-axis. Both companies cited this finding as inherent to the internal programming of the wearable accelerometers and could easily be inverted to reflect the accelerative forces perceived by the aircraft.

Of the 20 flights we monitored, 10 flights were excluded due to incomplete data. As mentioned in the results, 9 out of the 10 excluded flights were due to incomplete data from the F/A-18's data cards and not the wearable accelerometers. Given the operational tempo of the Blue Angel flight engineers and Boeing representatives whose primary mission was to maintain the aircraft and keep it operating in many other ways other than analyzing the output from the Inertial Navigation System, we consider ourselves fortunate to have been able to obtain 10 complete data sets to correlate. This difficulty in manually integrating the aircrafts' data cards and reliably obtaining full sets of data, despite a fully supported formal research study, suggest that routine interrogation of the aircrafts' data cards for accelerative data is not practical. That being said, for future in-flight investigations that require the retrieval of actual aircraft data, a more coordinated effort with maintenance personnel should strongly be considered. Perhaps most importantly, in only one instance was there incomplete data due to the wearable accelerometers. In this case the ACCEL 1's electrode adhesive pads slipped off the aviator's chest secondary to excessive perspiration. Poor adherence was avoided in future flights by applying ethyl alcohol swipes to the bare chest prior to applying the adhesive electrode pads.

Only in one flight did both the portable accelerometers yield correlations below 0.9, where correlations for the ACCEL 1 and ACCEL 2 were 0.77 and 0.82, respectively. Although this correlation is still strong, it is concerning for researchers seeking to infer accelerative data from these wearable accelerometers as being exactly what the aircraft is experiencing. Recall that the F/A-18's CAINS-2 samples acceleration at a rate of 65 Hz; however, the computer program which extracts this data randomly selects one of these 65 acceleration readings to report on the F/A-18's data card. This perhaps is potentially the crux of the difference found between data recorded from the static inertial navigation system of the F/A-18 and the wearable accelerometers. Of interest, during this flight both the wearable accelerometers had their highest correlations to each other, $r = 0.97$. Because both wearable accelerometers had such a high correlation to each other, an alternate explanation for the lower

Table II. Pearson Product Correlations of the ACCEL 1, ACCEL 2, and the F/A-18's CAINS-2 during 10 Separate Flight Demonstrations.

ACCEL 1-F/A-18 G_z CORRELATION	ACCEL 2-F/A-18 G_z CORRELATION	ACCEL 1 VECTOR MAGNITUDE/ ACCEL 2 VECTOR MAGNITUDE	SECONDS CORRELATED	FISCHER'S Z TRANSFORMATION
0.931	0.933	0.942	2326	1.2
0.932	0.874	0.865	2516	11.6*
0.773	0.815	0.967	2306	3.75**
0.914	0.982	0.871	2788	27.35**
0.938	0.961	0.921	2797	7.78**
0.951	0.936	0.924	2670	4.95*
0.953	0.978	0.957	2434	14.36**
0.927	0.932	0.957	2702	1.24
0.942	0.961	0.962	2434	7.24**
0.932	0.934	0.942	2729	1.44
AVG 0.919	AVG 0.931	AVG 0.930	AVG 2570	

* ACCEL 1 correlated significantly more than ACCEL 2.

** ACCEL 2 correlated significantly more than ACCEL 1.

Table III. Likert Scale Perception of Wearable Accelerometers Being Noticed or Distractible.

	NOTICED AVERAGE		DISTRACTIBLE AVERAGE	
FLIGHT SHOW	**ACCEL 1**	**ACCEL 2**	**ACCEL 1**	**ACCEL 2**
Show 1	3.0	4.5	2.0	3.4
Show 2	2.0	0.3	1.0	0
Show 3	2.0	0.3	1.0	0
Show 4	3.0	0	1.0	0
Average	2.5*	1.2*	1.3**	0.8**

* $P = 0.39$.

** $P = 0.67$.

correlation between the aircraft and the accelerometers during this flight could be the aircraft's inertial navigation system was less accurate.

Upon comparing the two accelerometers head to head, statistically the ACCEL 2 held a slight 0.01 average correlative advantage over the ACCEL 1, and had a significantly greater correlation via the Fisher Z transformation score on five of the flights compared to two for the ACCEL 1 (Table II). Given our power calculation determined a minimum of 6 s of total correlation to determine a statistical difference at 0.9 correlation, and we obtained an average of 2570 s per flight, obtaining a significant difference with this amount of data was highly probable and it is doubtful that this difference is operationally relevant. Of note, the ACCEL 2 was placed in no consistent place on the pilot and was most often placed in the lower flight suit pocket secondary to comfort. This would appear to be an advantage for researchers who wish to perform minimally intrusive research exclusively involving the analysis of accelerative data, as the ACCEL 2 currently does not by itself perceive any physiological data unless paired with separate physiological monitoring devices. On the other hand, the ACCEL 1 accelerometer offered a myriad of physiological data within its bio-module such as heart rate, body temperature, respiration rate, and kilocalorie expenditure. A description of this physiological data will be reported in a future manuscript.

Both wearable accelerometers were minimally to moderately noticed during flight. Although the ACCEL 2 was more noticed than the ACCEL 1 when worn on the waist, it was not reported to be noticed at all when worn in the lower flight leg pocket. One aviator during the first flight reported the ACCEL 2 to be moderately distracting during his first flight when worn on the waist, presumably because his harness strap was directly over this portion of his body. Following the first flight all aviators were encouraged to wear the ACCEL 2 in the most comfortable area of the flight suit. This variable orientation of the ACCEL 2 did not affect the overall correlation of the ACCEL 2 to the aircraft or to the other wearable accelerometer. Future use of wearable accelerometers should necessitate consultation with platform specific Aeromedical Safety Officers to ensure positioning of these devices is in the optimal place to avoid

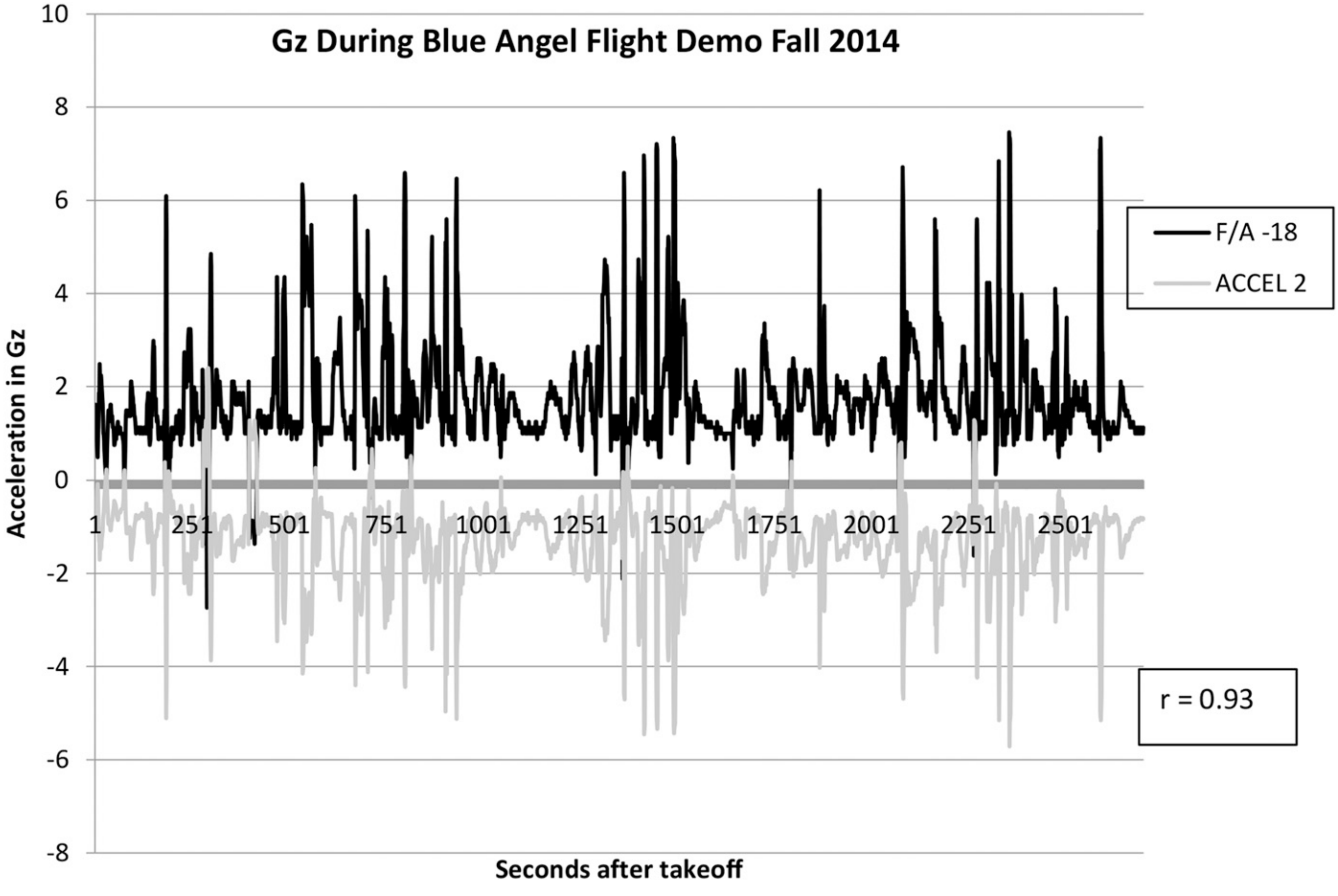

Fig. 2. Example flight comparing the detection of accelerative forces over time from the ACCEL 2 vs. the F/A-18 CAINS-2.

distractions from compression caused by safety harnesses or aviation life support equipment.

In conclusion, both wearable accelerometers examined correlated highly with the G_z acceleration detected by the F/A-18 CAINS-2 system. This study suggests that these wearable accelerometers may be used as a surrogate means of detecting accelerative forces in high performance aircraft in lieu of retrieving data from the internal navigation systems of the aircraft. Future studies evaluating physiological data from these wearable accelerometers may yield new insights with regards to human tolerance in extreme operational environments and hence a "New Golden Age" of aerospace medicine research.

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