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REVIEW ARTICLE

LOWER BODY NEGATIVE PRESSURE AS A SIMULATION METHOD FOR +GZ ACCELERATION STRESS: A FEASIBILITY AND COMPARATIVE ANALYSIS

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Introduction: This paper explores the utility of Lower Body Negative Pressure (LBNP) as a simulation method for replicating the physiological effects of +Gz acceleration stress experienced by aviators during high-performance flight maneuvers. The study investigates the feasibility of using LBNP to induce cardiovascular responses akin to those observed during +Gz acceleration, including changes in heart rate, blood pressure, stroke volume, cardiac output, mean arterial pressure, and central venous pressure.

Method: Through a comprehensive review of existing literature and empirical data (keywords and filters such as LBNP, aerospace, centrifuge, simulator, acceleration, Gz, and databases including PubMed, IEEE Xplore, ScienceDirect, and others relevant to this field of study were selected for the search), we evaluate the efficacy of LBNP in simulating the hemodynamic challenges associated with high-G environments.

Results: The results of the review were organized by thematic categories (advantages of the LBNP test compared to a human centrifuge, changes in heart rates during exposure to +Gz and in the LBNP test, and the relationship between tolerance to LBNP and G-tolerance level). Syntheses of the results are presented, highlighting key themes and insights.

Discussion and Conclusion: LBNP appears to be effective in simulating the impact of +Gz acceleration, particularly in conditions where the acceleration changes slowly (0.01 G/s) or moderately (0.05 G/s). Our findings suggest that LBNP holds promise as a versatile and practical tool for investigating physiological responses to +Gz acceleration stress and for advancing our understanding of human adaptation to extreme gravitational forces. Considering the high cost of installing a human centrifuge to assess +Gz acceleration tolerance, LBNP may serve as a cost-effective alternative for studying human physiology during exposure to moderate and slowly varying acceleration (+Gz).

Keywords: aviation medicine, LBNP, negative pressure, acceleration stress, centrifuge

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INTRODUCTION

Simulating G-forces acting on fighter pilots during flight maneuvers presents unique challenges on the ground. However, several methods can effectively simulate G-forces on the ground for training and research purposes. The most popular is the human training centrifuge simulator [51,65], designed for testing military pilot candidates and training pilots of highly maneuverable aircraft (i.e., combat, aerobatic, and sport), as well as for experimental technical testing. Moreover, the centrifuge provides a safe alternative for raising awareness among aircrews about the potential of adverse effects of acceleration, such as G-induced loss of consciousness (G-LOC) or spatial disorientation. This flight simulator is capable of reproducing a real flight [40,41,49,56,57], thereby ensuring the perfect professional preparation of pilots for complicated and dangerous air missions.

The Vertical Motion Simulator is another simulator for generating and studying the effects of G-forces on pilots during flight [4,5]. It consists of a platform capable of moving up and down along a vertical axis. By rapidly raising and lowering the platform, pilots can experience sensations similar to those of vertical acceleration. While not a perfect simulation of G-forces, this method can help familiarize pilots with the feeling of acceleration and deceleration.

Another example is the tilt platform, which consists of a table or chair mounted on a tilting mechanism. This design allows the simulation of sensations corresponding to different levels of acceleration (ranging from 1 to -1 g) along various axes. However, the platform can only simulate G-forces within a limited range. The next method used to simulate G-forces on the ground is the g-seat system [77–79]. This system is equipped with pneumatic pressure modules that provide sustained g-cueing. Multiple airbags in the seat and harness expand and contract to apply localized and sustained pressure, simulating the G-forces experienced during turns or maneuvers in an aircraft [77].

An alternative method for simulating +Gz stress and evaluating orthostatic response is a chamber that generates negative pressure in a pilot's lower body [50,55,68,70,76]. While not directly simulating G-forces, reducing the ambient pressure inside the chamber (around a pilot's lower body) can induce physiological effects similar to those experienced during high-G maneuvers, such as reduced blood flow to the brain, tachycardia, hypotension, and eventual loss of consciousness (i.e., presyncopal symptoms) [11,66,67,69].

A final example of a method for simulating the effects of G-forces on pilots during flight is virtual reality simulation [26,33]. This type of simulation can create immersive environments that replicate the visual and auditory aspects of flight maneuvers, including G-forces. While virtual reality alone cannot replicate the physical sensations of G-forces, it can be combined with motion platforms or other simulation techniques to enhance realism. Each of the methods mentioned above for simulating G-forces on the ground has unique advantages and challenges. The choice of method depends on factors such as the desired level of realism, available resources, and specific training objectives.

In this paper, we focused on the method by which the effects of G-forces are simulated using Lower Body Negative Pressure (LBNP). LBNP is a technique used to simulate the effects of gravity on the human body [42]. It involves creating a negative pressure (i.e., pressure below atmospheric level) around the lower limbs to induce cardiovascular and physiological responses similar to those under conditions of upright posture and gravitational stress [61,75].

LBNP was first used in research settings to study the effects of simulated gravitational changes on the human body, particularly in the field of aerospace medicine [7]. In space, astronauts experience microgravity, which can lead to physiological changes such as fluid redistribution, muscle atrophy, and cardiovascular deconditioning. By applying negative pressure to the lower body, LBNP effectively pulls blood towards the lower extremities, mimicking the gravitational forces that act on the human body when sitting or standing upright on Earth [19,20,45,46,48]. Researchers also use LBNP to simulate the effects of experiencing gravitational forces encountered during launch, re-entry, or planetary exploration [6,34,39,55]. This simulation enables the investigation of cardiovascular responses to changes in gravity and helps researchers develop countermeasures to mitigate the negative effects of space travel on astronaut health. Since its initial use in aerospace medicine research, LBNP has also found applications in other fields, such as orthostatic intolerance research [1,13,14,21,59–61], cardiovascular physiology studies [16,32,35,37,54,63], cerebral blood flow studies [18], and the development of medical interventions for conditions such as orthostatic hypotension and syncope [8,27,36,44].

Table 1. Result of the literature review.

Keyword	Phrase	Number of articles found in the database		
		PubMed	IEEE Xplore	ScienceDirect
LBNP	centrifuge	42	2	124
	aerospace	190	6	96
	simulator	403	1	22
	acceleration	78	2	142
	Gz	49	5	43

METHODS

The systematic literature review was based on searching, reviewing, and selecting articles based on predefined criteria. The selected databases were PubMed, IEEE Xplore, ScienceDirect. Searches were performed using predefined keywords (LBNP, aerospace, acceleration, centrifuge, simulator, and Gz). The search was not limited by publication date, language, or type of study. Table 1 presents the outcomes of the search conducted across the three databases, in accordance with the previously outlined criteria. A total of 71 articles were deemed eligible for analysis.

Advantages of LBNP over a human centrifuge

As an equivalent of the human centrifuge in terms of assessing acceleration tolerance in pilots (i.e., the pilot's ability to withstand high G-forces without losing consciousness) [3,25,74], LBNP offers several advantages [23]:

- allows the use of measurement techniques and technologies that are sensitive to movement or require a supine or sitting position (e.g., magnetic resonance imaging),
- keeps subjects in an unchanged position, enabling more efficient physiological measurements and avoiding the adverse effects of changing body position on the quality of signal recording, as observed in echocardiography and impedance reography; Nevertheless, for the low accelerations generated in the human centrifuge, when the test subject is not performing muscle tension maneuvers (no muscle contraction), physiological signals of good quality can also be obtained,
- enables the maintenance of central hypovolemia in the supine or sitting position, minimizing the influence of skeletal muscle activity. This allows for the study of isolated cardiovascular mechanisms involved in blood pressure control without considering the effects of the so-called muscle pump,
- ensures that the subject's head position remains unchanged, resulting in no stimulation of the vestibular receptors. It is well-established that changes in head position can affect autonomic responses involved in blood pressure regulation [9]. When testing in a human centrifuge, both linear and angular accelerations are used to stimulate the vestibular organs, inducing variable postural muscle contractions,
- allows for easy dosing of the stimulus and rapid restoration of atmospheric pressure in the chamber in case of symptoms of threatened cardiovascular collapse. This facilitates quicker interruption and termination of the test, reducing the incidence of syncope [17],
- provides an opportunity to determine the total capacity of the cardiovascular system to regulate blood pressure, as well as to assess the compensatory reserve during central hypovolemia by allowing investigators to induce pre-fainting states under controlled and relatively safe experimental conditions,
- assures a more effective and practical way to simulate the effects of gravity on the cardiovascular system than centrifugation [72],
- is less stressful [50].

It is worth noting that one of the significant shortcomings of human centrifuges is the rotational movement of the cabin, which is a side effect of the generated linear acceleration (Gz). This movement causes strong stimulation of the semicircular canals of the vestibular system, known as the cross-coupling effect. Considering the relationship between vestibular organ excitation and autonomic responses in blood pressure regulation [9], as well as the potential for variable postural muscle contractions, the hemodynamic responses obtained in the human centrifuge may differ from those experienced during real flight. Therefore, it may be questionable whether the evaluation of LBNP-induced changes should be based on the cardiovascular response observed during the human centrifuge test or actual flight. The answer to this question can be found in studies that compare the differences in cardiovascular response between these two environments.

Table 2. Effect of +Gz acceleration and LBNP on selected hemodynamic parameters [24,55,64,67].

Parameter	Change under stimulus (↑ - increase, ↓ - decrease)	
	+Gz	LBNP (mmHg) *
Heart rate (HR)	↑	↑
Stroke volume (SV)	↑	↓
Cardiac output (CO)	↑	↓
Systolic/Diastolic blood pressure (SBP/DBP)	↑	↓
Mean arterial pressure (MAP)	↑	↓
Central venous pressure (CVP)	↑	↓

* LBNP-induced effects depend on the profile of changes (negative pressure value, duration, etc.) [24].

Despite the above-mentioned advantages of the LBNP in Gz simulation applications, the human centrifuge still remains the most reliable device and an essential tool in the preparation of pilots who are exposed to high levels of acceleration (G-forces). Compared to other alterative techniques for simulating Gz acceleration, including LBNP, the human centrifuge:

- includes the use of flight suits, helmets, and other equipment. Familiarity with these items in high-G conditions ensures that trainees can use them effectively during actual operations,
- helps strengthen the muscles used to counteract the effects of G-forces, particularly those involved in the Anti-G Straining Maneuver (AGSM),
- allows individuals to build G-tolerance, enabling them to withstand higher G-forces for longer durations. This capability is crucial for maintaining performance during combat maneuvers or emergency procedures,
- enables trainees to become familiar with the symptoms of G-stress, such as tunnel vision or gray-out,
- simulates the exact conditions of high-G environments encountered in flight or space missions. This realistic training ensures that individuals are well prepared for the specific challenges they will face.

Therefore, the use of a human training centrifuge in preparing individuals for the challenges of high-G environments does not appear to be quickly replaced by other Gz simulation techniques.

Table 2 shows the hemodynamic changes induced by +Gz and LBNP. The HR parameter consistently changes direction in response to both stimuli, while the other parameters show opposite changes.

Change in heart rate during exposure to +Gz and in the LBNP test

The first reports on the use of LBNP to simulate cardiovascular analogous to those elicited by +Gz acceleration stimuli date back to studies conducted in the 1970s. One such study [38] demonstrated that exposure to LBNP at -50 mmHg in the supine position induces changes in HR comparable to those observed in response to +2 Gz acceleration. In the standing position, ground acceleration (+1 Gz) result in a displacement of 500 to 600 ml of blood to the lower limbs. Additionally, there is a shift of fluids from the intravascular to the interstitial space and a decrease in cardiac output analogous to that induced by -40 mmHg LBNP in the supine position [2,31,52,62,75]. The HR values at -40 mmHg in the supine position (73.7 ± 2.6) were found to correspond to the control values without LBNP in the sitting position (74.1 ± 1.9 bpm). However, no significant differences were observed. A significant difference in heart rate was observed at -70 mmHg in the supine position (102.5 ± 4.4 bpm) and at -40 mmHg in the standing position (103.1 ± 4.0 bpm) [55].

Polese et al. [55] noted, however, that LBNP and human centrifuge are different physiological stressors and therefore induce different hemodynamic changes. Their findings indicated that peak HR values during exposure to +3 Gz (145.8 ± 7.7 bpm) and +4 Gz (152.3 ± 6.5 bpm) significantly exceeded the HR levels recorded during LBNP in the supine and standing positions [55]. For +2 Gz acceleration (104.8 ± 5.5 bpm), HR values closely matched those observed at -40 mmHg in the standing position (103.1 ± 4.0 bpm) and at -70 mmHg in the supine position (102.5 ± 4.4 bpm). Table 3 presents the LBNP values for which studies demonstrated consistency between HR changes observed during exposure to Gz acceleration and those induced by LBNP.

Polese et al. [55] also demonstrated that, in a subject in the upright position exposed to -40 mmHg LBNP (Table 3), mean arterial pressure (MAP) (90.6 ± 2.6 mmHg) and diastolic blood pressure (DBP) (75.8 ± 2.0 mmHg) were similar to the peak values observed during exposure to +2 Gz acceleration (93.2 ± 4.5 mmHg and 80.7 ± 5.5 mmHg, respectively). In the same study, venous

Table 3. LBNP values for which studies have shown HR changes to be consistent with those occurring during exposure to +Gz acceleration.

Heart rate (bpm)				**Number of subjects**	**Reference**
Acceleration	**M±SD**	**LBNP**	**M±SD**		
+1 Gz	data not available	-40 mmHg in supine position	data not available	7	[53]
+1 Gz and tilt at 70°	90	-50 mmHg in supine position	90	5	[52]
+2 Gz	74.1 ± 1,9	-40 mmHg in a sitting posture	73.7 ± 2.6	8	[55]
combined +1 Gz and -40 mmHg in upright position	103.1 ± 4.0	-70 mmHg in supine position	102.5 ± 4.4	8	[55]
+2 Gz	104.8 ± 5.5	-40 mmHg in upright position	103.1 ± 4.0	8	[55]
		-70 mmHg in supine position	102.5 ± 4.4	8	

M – mean; SD – standard deviation

Table 4. Correlation between the scores obtained for the +Gz and LBNP stimulus tolerance tests [47].

		Gz onset		
		fast (0.2 G/s)	**medium** (0.05 G/s)	**slow** (0.01 G/s)
LBNP	**fast** (2.0 mmHg/s)	0.40	**0.54**	**0.52**
	medium (0.3 mmHg/s)	-0.05	0.25	**0.53**
	slow (0.067 mmHg/s)	-0.23	0.07	0.32

pooling in the lower limbs induced by LBNP in the sitting position, as measured by impedance plethysmography, was 65% of that recoreded during +3 Gz and +4 Gz, and 64% of that during +2 Gz. These findings provide evidence that LBNP exposure at -40 mmHg in the sitting position can serve as a static simulator of HR and MAP changes induced by a gradually increasing acceleration stimulus of +2 Gz [55]. It was also found that during seated LBNP, blood pooling in the legs was significantly lower compared to acceleration [55]. The researchers suggested that LBNP at -80 or -90 mmHg during flight could simulate +2 Gz HR effects in the presence of weightlessness.

In a study conducted by Ludwig et al. [47], the tolerance of subjects to two stressors, LBNP and +Gz, was compared. The study involved 17 participants who were subjected to centrifugation and LBNP in the sitting position. Three different Gz onset rates (the rate of change in acceleration) were employed: 0.01 G/s (slow), 0.05 G/s (medium) and 0.2 G/s (fast). The rates of negative pressure change were 0.067 mmHg/s (slow), 0.3 mmHg/s (medium) and 2.0 mmHg/s (fast), respectively. It is worth noting that the Gz onset rates used in the study are significantly lower than those encountered during actual fighter jet flights. The results of this study demonstrating the relationship between human responses to LBNP and +Gz acceleration are presented in Table 4.

This study showed that the fastest rate of LBNP change (2.0 mmHg/s) is most strongly correlated with tolerance to slow (0.01 G/s) and medium (0.05 G/s) +Gz onset, but not with fast (0.2 G/s) +Gz onset. A moderate correlation was also observed between the medium rate of LBNP change (0.3 mmHg/s) and the slow (0.01 G/s) +Gz onset. These findings suggest that LBNP may only be a useful method for assessing +Gz tolerance to a limited extent when lower body decompression occurs at a sufficiently rapid rate.

In addition to the mapping the effects of +Gz stress in the LBNP test, it is also important to establish the correlation between +Gz tolerance levels determined using a human centrifuge and those obtained using LBNP.

Relationship between tolerance to LBNP and G-tolerance level

According to some researchers [50,55,68,70,76], the LBNP test is considered equivalent to human centrifuge testing due to similarities in the displacement of body fluids into the lower body and associated hemodynamic responses. Furthermore, some studies [71] indicate that LBNP has already been used as a method for estimating G-tolerance with a 90% accuracy level.

In studies [58,70,76], the possibility of applying the LBNP test to assess acceleration (+Gz) tolerance among military pilots was discussed. During the LBNP test (-50 mmHg), a difference in the low-frequency component of HR variability was found between groups with high (+6.7-8.0 Gz) and low (+4.8-6.1 Gz) acceleration tolerance [76]. This component was higher in the latter group. The study also revealed a statistically significant decrease in sympathetic nervous system activity among participants with high acceleration tolerance during LBNP exposure at -50 mmHg.

In another study [50], a moderate correlation (r=0.6) between +Gz tolerance (+5.94 ± 0.98 Gz) and QZ values (the time between ventricular depolarization [beginning of the Q wave in ECG] and the local maximum of the first derivative in impedance cardiography) was found. The LBNP test involved pilot candidates (n=14) who were exposed to -40 mmHg for 3 minutes in the supine position. For both baseline and maximal HR during LBNP (75 ± 12 bpm and 81 ± 13 bpm, respectively) and during +Gz (121 ± 19 bpm and 172 ± 21 bpm, respectively), the canonical correlation of exposure was r=0.72 (the result was statistically not significant). The researchers also indicated that high HR values prior to the centrifuge test in pilot candidates may lead to values that reach HR termination criteria [73]. As a result, tolerance to high +Gz forces may remain unrecognized. The authors suggest that the LBNP test could be a useful tool in selecting pilot candidates, particularly those with high baseline HR values.

Verghese & Prasad [70] compared the increase in heart rate observed in LBNP tests (-40 mmHg for 5 minutes, both in supine and sitting postures) with that reported by Lindberg et al. [43] during +Gz stress. It was observed that the physiological strain (estimated based on HR) induced by -40 mmHg in the seated position is comparable to the level induced by between +2 and +3 Gz.

The LBNP test for the pre-selection of pilots with low +Gz tolerance was also developed by Hanousek et al. [29]. The authors verified this method by comparing the physiological responses of pilots during LBNP, flight, and centrifuge load. The study found that changes in blood pressure and HR during the LBNP test were similar to those observed during exposure to +3.5 Gz in a human centrifuge [12]. The results also mostly corresponded to acceleration of +4.5 Gz during flight in a real aircraft [30]. In subsequent studies, Hanousek et al. [28] reconstructed the LBNP device not only to estimate the +Gz tolerance level but also to identify pilots with low tolerance to the push-pull effect.

In other studies [67,69] researchers examined the relationship between six parameters (arterial blood pressure, HR, thoracic impedance reography, non-standard electrocardiographic leads, phonocardiography, and air plethysmography on the middle finger of the right hand) measured during a 20-minute-long LBNP and during +Gz tolerance tests. This analysis revealed, with high statistical significance (p<0.01), that based on responses to the LBNP test (six parameters mentioned above), it is possible to group subjects according to their +Gz tolerance. The accuracy of the decision making during this selection was 82.1%. A strong dependence of +Gz acceleration tolerance on six listed hemodynamic and hormonal parameters, measured during LBNP exposure at -60 mmHg for supine subjects (n=65), was described by the following linear equation [67]:

$$
\begin{aligned}
+GZ = {} & -0.13\,PRA + 0.01\,LVET + 0.005\,CO + \\
& + 0.01\,PEP + 0.11\,PAC + 0.01\,HR + 2.18
\end{aligned}
\tag{1}
$$

where:

PRA – plasma renin activity,
LVET – left ventricular ejection time, calculated as the time between the beginning of the ascendant arm of the dZ/dt wave and the dicrotic notch on the same wave (dZ/dt) [msec],
CO – cardiac output, calculated as the product of stroke volume and heart rate [ml/min],
PEP – pre-ejection period, calculated as the time between the beginning of the QRS complex and the beginning of the ascendant arm of the dZ/dt wave (the first derivative of the reography wave dZ) [msec],
PAC – aldosterone,
HR – heart rate.

Equation (1) can be used to predict the individual +Gz tolerance values with a mean error of 0.26 G. Researchers using LBNP have noted that this test may lead to vasovagal syncope and/or cardiac arrhythmias. Therefore, caution should be exercised when performing LBNP tests, with appropriate monitoring of physiological parameters and the presence of medical personnel, such as a physician.

Finally, it should be noted that the definition of G-tolerance was not uniform across the reviewed studies. While some focused on autonomic nervous system responses (e.g., HR variability, HR changes), others relied on cardiac hemodynamics or multi-parametric models. These differences could influence comparability between studies, emphasizing the need for standardized criteria in future LBNP studies on G-tolerance assessment methods.

CONCLUSIONS

In summary, LBNP has the potential to simulate +Gz acceleration and generate reproducible physiological responses. However, before any application, LBNP-based methods must be properly validated to ensure their effectiveness.

Considering the high cost of the installing a human centrifuge to assess +Gz acceleration tolerance, LBNP may serve as a cost-effective alternative for studying human physiology during exposure to moderate and slowly varying acceleration (+Gz) [15,22]. It is important to note, however, that LBNP-induced hemodynamic and neurohormonal responses, as well as tolerance, vary among individuals [10,24]. Therefore, when designing experiments and selecting participants, it is important to consider the various factors (i.e., participant-specific and LBNP protocol-related variables) that may influence LBNP-induced responses.

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The authors declare that there is no conflict of interest.

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