Institution: King's College London		
Unit of Assessment: 24 Sport and Exercise Sciences, Leisure and Tourism		
Title of case study: Enhancing defence capabilities: An Aircrew Conditioning Programme to improve fast-jet pilot performance		
Period when the underpinning research was undertaken: 2014 - 2019		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof Stephen Harridge	Director, Centre for Human & Applied Physiological Sciences	From 2005
Dr Ross Pollock	Lecturer in Aerospace Physiology	From 2018
Prof Di Newham	Professor of Physiotherapy	1989 – 2014
Period when the claimed impact occurred: 2017 - 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Fast-jet pilots can experience incredible acceleration (G) forces, posing risks of career-impacting and life-affecting neck injury, or even death, due to aircraft crash owing to G-induced loss of consciousness (G-LOC). King's College London researchers, in close partnership with the Royal Air Force (RAF) Centre of Aviation Medicine, have designed and developed a new Aircrew Conditioning Programme (ACP) to reduce fatigue, improve G-tolerance and reduce neck injury. The ACP is now mandated as part of the RAF Aircrew Training Pathway, has been taken up by other branches of the UK military and by other international air forces, and has been key in shaping recommendations of the NATO Research Task Group on Aircrew Neck Pain.

2. Underpinning research

Prevalence & Risk of G-Induced Loss of Consciousness

Fast-jet pilots routinely experience extremely high G-forces, particularly in the head to feet direction (+G*z*). This physically demanding environment can result in fatigue, neck injury and, even more concerning, loss of consciousness (G-LOC). G-LOC usually manifests as a period of complete motor and cognitive impairment followed by relative incapacitation, which can cause a significant occupational hazard to aircrew. It has resulted in catastrophic consequences, including aircrew death and loss of aircraft.

In the early 2000s a survey was conducted by the RAF to identify the extent of G-LOC in 2259 UK military aircrew, the results of which led to the UK Ministry of Defence (MOD) mandating human centrifuge training for all fast-jet aircrew to optimise their anti-G straining manoeuvre (AGSM) and improve their protection against +Gz. To identify whether the introduction of centrifuge training reduced the incidence of G-LOC, along with views on current practices to prevent G-LOC, researchers at King's College London's Centre for Human & Applied Physiological Sciences, in partnership with the RAF Centre of Aviation Medicine (RAF CAM), conducted a new anonymous survey of all RAF aircrew [1]. Research identified that 15% of respondents had experienced G-LOC and that it was particularly prevalent during the initial phases of flight training. In addition, ~70% had experienced neck injury at some point during their career.

In parallel, the research team also identified the cardiovascular challenges experienced by aircrew during repeated G*z* exposures [2] and showed that current RAF anti-G systems did not fully protect aircrew against the highest levels of G [3]. This, taken with the high incidence of G-LOC being reported by aircrew, despite the introduction of mandatory centrifuge training, emphasised the

need to develop further interventions targeted at reducing the risks of G-LOC associated with exposure to high G forces in fast-jet pilots.

Development of Interventions: The Aircrew Conditioning Programme

With the introduction of technically more advanced aircraft such as the Eurofighter Typhoon and F35B-Lightning, aircrew can be exposed to high and sustained levels of G*z*, and thus the threat of long-term injury and G-LOC remains significant. Aircrew themselves have also recognised that the performance of the AGSM can become very fatiguing, thereby lowering its effectiveness over time, and possibly reducing overall flying performance. These considerations, along with the research conducted in partnership with the RAF CAM, led to the recommendation that a structured physical conditioning programme be designed to increase the general strength of muscle groups involved in the AGSM.

To address this, we designed an innovative and novel Aircrew Conditioning Programme (ACP) to target the specific needs of aircrew [4]. It was well known that appropriate physical conditioning can reduce or delay the development of fatigue, improve the strength of the muscles supporting the head and neck, and would thus help reduce the risk of neck injury resulting from acceleration exposure. However, the potential effect of any conditioning programme on G-tolerance was less clear, with it being previously suggested that it could either improve, or indeed worsen, G-tolerance depending on the type of exercises performed. Therefore, the ACP went through a rigorous validation phase where its content was assessed by six international aviation medicine experts to ensure that: i) it was highly relevant to aircrew and ii) would be unlikely to adversely impact aircrew performance/G-tolerance [4]. This led to the ACP being a structured and progressive exercise programme that targets improvements in strength, aerobic fitness and flexibility as well as the stability/motor control of the neck and upper torso [4]. Having aircrew complete the ACP would improve their ability to repeatedly perform an effective AGSM and reduce strain injuries to the neck, thus helping enhance overall aircrew performance.

Testing the ACP

While the theoretical underpinning of the ACP had been validated, its practical application still required investigating. A 12-week controlled trial was therefore conducted to evaluate the effect of the ACP on different aspects of G-tolerance in 36 serving RAF and Royal Navy (RN) aircrew [5]. The participants in the study underwent testing on a human-rated centrifuge before and after 12 weeks of either the new ACP or continuing their routine military training. A series of centrifuge assessments were conducted to determine whether the physiological response to acceleration exposure was altered, as well as the effects on relaxed G-tolerance. This study revealed that the ACP could reduce the physiological strain associated with the AGSM, indicating a positive impact on G-tolerance, and that it could delay the onset of fatigue development. Importantly, it also demonstrated that the ACP did not detrimentally affect G-tolerance. This study thus demonstrated that the ACP could be an effective means of enhancing G-tolerance and reduce the risk of G-LOC in the fast-jet pilot community. The improvements it has made to the strength of the muscles supporting the head and neck will also be beneficial in reducing the incidence of neck pain in aircrew. This is the first structured ACP to have been developed specifically targeted at optimising the performance of fast-jet pilots and has subsequently become a world-leading example, influencing practice globally.

3. References to the research

[1] Slungaard E, McLeod J, Green NDC, Kiran A, **Newham DJ, Harridge SDR** (2017) Incidence of G-Induced Loss of Consciousness and Almost Loss of Consciousness in the Royal Air Force. *Aerospace Medicine and Human Performance*. 88(6):550-555. DOI:10.3357/AMHP.4752.2017

[2] Stevenson AT, Scott JPR, Chiesa S, Sin D, Coates G, Bagshaw M, **Harridge SDR** (2014) Blood pressure, vascular resistance, and +Gz tolerance, during repeated +Gz exposures. *Aviation Space and Environmental Medicine* 85: 536-442. DOI: 10.3357/ASEM.3816.2014

[3] **Pollock RD**, Firth RV, Storey JA, Phillips KE, Connolly DM, Green NDC, Stevenson AT (2019) Hemodynamic Responses and G Protection Afforded by Three Different Anti-G

Systems. *Aerospace Medicine and Human Performance* 90 (11): 925–933. DOI:10.3357/AMHP.4927.2019

[4] Slungaard E, Green NDC, **Newham DJ, Harridge SDR** (2018) Content Validity of Level Two of the Royal Air Force Aircrew Conditioning Programme. *Aerospace Medicine and Human Performance*. 89(10):896-904. DOI:10.3357/AMHP.4994.2018

[5] Slungaard E, **Pollock RD**, Stevenson AT, Green NDC, **Newham DJ, Harridge SDR** (2019) The impact of an Aircrew Conditioning Programme on +Gz tolerance. *Aerospace Medicine and Human Performance*. 90(9):764-773 DOI: 10.3357/AMHP.5318.2019

4. Details of the impact

The *"research conducted as a partnership between the Centre of Human & Applied Physiological Sciences at King's College London and the Royal Air Force Centre of Aviation Medicine has had direct, significant and lasting impact on military aircrew worldwide"* [A].

Prior to this research and despite the acknowledgement that G protection is an important component of fast-jet pilot safety, it needed a significant and tragic event to give the issue more prominence. This was, sadly, provided by the Bournemouth Red Arrows crash of XX-179 in 2011, when one of the RAF's most experienced high-G pilots from their world-renowned display team was overcome by the effects of G and fatally crashed his aircraft. The subsequent Service Inquiry highlighted concerns around the physical state of the pilot at the time of the incident and how this might have contributed to his susceptibility to G. The fatal crash occurred at the end of a flight and one concern raised was whether physical fatigue may have played a contributing part. At the time, there was conflicting information in the scientific literature around whether physical conditioning may enhance, or worsen, an individual's G-tolerance. Therefore, there was uncertainty about whether someone should undertake physical training and, if so, what type of training they should undertake to address this concern. The Service Inquiry also raised numerous questions around the cultural and organisational approach to the effects of G and precipitated a root-and-branch change to how it was considered and prioritised. Our research in response to this has *"changed UK Defence aviation medicine policy, such that the ACP is now a mandated component of the aircrew training pipeline"* [A].

Tackling G-LOC and reducing neck injury in the RAF – creating a new training programme
To begin to tackle these problems, King's researchers were called upon by the RAF to facilitate a repeat of the G-LOC survey outlined above [1]. This second survey demonstrated important new information to the RAF, showing that G-LOC was occurring in pilots during elementary flying training (EFT) (i.e. before they are selected for fast-jet training) and, critically, before they receive any G training [B]. The G-LOC survey was, therefore, a key piece of evidence in convincing the RAF that another layer of G training needed to be introduced early in EFT to address this previously unrecognised risk. The G-LOC survey also served as an important piece of evidence in the justification for significant investment (~£44 million) in a new human-carrying centrifuge [C] which was opened at RAF Cranwell in 2018. The RAF Centre of Aviation Medicine (RAF CAM) have said that *"the weight of evidence supported both a new national capability for high G training and a requirement for a bespoke and evidence-based physical conditioning programme"* [A].

In addition, the research programme around the Aircrew Conditioning Programme (ACP) [1,4,5] was not only formulated to address research gaps, but to address the issue of the significant morbidity associated with musculoskeletal injury in fast-jet aircrew populations, and in particular neck injury. As such, an important part of the ACP is to provide a conditioning programme that incorporated targeted approaches to tackling musculoskeletal injury. RAF CAM report that the ACP *"delivered immediate gain through the management of fatigue when under G"* [A].

As described above one of the main findings of our research was the high incidence of G-LOC in aircrew during the very early phases of flight training. The relevance of this finding and its implications have gained greater prominence due to the introduction of a new higher performance EFT aircraft. During EFT, pilots previously would fly the Grob Tutor. However, during the period of our research, the RAF transitioned to using the Grob Prefect as their primary training aircraft. The Grob Prefect can sustain significantly higher levels of G and does not include an anti-G protection system. The RAF recognised that there was now going to be an even greater risk of G-

LOC with the use of this new aircraft during EFT, magnifying the findings of our G-LOC survey and reinforcing the importance of the introduction of centrifuge training for EFT pilots.

Prior to the research described above, a structured conditioning programme did not exist for any aircrew within the RAF. Despite increasing awareness of aircrew around the importance of physical conditioning in preventing G-LOC, as evidenced in the G-LOC survey [1], participation in regular physical conditioning by aircrew remained low, which the ACP and our research helped to address.

With its strong empirical underpinning and validity, the ACP was introduced as policy by the RAF in 2017 as an integral component of aircrew training (~40 trainee fast-jet aircrew per year) [A]. This is helping to transform the training and awareness associated with the issues surrounding high G forces for fast-jet pilots [A].

All aircrew at each stage of their training now have to meet minimum standards to progress to the next stage of flight training, with centrifuge training and the AGSM being a key component for fast-jet pilots [B,D]. After the ACP became mandatory for fast-jet pilots *"the feedback was rapid and positive: the programme was so welcomed by fast-jet aircrew that it was now extended to crews of other manned platforms"* [A]. This is supported by reports of fast-jet aircrew having an improved ability to cope with air combat manoeuvring and less neck pain during training due to their participation in the ACP [D]. The physical benefit it has also impacts protective clothing, with anecdotal reports that many aircrew are now having to have their anti-G trousers re-fitted due to the increases in muscle mass as a result of the ACP. Indeed, some are having to have specially tailored trousers as they no longer fit within the 1970s-based anthropometric size role of the skeletal anti-G trousers used in some aircraft.

The Aircrew Conditioning Programme in action – changing national practice

The effectiveness of the ACP for musculoskeletal injury prevention has also been more widely recognised and is now delivered not only to fast-jet pilots, but all aircrew within flying training, regardless of aircraft type. There are currently ~2500 aircrew in the UK military across all aircraft types who will now benefit from ACP throughout their careers.

Since the adoption of the ACP as standard practice by the RAF, other services have also identified the importance of rolling out this kind of training. The ACP has been further developed for different aircrew populations. For example, it has been modified for helicopter aircrew to address different activities that occur in rotary wing, compared to fast-jet, aircrew. This has resulted in the ACP being adopted by the UK Joint Helicopter Command for all Army rotary wing assets and all Royal Navy aviators [A]. In addition, helicopter aircrew have reported less fatigue and pain associated with flying while wearing night-vision goggles, due to the ACP [D]. The ACP is also of particular relevance to the Royal Navy and the success of their new F35B Lightning fast-jet aircraft (costing ~GBP138,000,000 each) now in service on the UK's two new aircraft carriers - HMS Queen Elizabeth and HMS Prince of Wales.

The ACP has thus become a UK tri-service (RAF, Army and Royal Navy) conditioning programme. This has, in part, been with the aim of reducing the operational and financial burdens on the Ministry of Defence associated with the high prevalence of musculoskeletal injuries in aircrew, while also reducing the serious risk of G-LOC in fast-jet aircrew, and *"has a vital role in supporting sovereign capability"* [A]. In growing recognition of the ongoing problems with neck pain in aircrew, the NATO HFM-252 Research Task Group on Aircrew Neck Pain was set up in 2014. This was with a remit to identify solutions, develop a report and produce recommendations to reduce aircrew neck pain [E] with its findings disseminated internationally [F]. The ACP was presented to this working group and *"is one of the top solutions recommended"* [H] as a strategy that should be employed to reduce the risk of neck pain in aircrew [E,F].

Having been designed and tested by physiotherapists and physiologists, the ACP is now delivered through the Physical Education branches of the RAF, Royal Navy and Army and by those who have undergone training in the delivery of the ACP and completed the ACP Instructors Course Competence [D]. This represents a significant investment of resource, especially from the RAF in training physical instructors to deliver the programme, and in terms of aircrew physical training time to undertake the programme. For aircrew, this is both in training and on frontline operational squadrons where they now have protected time in their working week dedicated to following the

ACP. This sends important, visible messages about the importance and prioritisation of G and prevention of musculoskeletal injuries in the Military.

In addition to aircrew, the ACP has wider impact in that it is promoted to all RAF personnel through The RAF Total Safety Magazine: AirClues [G]. This has allowed the entirety of the RAF and any civilians who subscribe to the magazine (rather than just the aircrew going through training) to gain an understanding of the importance of the ACP and why it is an essential part of aircrew training and serves to reinforce the needed cultural change.

The Aircrew Conditioning Programme Beyond the UK

In part due to the ACP contributions to the NATO working group and the development of their report, the ACP now has global reach where *"its success and value was further evidenced by adoption by other international Armed Forces"* [A]. The Naval Air Warfare Center Aircraft Division of the US Navy have stated that the ACP *"remains the most validated and data-supported physical conditioning program which has demonstrated effectiveness in military aviators"* [H]. After gaining permission from the RAF, the Finnish Air Force, Belgian Armed Forces and Royal Norwegian Air Force have now also begun using the ACP as a standard training programme for their aircrew. Furthermore, the Royal Canadian Air Force [I] and the US Navy [H] are currently evaluating and tailoring the ACP to become standard practice for their aircrew. The Canadian Air Division have said: *"the research has influenced the majority of aircrew conditioning programs in existence around the world today and will continue to be the standard to which all other programs are held going forward"* [I]. Whilst the *"successful implementation of the ACP within the RAF and its roll out to the Royal Navy and Army and the associated publications have proved invaluable in the justification to progress with an ACP pilot study conducted in US Naval aviation and were crucial in garnering senior leader support"* [H]. This greatly increases the potential impact of this work by orders of magnitude; the US Navy alone, for example, has almost 10 times the number of fast-jets (1030 in 2017) compared with the RAF (119 in 2019). As noted by the Canadian Air Division *"the significance of this work to the scientific and operational communities around the world cannot be understated"* [I].

With high-performance training aircraft (such as the Prefect or Hawk T2) and technically more advanced frontline fast-jets (such as the Typhoon, or the more recently introduced F35B-Lightning), aircrew will continue to be exposed to even higher and sustained levels of Gz. Thus, the threat of long-term injury and G-LOC will remain high to the end of Service life of those aircraft, which is currently in the 2040-50 timeframe. In addition, the UK Team Tempest project is currently addressing plans for a 6th Generation high-G fast-jet to enter service in 2035-2040. As such, *"this maintains an essential and enduring requirement for the results of this research over many decades to come"* [A].

5. Sources to corroborate the impact

[A] Testimonial letter from the Royal Air Force Centre of Aviation Medicine.

[B] Military Aviation Authority Flying (Fly) 2000 Series Regulatory Articles – Issue 20.

[C] Thales Group (2019) A UK Technology First: High G Training and Test Facility [press release]

[D] Royal Air Force (2015) AP3456 The Central Flying School Manual of Flying, Volume 6 – Aviation Medicine

[E] NATO (2020) Aircrew Neck Pain Prevention and Management. *Science and Technology Organisation Technical Report*. TR-HFM-252

[F] Slungaard E, Day S, Goff C (2019b). UK implementation of recommendations from NATO NFM-252 Research task group report on aircrew neck pain. Aerospace Medicine and Human Performance 90(3):163

[G] Royal Air Force Safety Centre (2018). Aircrew Conditioning Programme. AirClues Issue 27

[H] Testimonial letter from the Department of the US Navy, Naval Air Warfare Center Aircraft Division

[I] Testimonial letter from the Canadian Air Division.