Unpredictability of Fighter Pilots' G Duration Tolerance by Anthropometric and Physiological Characteristics

Myunghwan Park; Seunghoon Yoo; Hyeongju Seol; Cheonyoung Kim; Youngseok Hong

BACKGROUND: While the factors affecting fighter pilots' G level tolerance have been widely accepted, the factors affecting fighter pilots' G duration tolerance have not been well understood.

METHODS: Thirty-eight subjects wearing anti-G suits were exposed to sustained high G forces using a centrifuge. The subjects exerted AGSM and decelerated the centrifuge when they reached the point of loss of peripheral vision. The G profile consisted of a +2.3 G onset rate, +7.3 G single plateau, and −1.6 G offset rate. Each subject's G tolerance time was recorded and the relationship between the tolerance time and the subject's anthropometric and physiological factors were analyzed.

RESULTS: The mean tolerance time of the 38 subjects was 31.6 s, and the min and max tolerance times were 20 s and 58 s, respectively. The correlation analysis indicated that none of the factors had statistically significant correlations with the subjects' G duration tolerance. Stepwise multiple regression analysis showed that G duration tolerance was not dependent on any personal factors of the subjects. After the values of personal factors were simplified into 0 or 1, the *t*-test analysis showed that subjects' heights were inversely correlated with G duration tolerance at a statistically significant level. However, a logistic regression analysis suggested that the effect of the height factor to a pilot's G duration tolerance was too weak to be used as a predictor of a pilot's G tolerance.

CONCLUSION: Fighter pilots' G duration tolerance could not be predicted by pilots' anthropometric and physiological factors.

KEYWORDS: G tolerance, G level tolerance, G force training profile.

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High performance aircraft impose extreme physiological stress on the pilot during an aerial combat maneuver (ACM). It has been reported that more than 10% of fighter aircraft pilots in the U.S. naval forces have experienced an unexpected loss of consciousness during an ACM because of gravity forces.[9] Therefore, G tolerance has been considered a crucial factor for pilots flying modern fighter aircraft.

Burton[2,3] categorized pilots' G tolerance into two dimensions: 1) G level tolerance; and 2) G duration tolerance. G level tolerance was defined as the G level at which a pilot cannot stand higher G force and is measured using light-loss criteria such as greyout (loss of peripheral vision), blackout (loss of central vision), or G-induced loss of consciousness (G-LOC). G duration tolerance was defined as the duration of time that a pilot can stand a particular or varying G exposures continuously until the pilot becomes fatigued.

The factors affecting pilots' G level tolerance have been broadly studied and are reasonably well understood. The anthropometric and physiological factors (e.g., age, height, weight, blood pressure, cholesterol, and flight hours) appear to have little effect on pilots' G level tolerance,[5,16] whereas an anti-G straining maneuver (AGSM), anti-G suit, or tilt seat have a strong positive relationship with pilots' G level tolerance.[6,8]

While other factors have been explored, G duration tolerance has been relatively unexplored, particularly in dealing with the factors affecting pilots' G duration tolerance. The primary factor limiting G duration tolerance is fatigue, which prevents the pilot from maintaining the performance of the AGSM. Pilots exposed to a high G force must continually perform the AGSM to avoid incapacitation. Since the AGSM requires

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intense physical activity such as straining muscles, it can be extremely energy-consuming, and is probably a major contributor to the pilot's fatigue. To date, however, not much is known about anthropometric and physiological factors which affect pilots' fatigue tolerance during a high sustained G force.

Previous studies have reported conflicting results about the factors that affect G duration tolerance. Tesch et al.[15] found that G duration tolerance had a significant direct relationship with blood lactate levels. In contrast, Burton[2] found that blood lactate levels were related to G level tolerance, but it was somewhat independent of G duration tolerance. Epperson et al.[4] reported that the most important muscles in determining G duration tolerance are the abdominal and bicep muscles. Mizumoto[12] found that G duration tolerance was correlated with abdominal strength, body fat ratio, and skin-fold thickness. In contrast, Spence et al.[14] and Balldin et al.[1] demonstrated that the abdominal muscles were not correlated with G duration tolerance. However, Webb et al.[16] concluded that G duration tolerance could not be predicted by pilots' anthropometric and physiological factors.

These conflicting findings raise a question about the existence of factors that affect G duration tolerance. Thus, this study was designed to determine if anthropometric and physiological variables of a pilot could be used to predict pilots' G duration tolerance.

METHODS

Subjects

Volunteers for the experiment were 38 Korea Air Force fighter pilots who were attending the high G force training course in the Aerospace Medical Center at the time. All subjects were men since no female subjects volunteered. Each pilot had considerable high G force experience with an average of 732 flight hours (max: 2241, min: 232). The flight hours during 1 wk prior to the experiment was an average of 2.4 h (max: 7, min: 0), during the prior 2 wk was an average of 4.8 h (max: 15, min: 0), and during the previous 1 mo was an average of 9.7 h (max: 32, min: 0). The subjects' average age was 29 yr old (max: 41, min: 29). The details of these factors are shown in **Table I**. The subjects who participated in this experiment were fully informed about the experiment protocols and gave their written consent for the experiment. The experiment protocol was reviewed and authorized by the Korea Air Force Aerospace Medical Center IRB.

Equipment

A Korea Air Force Aerospace Medical Center centrifuge (ETC ATFS-400) was used for this experiment. The centrifuge was installed with a gondola of an F-15 configured cockpit. The pilot seat in the gondola was in an upright position.

Procedure

The subjects wore anti-G trousers and were instructed to perform the fully exerted AGSM (L-1 method with the optimal body position) during exposure to a high sustained single-level G force. The sustained G force level that the subjects were exposed to was +7.3 G_z. The onset rate of the sustained G force was 2.3 $G \cdot s^{-1}$. This G force level and onset rate were determined by the G force training protocol of the Korea Air Force. Every fighter pilot in the Korea Air Force has to attend a high G force training course every 3 yr. In the G force training profile, the G force is accelerated from 2.3 $G \cdot s^{-1}$ to 7.3 G. The G force level is maintained for 20 s from 1.4 G to 7.3 G with a 2.3 $G \cdot s^{-1}$ onset rate. Our experiment was performed by slightly changing the G force training profile. The G force was decreased after 20 s at 7.3 G in the training profile. However, the subjects who participated in our experiment had the G force decreased if both of two conditions were met: 1) if 20 s passed at 7.3 G; and 2) if the pilot lost peripheral vision. The moment when the subjects lost peripheral vision was subjectively determined by the subjects themselves. However, since all subjects were very familiar with physiological responses to high G force exposure, they were expected to precisely recognize the moment when they reached the level of peripheral vision loss. The subject's G duration tolerance was defined as the time spent constantly at a 7.3 G_z. The experiment profile is shown in **Fig. 1**.

Few subjects experienced G-LOC during the G force training. According to training protocol, they have to retake the

Table I. Details of Physical Parameters of the Experimental Subjects.

VARIABLES	MAX	MIN	AVG	SD	MEDIAN	SKEW	KURTOISE
Age (yr)	41	24	29.1	4.03	28	1.05	0.73
Total flight time (h)	2241	232	731.7	543.4	536	1.25	0.71
One week flight time (h)	7	0	2.4	2.1	2	0.95	0.1
Two week flight time (h)	15	0	4.79	3.67	4	1.2	1.19
One month flight time (h)	32	0	9.68	7	7.5	1.29	2
Height (cm)	193	164.7	174.5	5.64	174.8	0.83	2
Weight (kg)	114	55.4	76.4	10.38	75.8	1.07	3.58
Systolic BP (mmHg)	138	108	121.87	7.29	120	−0.09	−0.32
Diastolic BP (mmHg)	88	57	75.37	8.27	75	−0.21	−0.67
Skeletal muscle mass (kg)	49	27.2	34.73	4.51	34.2	1.11	2.45
Body fat mass (kg)	32	5.9	15.82	5.6	15.05	0.76	0.89
Body fat ratio (%)	30.4	10.5	20.3	5.16	20.65	−0.07	−0.51
Neck size (cm)	41	34.5	37.46	1.63	37.25	0.26	−0.36
Chest size (cm)	112.8	87.7	99.84	5.6	99.5	0.16	−0.03
Abdominal size (cm)	114.5	69	86.5	9.12	85.55	0.99	1.83

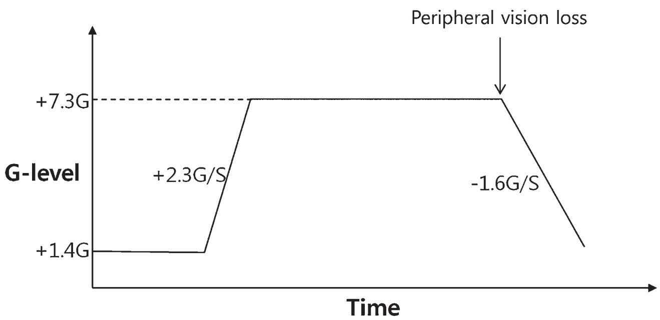

Fig. 1. Experiment profile.

same training profile until they succeed in enduring 20 s at 7.3 G. The retake is carried out after they fully recover from fatigue (a few hours later or the next day). All subjects who failed the first time successfully finished the G force training the second time.

The IRB for this study did not give approval to repeat our experiments for those who retook the G force training, so we did not use the data of subjects who experienced G-LOC on the first attempt. The reason is because if they failed to endure 20 s the first time but succeeded the second time, it would have been unclear which one reflected their intrinsic G duration tolerance. We believe that G duration tolerance of a person would not dramatically change within a few hours or a day, but G-LOC might occur because of a poor quality AGSM or a temporal physical condition rather than a subject's weak G duration tolerance. Nevertheless, we only used the experimental data of the subjects who endured more than 20 s at 7.3 G without G-LOC the first time.

Several anthropometric and physiological variables of the subjects were selected for the experimental variables to determine the degree of effect on the subjects' G duration tolerance. The variables used were height (cm), weight (kg), systolic blood pressure (BP), diastolic BP, skeletal muscle mass (kg), body fat mass (kg), body fat ratio (%), neck size (cm), chest size (cm), and abdominal size (cm). The subject's aircraft type, age, and flight hours were also considered experimental variables. Every Korea Air Force pilot has a medical checkup in the hospital every other year. During the checkup, pilots' anthropometric and physiological values are measured, so we used those values for each subject. To measure the skeletal muscle mass, body fat mass, body fat ratio, neck size, chest size, and abdominal size, the direct segmental multifrequency bioelectrical impedance analysis[11] was used with InBody720 equipment (InBody Co., Ltd., Seoul, Korea). The time discrepancy between the medical checkup date and the experiment date was an average of 111 d (max: 477 d, min: 1 d). The details of the physical parameters of the experimental subjects are shown in Table I.

RESULTS

The distribution of the G duration tolerance of the subjects is shown in **Fig. 2**. The mean tolerance time of the 38 subjects was 31.6 s and the min and max tolerance times were 20 s and 58 s, respectively. Initially, the relationship between the subjects' aircraft type and G duration tolerance was investigated using ANOVA analysis. Because of the small sample size of the subjects, F-16 (2 subjects) and KA-1 (4 subjects) pilots were excluded from the analysis. Thus, F-4 (7 subjects), F-5 (18 subjects), and F-15 (7 subjects) pilots were analyzed. Any mean difference in G duration tolerance among the different aircraft pilots was not shown in the ANOVA analysis [$F(2,29) = 1.38$, $P = 0.269$].

Next, the correlations between the pilots' G duration tolerance and other variables were investigated. None of the variables had statistically significant correlations with the subjects' G duration tolerance ($P < 0.05$). Many of the subjects' variables were interrelated. For example, the pairwise correlation between age and flight hours was significantly high ($r = 0.92$, $P < 0.001$). Height, skeletal muscle mass, weight, neck size, chest size, and abdominal size were all strongly correlated ($r > 0.8$, $P < 0.001$). Thus, a stepwise multiple regression procedure was used to investigate the effects of each variable on the subjects' G duration tolerance. However, the subjects' G duration tolerance was found to not be dependent on any experimental variables at a statistically significant level ($P < 0.05$).

Since the sample size of this experiment was relatively small ($N = 38$), the influence of a few outliers might dominate the sample and it might alter the results of the analysis. To remove the influence of the outlier data, the value of the subjects' G duration tolerance was simplified. The variable was categorized into two values (G tolerant or G intolerant). If a value was less than or equal to the median, it was categorized as 0 (G intolerant) and 1 (G tolerant) otherwise.

The independent sample *t*-test analysis with the simplified data was run on all variables to investigate whether there was any mean difference between the subject groups: one group with G duration tolerance 0 and the other group with 1. The results are summarized in **Table II**. None of the variables showed a statistically significant mean difference ($P < 0.05$).

We also simplified the value of other variables to 0 or 1 to remove the effect of outlier data. However, we used a different grouping method in this case. Whereas we simply used the median value to group the pilot's G duration tolerance, we used a data mining technique, decision tree analysis,[7] to determine the basis datum. The purpose of using the decision tree technique was to choose the most decisive value as the basis datum, which maximizes the difference in the averages of the two groups. The decision tree analysis identified the basis data in five variables: flight hours, height, weight, systolic BP, and abdominal size. Using these basis data, the values of the variables were transformed into 0 or 1, and the independent sample *t*-test analysis was performed to compare the difference in the averages. **Table III** shows the results of the *t*-test analysis.

As shown in Table III, the subjects' heights revealed a statistically significant ($P < 0.05$) mean difference between the two groups. Logistic regression analysis was run to check the effect of this variable on subjects' G duration tolerance. The regression equation ($P = 0.034$, $EXP(B) = 0.188$, Nagelkerke $R^2 = 0.165$) was as follows:

$$\ln(T) = 0.981 + -1.674H,$$

where T = odds predicted by the model and H = height.

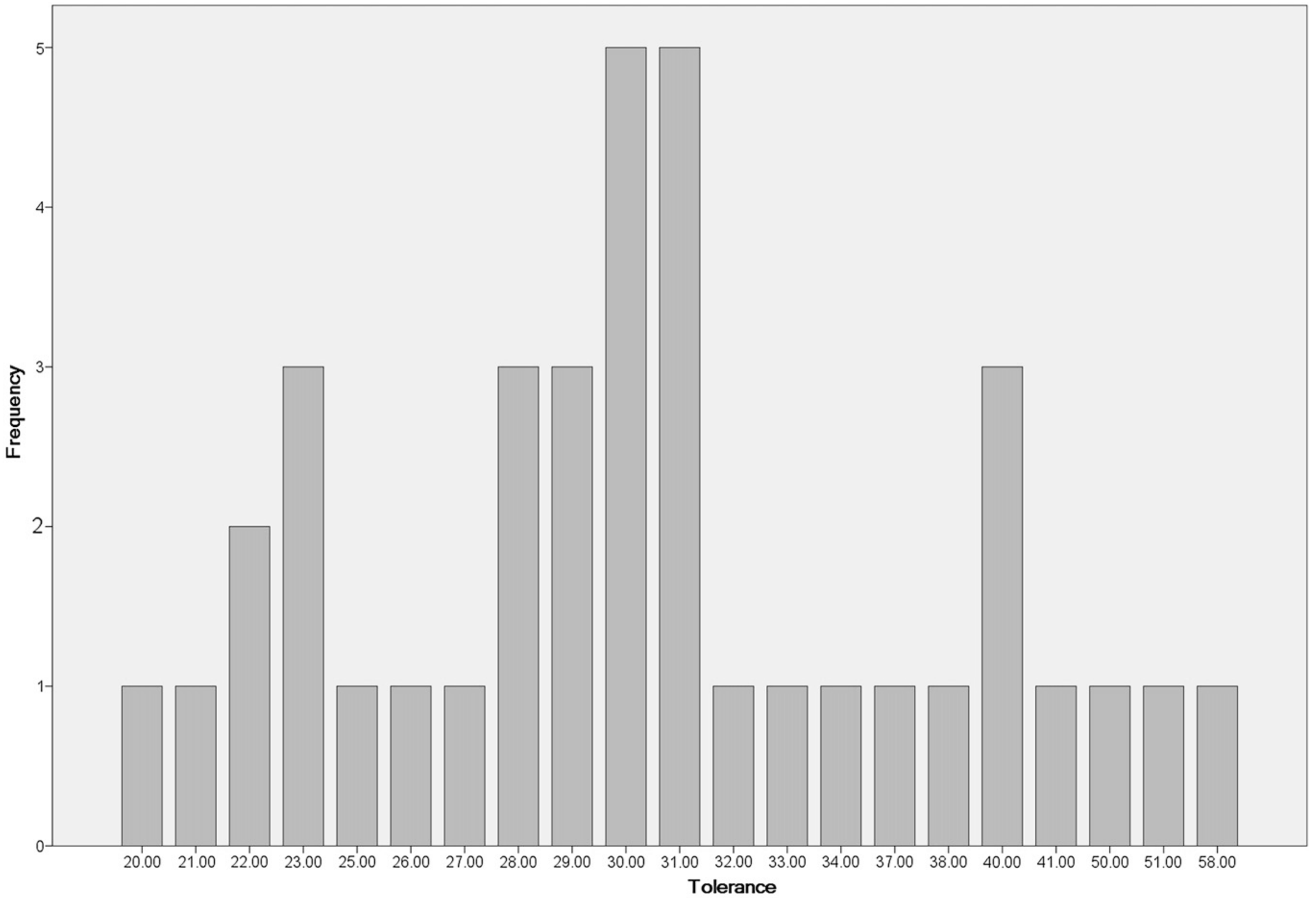

Fig. 2. Subjects' tolerance time distribution.

The regression analysis indicated that a subject's G duration tolerance was inversely related to the subject's height. However, the subject's height may just influence a small amount (16%) of the subject's G duration tolerance (Nagelkerke $R^2 = 0.165$).

DISCUSSION

The present study was designed to determine if pilots' personal factors, such as anthropometric, physiological, aircraft type, age, and flight hours, could be used to predict pilots' G duration tolerance. The results obtained in this study show that none of the above factors were significantly correlated with pilots' G duration tolerance. This is consistent with the findings of Webb et al.[16] and Forster et al.,[5] who studied the factors affecting pilots' G tolerance. Webb et al.[16] investigated influential factors that affect G duration tolerance (ROR G tolerance) and found no factors which affected pilots' G duration tolerance. Similarly, Forster et al.[5] showed that a pilot's age and flight hours did not have any effect on G duration tolerance (ROR G tolerance). In contrast, Morgan[13] found that pilots who had been given 4-wk layoffs experienced significantly reduced G duration tolerance. However, our results showed that pilots' recent flight experience did not affect G duration tolerance.

After the experimental data were simplified to two values, an independent sample *t*-test analysis was conducted for the data.

Table II. Analysis Using the *t*-Test with Simplified G Duration Tolerance Variables.

VARIABLES	AGE	FLIGHT HOURS	HEIGHT	WEIGHT	SYSTOLIC BP	DIASTOLIC BP
t	−0.379	−0.088	1.761	1.674	−0.909	−0.344
P	0.707	0.930	0.087	0.103	0.370	0.733

VARIABLES	SKELETAL MUSCLE MASS	BODY FAT	BODY FAT RATIO	NECK SIZE	CHEST SIZE	ABDOMINAL SIZE
t	1.943	0.992	0.560	0.764	1.415	1.285
P	0.060	0.328	0.579	0.432	0.166	0.207

Table III. Analysis Using the *t*-Test with Five Simplified Variables.

VARIABLES	FLIGHT HOURS	HEIGHT	WEIGHT	SYSTOLIC BP	ABDOMINAL SIZE
Base datum	292	171.35	87.2	119	86.4
Sample size	< 292: 10	< 171.35: 11	< 87.2: 32	< 119: 9	< 86.4: 21
	> 292: 28	> 171.35: 27	> 87.2: 6	> 119: 29	> 86.4: 17
t-test	*t*: 0.077	*t*: 2.225	*t*: 0.611	*t*: -1.626	*t*: 1.746
	P: 0.708	*P*: 0.034	*P*: 0.545	*P*: 0.113	*P*: 0.089

The results indicated that a pilot's height seemed to have a relationship with the pilot's G duration tolerance. This finding corroborates with those of Klein et al.,[10] who found that heart-eye distance is negatively related to G force tolerance. However, logistic regression analysis of the height variable suggests that the contribution of this variable to the pilot's G duration tolerance was too weak to be used as a predictor of a pilot's G duration tolerance. The results of our experiment suggest that pilots' G duration tolerance might depend on many uncontrollable factors such as self-confidence with G force and the quality of the AGSM rather than pilots' personal factors, including anthropometric and physiological factors.

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