Rearward facing seats in flight: an aviation review

Jeffrey C Stephenson

REARWARD FACING SEATS have been used in aircraft and airships for many decades. There are numerous images of the interior of hydrogen and helium airships showing seating arrangements not dissimilar to a dining room or lounge area in a club. In addition, there have been many airframes with at least some seats facing rearwards. Examples include the RAF VC-10 (all seats facing rearward), BAC1-11, Trident 1E 2 and 3, V951 Vanguard, Comet-4 1970, ATR-42,[1] B727 1975, Bell 206 Jet Ranger,[2] the Lockheed Electra, VC-10 C1 1966,[3] C-141, C-5,[4] and the Apollo Command Re-entry module.[5] The Royal Air Force (RAF) adopted rearward facing seats as early as 1945, as this seating arrangement was recognised as allowing higher (survivable) impacts in the event of an accident.[4] Various bodies have discussed whether rearward facing seats should be mandated,[6] and have generally concluded that they would not be accepted, either because of unpopularity with passengers (as travellers generally dislike travelling backwards), or with airlines (because of the higher costs of converting and building this type of seating). Apart from cost and engineering considerations, there is debate as to whether rearward facing seats confer increased survivability in an aircraft accident. Although it would appear that rearward facing seats confer increased tolerance to isolated test subjects,[7,8] the survivability data are confounded by increased vulnerability to the lethal impact of cabin projectiles.[9,10] There is a paucity of reports that indicate that rearward facing seats confer increased survivability; however, the M1-Kegworth disaster in 1989 investigation reports[9,11,12] were supportive. Further evaluation of the safety of rearward facing seats is required.[10,13]

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Abstract

- Most aircraft seats face forward. It is generally believed rearward facing seats would not be accepted by passengers, (as they dislike travelling backwards) or airlines (because of increased costs and weight).
- It is unclear if rearward facing seats confer overall increased survivability. Although there is greater acceleration tolerance and fewer restraint injuries, there is greater exposure to missile injury from loose debris.
- Further evaluation of the safety of rearward facing seats is required.
- Widespread use of rearward facing seats is likely to require legislation, given passenger reluctance to travel backwards and airlines' aversion to the greater costs.

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Engineering differences between rearward and forward facing seats

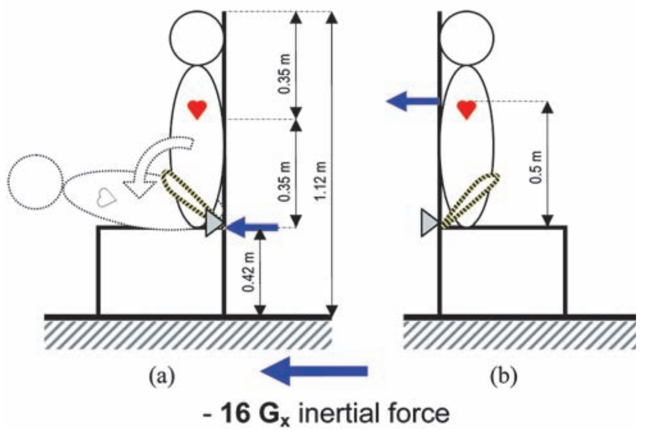
Most aircraft seats are designed to be forward facing. The current seating standards for new airline seats mandate that passenger seats meet improved survivability standards, whereby the seat remains structurally intact for impacts up to $16\,g$. The Federal Aviation Administration (USA) has not made retrofit of these new ($16\,g$) seats compulsory, and the balance of the older seats are designed to withstand $-9\,g_x$, $+5\,g_z$ and $\pm 3\,g_y$[8] (and before this $-6\,g_x$) impacts. The forward facing $16\,g$ seats are designed to withstand up to $-16\,g_x$ and $+16\,g_z$.[14] In addition to the structural integrity of the seat, the passenger restraint system (two-point lap belt) and the seat floor track attachment must also be rated to withstand the same g forces. It should be noted that the $-16\,g_x$ rating for this seat applies *only* when the seat is facing forwards. The same seat when rotated to face rearwards will *not* withstand the same acceleration.

An engineering analysis of forward and rearward facing seats

To illustrate the markedly different force vectors and turning moments directed through an aircraft seat, the following example compares the crash dynamic forces for a $-16\,g_x$ acceleration applied to a standard passenger seat facing forwards or backwards (Box 1).

In the case of the rearward facing seat, there is an enormous increase in the turning moment exerted upon the seatback

1 Comparison of the force vectors sustained at the engineering limit for a standard seat



The $-16\,g_x$ vector force is an inertial force exerted on the passenger and the seat during an accident. For simplicity, the $+g_z$ force vector has been omitted in the crash scenario. The aircraft seat is exceptionally strong in the box section and is weakest at the junction of the seat back with the seat pan. This junction is a fulcrum point (shown as ▶). The vector force exerted on the seat is exerted at a distance from the fulcrum. The combination of a force vector acting at a distance from a fulcrum creates a turning moment: the product of force (F) times perpendicular distance (d), measured in $kg\,m\,s^{-2}\,m$ or N m.

Assumptions are:

- mass of passenger = 70 kg
- mass of torso, upper limbs and head = 50 kg
- mass of lower limbs = 20 kg
- centre of torso mass is at heart level
- seat dimensions as per diagram[15]
- seat back mass = 2 kg.[15]

(a) The forward facing passenger is held by a two-point restraint. The torso mass rotates forward into the horizontal, effectively transferring the inertial force of the torso through to the seat via the restraint. The restraint attachment is at the junction of the seat pan and seat back. As this force is exerted at the fulcrum, there is no turning moment exerted by the torso. The turning moment exerted around the fulcrum is due to the accelerating back rest mass:

Moment = F d (as F = m·a)
= m·a·d
= $2\,kg \times 16 \times 9.8\,m\,s^{-2} \times 0.35\,m$
= 109.8 N m

(b) The rearward facing passenger remains sitting vertically. The accelerating passenger mass exerts a force vector about 0.5 m above the fulcrum (the centre of mass for a human torso is near the level of the heart). In this case the turning moment exerted around the fulcrum is:

Moment = m·a·d
= $50\,kg \times 16 \times 9.8\,m\,s^{-2} \times 0.5\,m$ (*plus* the turning moment exerted by the seat 109.8 N m)
= 3920 N m + 109.8 N m
= 4029.8 N m

The Apollo command re-entry module — a historic, high speed, rearward facing seat

during a crash deceleration sequence (an increase of 36.7 times). Clearly, the seat back in a rearward facing seat will need to be engineered to a much higher rating. The rearward facing seat thus presents a significant problem relating to engineering, weight and cost. The requirement for increased strength of rearward facing seats has been documented in studies by the US Navy.[16]

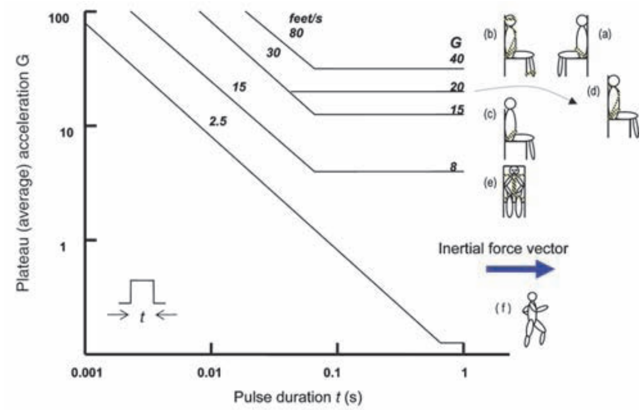
Restraints and rearward facing seats

Applying Newton's first law of motion to an aircraft passenger, we can say that an occupant of an aircraft seat will tend to remain in uniform motion (or remain at rest) unless acted upon by an external force. Application of a $-g_x$ acceleration force to an occupant of a forward facing aircraft seat will result in them being "flung" forward into the restraint harness. The tolerance to this type of acceleration depends on the type of harness being used.[7] Passengers are usually provided with a two-point harness, which allows the torso to rotate forward. The resulting impact is between the head and seat back of the adjacent seat, or the torso and the passenger's femurs. There is a high risk of severe head injury and femoral fracture with this restraint system.[12,17] This should be compared with a rearward facing seat, where the high $-g_x$ acceleration force is applied over the entire back of the passenger. There will initially be only minor forces applied to the passenger from the restraint with a significantly decreased incidence of restraint injury. The restraint will hold the passenger in place and prevent them being flung aft-wards during rebound. The acceleration force during rebound is significantly less in magnitude.

Head rests and rearward facing seats

Rearward facing seats must have high backrests to prevent cervical spine hyperextension during a $-g_x$ acceleration. The current seat back height, at about 0.7 m,[15] is too low for a large

2 Tolerance to whole-body impacts for horizontally acting force vectors



The seat direction and restraint system is indicated by the adjacent figures. The sloping lines represent tolerable velocity change (feet/s) for brief impacts and the horizontal lines represent tolerable *g* for longer duration accelerations. Acceleration and time are both plotted logarithmically. It can be seen that a rearward facing seat with a simple two-point restraint (a) is equivalent to a forward facing seat with head, torso, lap and leg restraints (b). Whereas a rearward facing seat permits tolerance of 40 g, a forward facing seat (c) with the same two-point harness permits 15 *g*. A forward facing seat with torso and lap restraint (d) permits 20 *g*. A sideways seated occupant (e) and a standing occupant (f) are included for comparison. Adapted from *Ernsting's aviation medicine,* 4th edition,[7] Figure 10.4.

proportion of the adult population and would need to be higher.[6] The 95th (2 SD) percentile for sitting height is 0.925 m for females and 0.994 m for males (US figures).[18]

Human tolerance to short duration acceleration

Human tolerance to short duration acceleration depends on multiple factors,[7] including:

- magnitude of acceleration,
- rate of onset,
- direction of force vector, and
- site of force vector application.

During an aircraft crash, the aircraft experiences an opposing force of (very) short duration, usually between 0.1 and 0.5 seconds.[7] The effects of short duration acceleration depend on the velocity change induced in the body and the structural strength of the body part upon which they act.

Acceleration tolerance (or dynamic response) in an individual depends on different factors, and they are effected at different phases of the acceleration pulse duration.[7] In simplistic terms, the response depends on:

- the velocity change (or "jolt") between 0.001 and 0.25–0.3 seconds,
- the acceleration pulse length between 0.25–0.3 and 3–10 seconds, and
- the peak acceleration duration from 3–10 seconds onwards.

The overlap between the three phases reflects differing dynamic responses between individuals and differing results obtained from one observation set to the next. The tolerance to whole-body impacts has been measured and these different phases are seen in Box 2 and Box 3.

An occupant sitting in a rearward facing seat will not experience the high-magnitude, dynamic overshoot deceleration from whiplash of the torso and head. They will initially decelerate at a lower rate than the fixed aircraft seat (assuming the seat remains attached to the floor) and then at a slightly higher rate than the seat — as the effect of dynamic overshoot in the cushioned seat back remains. Further slowing of the rate of onset of acceleration will occur from deformation of the very thin aluminium sheet pan riveted into the seat back — a process of energy attenuation. Thus, a rearward facing seat will help avoid the peak jolt from torso dynamic overshoot. In addition, a rearward facing seat will allow the $-g_x$ acceleration force to

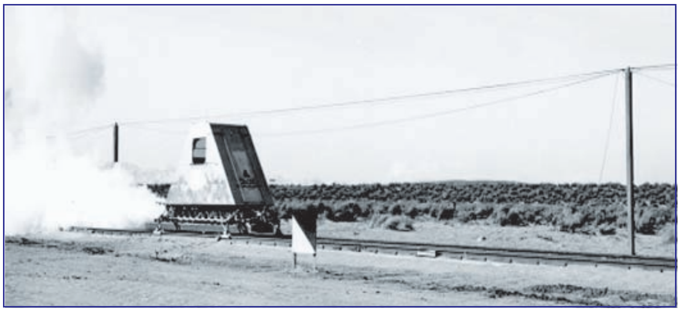
3 Jolt tolerance and intermediate duration *g* tolerance in human subjects in rearward and forward facing seats

Seat direction	Jolt tolerance (velocity change dependent) (feet/s)	Intermediate duration tolerance (pulse length dependent) (*g*)
Rearward facing seat (with head rest)	80	40
Forward facing seat (head, 4-point torso and leg restraint)	80	40
Forward facing seat (4-point torso restraint)	30	20
Forward facing seat (2-point restraint: lap belt)	30	15
Sideways facing seat (4-point torso restraint)	15	8

Various restraint devices were used. Sideways tolerances are included for comparison. Data sourced from *Ernsting's aviation medicine,* 4th edition,[7] Figure 10.4.

be spread over the entire back, hips and head of the passenger, rather than concentrating the force across the pelvis via the lap restraint. The stress induced on the human body is thus significantly less (as stress is proportional to the force applied and inversely proportional to the area of application; ie, stress = force/area).

In summary, tolerance to whole body acceleration is better in a rearward facing seat (with the exception of a forward facing seat incorporating head, four-point torso and leg restraints — this seating attitude affords the same acceleration tolerances as a simple rearward facing seat with lap belt).



Acceleration survivability studies using the G-Whiz sled 1947 — Captain P Stapp.

Factors that modify human tolerance

Seat stroking

Seat stroking is the means by which jolt-onset acceleration forces are decreased, permitting greater tolerance to injury. Forward and rearward facing seats have no significant differences in stroking performance during $+g_z$ acceleration. During $-g_x$ acceleration, the forward facing seat affords no stroking protection from the backrest (excluding rebound phenomena) and inadequate stroke protection in high g accidents when the torso rotates onto the femurs — usually resulting in bilateral femoral fractures caused by bending injury. The bending injury occurs at the fulcrum point of the front seat spar.[12]

Rearward facing seats slow the *rate* of acceleration onset, and hence decrease jolt. This is performed by the seat back closed-cell foam compression, and deformation of the aluminium seat back infill.

Seat collapse, especially collapse of the seat back, is much more likely to occur in a rearward facing seat because of the very high turning moment exerted on it by the passenger. The seat back needs to be exceptionally robust to withstand this force.

4 Advantages and disadvantages of rearward facing seats

Advantages	Disadvantages
■ Increased crash survivability	■ Increased seat weight
■ Only require simple restraints	■ Increased unit cost
■ 80 feet/s jolt tolerance	■ Increased air ticket costs
■ 40 *g* tolerance	■ Disliked by passengers
■ Fewer restraint injuries	■ Somatogravic illusion
	■ Pitch aft on take-off
	■ Possible increased motion sickness
	■ Increased risk of missile injury

Tolerance to short duration acceleration

Comparison of $+g_x$ and $-g_x$

Most short and intermediate duration acceleration studies conducted on humans have occurred with $-g_x$ and $+g_z$ forces applied to the upright-seated and forward facing individual.[19] The physiological responses to $-g_x$ as opposed to $+g_x$ forces are little known; however, with the major vascular structures lying posteriorly and adjacent to the vertebral column, it would be hypothesised that a human could better withstand a $-g_x$ acceleration if they were in a rearward facing seat.

Occupants of forward facing seats can withstand large forces applied in the $+g_x$ axis as there is a larger supported area (the torso). Force vectors in the $-g_x$ axis are also well tolerated *provided* there is full restraint. In aircraft accidents, there are very large $-g_x$ forces. By using rearward facing seats, these forces can be spread over a large area.

Comparison of $\pm g_x$ to $\pm g_z$

Acceleration in the $\pm g_z$ axis places high stresses on the suspended organs, and is less well tolerated than $\pm g_x$ forces.[7] Occupants of rearward (and frontward) facing seats that are fully reclined for sleeping are particularly at risk for shear injuries to organs and vascular structures during a large $-g_x$ acceleration, *provided* their restraints hold them in situ. It is more likely the occupant will slide under the restraints and sustain severe axial load injuries. Rearward facing sleeper beds are enjoying a return to service in new aircraft.

Comparison of $\pm g_x$ to $\pm g_y$

Human tolerance to $\pm g_y$ accelerations is poor. A hypothesised explanation for this is that the human skeletal frame is much more strongly supported by flexor and extensor muscles than by lateral flexors. The human spine would be the best example of this. Accelerations in the $\pm g_x$ axis are much better tolerated.[7]

Individual differences

There are marked individual differences in acceleration tolerance.[7] Whereas one individual may suffer significant injury, another may remain relatively unaffected. There is a paucity of acceleration studies on women.

M1-Kegworth accident 1989

The Kegworth accident generated many scientific papers and reports.[9-12,17] Among these there are comments supporting increased survivability being conferred by rearward facing seats (occupied by crew),[9,11,12] as well as comments recommending changes to the standard crash brace position.

Crash positions

The standard crash position for a forward facing seat is to place the torso onto the thighs and hold the shins, or to place the head onto your folded arms on the back of the seat forward. The crash position for the rearward facing seat is entirely different; the individual remains sitting upright placing their arms by their sides. The occupant adopting the upright brace position is significantly more exposed to airborne missiles within the cabin and more likely to suffer head injuries from collapsing overhead lockers.

Secondary injuries

Flail injuries

The occupant of a rearward facing seat is much less likely to suffer a flail injury of the torso and head — because of the support of the seat behind them. Flail injuries of the arms will still occur. Leg flail can be prevented by having a leg support that prevents hyperflexion of the knee. An example of this is seen on the Boeing 747 rearward facing crew seats. The rearward facing seat with this feature is only regularly encountered on modern aircraft crew stations.

Cervical spine flexion and extension injuries

Hyperextension injuries of the cervical spine will be seen with rearward facing seats *unless* an appropriately high backrest is present. Hyperflexion injuries to the cervical spine occur with forward facing seats.

Restraint injuries

Restraint injuries are much less frequently encountered with rearward facing seats. They are more prominent if there is an element of $\pm g_y$ acceleration. Forward facing seats are most commonly provided with a two-point harness. The force of the accelerating body mass is held by the restraint, leading to high stress forces across the pelvis. Although the pelvis is relatively strong, this concentration of stress can lead to pelvic fracture and disarticulation. In addition, large pressure forces are exerted on the intra-abdominal organs, causing burst injuries to the spleen and liver, as well as perforations of hollow organs and vascular injury. The forward facing seat with basic lap belt is also associated with a high incidence of lumbar vertebral fractures, femoral fractures and major head injury.

Injuries from aircraft structures and loose debris

Rearward facing seats significantly expose the occupant to secondary injuries from the missile effect of loose cabin objects, as well as head and chest injuries from loosened overhead lockers. It is usual for most overhead locker bins to tear free in an aircraft accident.[9,10]

Rearward facing seats and motion sickness

Rearward facing seats are reported as increasing susceptibility to motion sickness; however, there are no studies that validate this assertion.[4]

Rearward facing seats and illusions

On take-off (and to a lesser extent on landing) there is a false sensation of body tilt whereby a non-vertical gravitoinertial force is perceived as vertical.[13,20] This is known as a somatogravic illusion. During horizontal acceleration for take-off, the rearward facing passenger will perceive they are being pitched aft-wards. At rotation, this perception is compounded by the real vertical acceleration. The illusion is ameliorated by maintaining visual cues (ie, by looking out the window). The somatogravic illusion may be accompanied by the oculogravic illusion.

Rearward facing seats: passenger attitudes

There is a general perception that passengers have an aversion to rearward facing seats in aircraft. Some authors have asserted that passengers do not like being (relatively) pitch-down at take-off.[4] In darkness or with the absence of visual cues from the external environment, this aversion may be compounded by the somatogravic illusion.

Conclusion

Despite the evidence that rearward facing seats confer increased crash survivability, they remain little used in general aviation. The advantages and disadvantages of rearward facing seats are summarised in Box 4. Rearward facing seats have significantly different engineering requirements. Concomitant with this will be increased weight and costs. In addition, most passengers are reluctant to "face backwards" when being transported.

Any decision to implement widespread use of rearward facing seats would most likely require legislation on behalf of civil aviation authorities worldwide. Unless this occurs, the current status quo will remain.

Competing interests

None identified.

Disclaimer

The views, opinions, and findings in this report are those of the author and should not be construed as an official policy of the Royal Australian Air Force or the Australian Defence Force.

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Malaria update

Malaria in the ADF

Between 1 January 2007 and 30 June 2007, there have been two new cases of malaria reported to the Central Malaria Registry. Both are from members deployed to the Solomon Islands, and were diagnosed after returning to Australia.

These have been the first cases from the Solomon Islands for more than 2 years. The total number of malaria cases from the Solomon Islands now stands at 14.

This is a timely reminder that the risk of malaria remains quite high in the Solomons, and all members and their commanders should do their utmost to ensure that all levels of preventive care are taken. This includes use of personal protective measures, compliance with prophylactic medication while on deployment and, very importantly, completion of eradication medication on return home.

Malaria reporting

All Health Service personnel are encouraged to notify the Central Malaria Registry promptly when a malaria casualty is detected. Informal notifications preceding a PM40 can be made by telephone (07) 3332 4836 or by email Nathan.Elmes@defence.gov.au

Total malaria infections in ADF personnel in various deployments

Papua New Guinea, January 2006 – June 2007	
Diagnosed in Papua New Guinea	0
Diagnosed on return to Australia	4
Total	**4**
Sudan, January 2006 – June 2007	
Diagnosed in Sudan	3
Diagnosed on return to Australia	0
Total	**3**
East Timor, September 1999 – June 2007	
Diagnosed in East Timor	82
Diagnosed on return to Australia	389
Total	**471**
Solomon Islands, July 2003 – June 2007	
Diagnosed in Solomon Islands	0
Diagnosed on return to Australia	14
Total	**14**