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Tuomas Honkanen

Fighter Pilots' Physical Performance and Spinal-injury Induced Flight Duty Limitations

UNIVERSITY OF JYVÄSKYLÄ

FACULTY OF SPORT AND
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ABSTRACT

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This thesis investigates the effects of physical fitness, muscle cross-sectional area (CSA) and Gz exposure and their interaction in fighter pilots' spinal disorders and resulting flight duty limitations (FDL). The primary aim of the study was to evaluate the predictive role of physical and functional fitness tests and muscle CSA in overall low back pain (LBP) and FDL. Other aims were to investigate associations between cumulative Gz exposure and FDL and to study the effects of the gradual increase of exposure on exposure-induced muscular activity responses. Four different study settings were used. Association between functional tests and LBP was studied in a five-year follow-up. Shoulder and neck muscle activity was compared, via electromyography (EMG), between groups of experienced and inexperienced pilots under high Gz exposure. Association between early-career Gz exposure and physical fitness in the pilot selection phase was studied retrospectively among FDL-pilots and non-FDL pilots. Associations between CSA of the lumbar muscles and spinal disorders were studied in a five-year follow-up. The results showed an association between an isometric back endurance test and physical activity-related LBP. Pull-up and back extension test results obtained in the selection phase were associated with spinal disorder-induced FDL during fighter pilots' career, but similar association between aerobic fitness and FDL was not observed. Pilots who had experience in flying high-performance aircraft (HPA) had significantly lower shoulder and neck muscle EMG activity at high Gz levels and higher passive G-tolerance than pilots who had no experience in HPA flying. Cumulative Gz exposure during the early career was not associated with subsequent spinal disorder-induced FDL. No association was found between muscle composition or CSA and LBP. Thus, causes and development of spinal disorder -induced FDL seem to be multifactorial. In conclusion, the results show that an adequate level of axial strength and endurance may protect military pilots from spinal disorders. Pilots who had indicated in the selection phase that they do not participate in competitive and guided sports programs may be under an increased risk of spinal disorder-induced FDL. In addition, less experienced pilots may find similar missions more fatiguing than their more experienced colleagues. However, Gz exposure at an individual level does not have a predictive value on future FDL.

Keywords: neck pain, low back pain, flight duty limitation, physical fitness, high-performance aircraft, G-force

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Tämän väitöskirjatutkimuksen tarkoituksena on selvittää ennustaako sotilaslentäjien fyysinen suorituskyky tai kiihtyvyysvoimille altistuminen tuki- ja liikuntaelimistön oireilua ja lentopalveluksen rajoituksia. Lisäksi tutkimuksessa selvitetään yksilöllistä kuormittumista kiihtyvyyden lisääntyessä sentrifugissa sekä selän lihasten poikkipinta-alojen yhteyttä vartalon ja alaraajojen isometriseen voimantuottoon ja oireiluun. Tutkimuksen aineisto muodostui neljästä tutkimusjoukosta, joista ensimmäisen muodostavat kokeneet aktiivilentäjät, toisen kahden eri kadettikurssin lentäjät, kolmannen pysyvän lentokelpoisuuden rajoituksen saaneet lentäjät sekä heidän verrokit, ja neljännen kahden peräkkäisen kadettikurssin lentäjät. Fyysisen suorituskyvyn osalta tutkimuksessa selvitettiin: lentäjävalinnan aikainen lihaskunto ja aerobinen kestävyys, vuositarkastuksessa mitattu fyysinen toimintakyky ja vartalon ja alaraajojen isometrinen voima kadettivaiheessa. Kiihtyvyysvoimille altistumista analysoitiin lentäjäkohtaisella kiihtyvyysvoimakertymällä. Liikunta-aktiivisuutta ja oireilua mitattiin kyselyillä ja lentokelpoisuusrajoitteella. Niska-hartiaseudun lihasten aktiivisuutta mitattiin elektromyografialla sentrifugissa ja lihasten poikkipinta-ala mitattiin magneettikuvista. Tutkimuksen tulokset osoittivat, että alhaisella selän isometrisellä voimalla on yhteys vapaa-ajan liikunnassa koettuihin alaselkävaivoihin, ja huonolla lihaskunnolla lentäjävalinnan aikana on yhteys lentokelpoisuuden rajoittamiseen. Lisäksi havaittiin, että rajoituksen saaneilla lentäjillä oli harvemmin kilpaurheilutausta. Tulosten mukaan hävittäjälentäjät raportoivat alaselkäkivuista potkurikalustolla lentäviä enemmän, mutta toisaalta suurella kiihtyvyysvoimakertymällä ei ole yhteyttä rajoituksiin. Lisäksi havaittiin, että kokeneiden lentäjien lihasaktivaatio on alhaisempaa lennon aikana, ja että he aloittavat vastaponnistuksen myöhemmin verrattuna kokemattomiin. Lannerankalihasten poikkipinta-aloilla ei ollut yhteyttä oireiluun, mutta ne olivat yhteydessä isometristen voimatestitulosten kanssa. Tämän tutkimuksen tulokset viittaavat siihen, että hyvä lihaskunto ja aktiivinen urheilutausta suojaavat myöhemmältä uranaikaiselta tukirangan oireperäiseltä lentokelpoisuusrajoitukselta, ja selän lihasvoima suojaa alaselkävaivoilta. Näiden tulosten valossa sotilaslentäjävalinnassa tulisi jatkossa huomioida lihaskunnon ja urheilutaustan merkitys, minkä lisäksi lentäjien tulisi panostaa uran aikana lihaskuntoharjoitteluun.

Avainsanat: niskakipu, alaselkäkipu, lentokelpoisuusrajoite, fyysinen suorituskyky, hyvittäjälentäjä, G-voima

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LIST OF ORIGINAL PUBLICATIONS

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II. Honkanen T, Oksa J, Mäntysaari MJ, Kyröläinen H, Avela J (2017). Neck and Shoulder Muscle Activation Among Experienced and Inexperienced Pilots in +Gz Exposure. *Aerospace Medicine and Human Performance* 88: 90–95.

III. Honkanen T, Sovelius R, Mäntysaari M, Kyröläinen H, Avela J, Leino T (2018). +Gz Exposure and Spinal Injury-Induced Flight Duty Limitations. *Aerospace Medicine and Human Performance* 89: 552–556.

IV. Honkanen T, Mäntysaari M, Avela J, Kyröläinen H, Leino T (2018). Assessment of Muscular Fitness as a Predictor of Flight Duty Limitation. *Military Medicine* 183: e693-e698.

V. Honkanen T, Mäntysaari M, Leino T, Avela J, Kerttula L, Haapamäki V, Kyröläinen H (2019). Cross-sectional area of the paraspinal muscles and its association with muscle strength among fighter pilots: A 5-year follow-up. *BMC Musculoskeletal Disorders* 2019 20:170.

ABBREVIATIONS

AeMC	Aeromedical Centre
AFA	Air Force Academy
AFCOMFIN	Air Force Command Finland
AGSM	Anti-G straining maneuver
AIMWTS	Aeromedical Information Management Waiver Tracking System
ANOVA	Analysis of variance
BAF	Belgian Air Force
BMI	Body mass index
CES	Cervical erector spinae
CNPD	Concept of a Neck Protective Device
CROM	Cervical range of movement
CSA	Cross-sectional area
EMG	Electromyography
FDL	Flight duty limitation
FI	Fatigue index
FINAF	Finnish Air Force
FMS	Functional movement screen
FWC	Fixed wing carrier
G-LOC	G-induced loss of consciousness
GO	Gradual onset
Gx	Frontal direction of inertial force
Gy	Lateral direction of inertial force
Gz	Vertical direction of inertial force
HANS	Head and Neck Support
HG	Healthy group
HMD	Helmet-mounted device
HMV	High-mobility vehicle
HPA	High-performance aircraft
HQ	Headquarters
HR	Heart rate
HSG	High sustained G
IAF	Israeli Air Force
ICC	Intraclass correlation coefficient
JASDF	Japan Air Self-Defense Force
JHMCS	Joint Helmet-Mounted Cueing System
LBP	Low back pain
LSG	Low sustained G
MRI	Magnetic resonance imaging
MSFT	Multistage fitness test
MVC	Maximal voluntary contraction
NDI	Neck disability index
NHPA	Non-high-performance aircraft

NPG	Neck pain group
NVG	Night vision goggles
PAF	Polish Air Force
PBG	Positive pressure breathing for G-protection
PGT	Passive G-tolerance
PFA	Pre-entry assessment
RAAF	Royal Australian Air Force
RAF	Royal Air Force
RCAF	Royal Canadian Air Force
RDAF	Royal Danish Air Force
RNLAF	Royal Netherlands Air Force
RNoAF	Royal Norwegian Air Force
ROM	Range of movement
SACM	Simulated air combat maneuvering
SCM	Sternocleidomastoid
SENIAM	Surface Electromyography for the Non-Invasive Assessment of Muscles
SWEAF	Swedish Air Force
TRA	Trapezius
USAF	United States Air Force
USN	United States Navy
VAS	Visual analogue scale
VO_2max	Maximal oxygen uptake
WHO	World Health Organization

CONTENTS

1 INTRODUCTION

Fighter pilots' physical loading and flight-induced spinal disorders have been an aeromedical issue since the introduction of modern highly maneuverable aircraft. Exposure to high +Gz (headward acceleration resulting in a downward force) in high-performance aircraft (HPA) has been associated with an increased risk of spinal disorders. Physical loading of fighter pilots has been studied extensively during half a century, and studies of flight-induced musculoskeletal disorders extend back over a time span that is nearly as long. There is a wealth of literature on spinal disorders among fighter pilots in particular, and the reported prevalence of flight-induced symptoms is as high as 89% (Kikukawa et al. 1995). A comparison with this prevalence rate with rates found among the general population suggests that fighter pilots suffer from these symptoms more than their counterparts who are not exposed to high-performance flying.

The introduction of the Hawk jet trainer into Finnish Air Force (FINAF) service in the early 1980s aroused discussion of G-related disorders and the pilots' physical performance. During the same time period, the FINAF commander set up the first working group to study physical performance in collaboration with the University of Jyväskylä. The group looked at the training habits of fighter pilots and fielded several physical training methods. A manual titled *Physical Exercise Guide for Air Force Aircrew* was issued by FINAF in the late 1990s (Rintala 2012). During the same decade, a scientific work by Hämäläinen et al. (1992, 1993a,b,c, 1994a,b, 1996, 1998 and 1999) was published. It included epidemiological surveys, clinical measurements, and documentation on flight-induced disorders. The foregoing studies also examined muscular strain under high Gz exposure and premature disc degeneration among FINAF fighter pilots. In the late 1990s, Oksa et al. (1999) suggested that muscular strength, in particular in the neck and shoulder, is subjected to high demands. In the new millennium, the work has been carried on by Rintala in his study on military pilots' physical performance and occupational spinal disorders and Sovelius's study on the cervical loading analysis of fighter pilots (Rintala 2012 and Sovelius 2014).

Although a lot of work has been done in order to understand the etiology of spinal disorders and spinal loading under Gz exposure, there is no clear evidence of protective mechanisms and risk factors. Physical fitness has been seen as an important contributor to successful performance under high Gz exposure due to the exhaustive nature of the anti-G straining maneuver (AGSM). It has also been suggested that unfit pilots may have an increased risk of flight-induced disorders, and that – while the fundamental problem is related to load-carrying capability – stronger muscles may give more support. However, there is little evidence of the causality of stronger muscles or the superiority of a specific training method as protection against disorders. Few randomized controlled trials on training methods have been conducted. There is a particular lack of studies that would determine the predictive factors of flight-induced spinal disorders. Neither is there evidence of whether certain anthropometric factors or a physical performance level may increase or decrease the risk of flight-induced disorders. Furthermore, previous studies have reported G-exposure by flight experience (years or hours) or by aircraft types flown (HPA vs. other fixed-wing aircraft), even though pilots who fly the same fighter aircraft type may become under totally different +Gz exposure due to different mission profiles and flight syllabi, and association between the actual cumulative G-exposure and musculoskeletal disorders is therefore not clear. Previous studies have typically used pain indicators and measurements that were mostly based on questionnaires and pain indexes, and only few reports have used objective (i.e., medical flight disqualification) data.

Spinal disorders among military pilots are common. They may lead to temporary (Knudson et al. 1988) or permanent (McCrary & Van Syoc 2002) flight disqualification and thereby affect a pilot's career and result in the loss of predicted working years. Early career limitations and, in the worst-case scenario, permanent flight disqualification affect squadrons' human resources and operational capability. Fully trained fighter pilots transferred to desk jobs or to flying non-high-performance aircraft (NHPA) are a huge loss for a nation, both economically and operationally. It is therefore important to reveal the risks, causes, and predictive factors of flight-induced disorders by all available means. The main aim of this dissertation was to determine any association between fighter pilots' physical performance levels – measured in the application phase or over the subsequent career – and flight-induced spinal disorders.

2 REVIEW OF LITERATURE

2.1 Acceleration physiology

2.1.1 Magnitude and direction of acceleration forces

Modern fighters can fly at very high speeds and they are highly maneuverable. Maneuvering generates acceleration-inducing forces that are higher than Earth's gravity. These forces have an equal and opposite reactive force called inertial force. The physiological effects of acceleration are caused by an inertial reaction on the pilot's body. The unit of this reaction is expressed in aerospace medicine with the letter G, and the resultant exposure is known as G-force. G is the unit that expresses the ratio of an applied acceleration to the gravitational constant (Gell 1961).

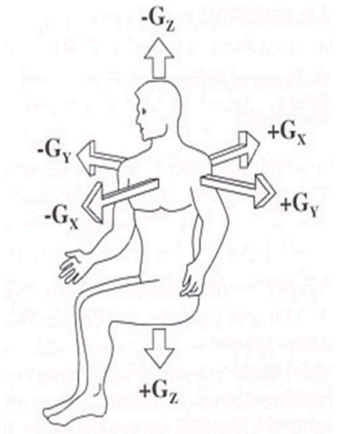

FIGURE 1 Directions of inertial forces (Sovelius 2014).

G-forces are classified according to the directions in which the inertial forces act (Figure 1). These directions are described using a three-axis coordinate system (Gell 1961). The vertical (z) axis is parallel to the long axis of the body, the frontal (x) axis is oriented from front to back, and the lateral (y) axis is oriented from side to side. Accelerations can be further categorized as positive and negative G-forces (Gell 1961). Positive (headward) acceleration along the z axis (+Gz) is a major physiological concern in military aviation. Negative (footward) acceleration along the z axis (-Gz) may occur occasionally during outside loops and spins. It produces unpleasant symptoms at low – even as low as -2 Gz – levels. Higher -Gz levels are uncommon in military aviation. No significant lateral (Gy) or transverse (Gx) accelerations occur during normal military flying.

Acceleration forces are also classified as short-duration (<0.5 s), intermediate-duration (0.5–2.0 s), and long-duration (>2 s) forces (Green 2016). Long-duration forces are usually encountered during maneuvering. For approximately 20% of the time during an air combat, a pilot is exposed to above +2 Gz while the peak levels can range from +7 to +9 Gz (Newman & Callister 1999). An F/A-18 pilot may be exposed to above +5 Gz for over a minute during an engagement, and peak forces (from +7 to +9 Gz) may be sustained from 5 to 10 s during maneuvering (Green 2016) (Figure 2).

Current high-performance fighters operate at +9 Gz maximum. The average maximum Gz in air combat is +8.2 Gz in the F-15 and +8.4 Gz in the F-16. Exposures as high as +12 Gz have reportedly been measured in a centrifuge (Burns et al. 2001).

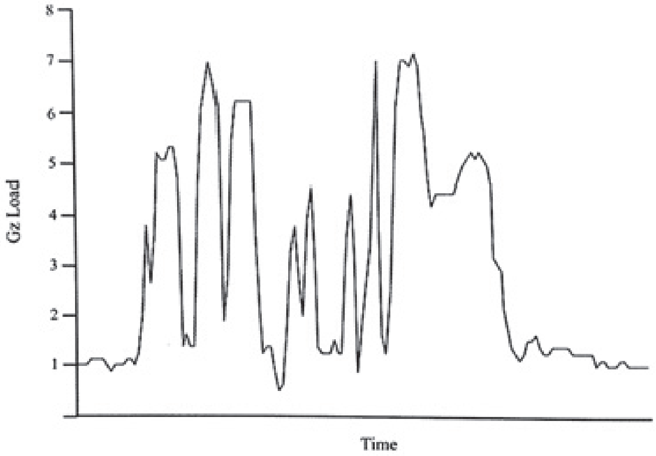

FIGURE 2 G-exposure in 1 vs 1 air combat in Royal Australian Air Force F/A-18 (Newman 2015).

2.1.2 Physiological effects of +Gz acceleration

Exposure to high +Gz has been associated with effects on the cardiovascular system. These effects have a profound impact on pulmonary functions, vision, and the level of consciousness (Cochran et al. 1954). The most hazardous form of visual impairment is G-induced loss of consciousness (G-LOC), which occurs when blood flow in the brain reduces critically due to increased acceleration

(Burton 1988). These physiological effects have widely been discussed in aeromedical literature (Green 2016). +Gz exposure also affects the musculoskeletal system. It is known that frequent exposure to high +Gz causes static muscle stress on the trunk and the extremities (Cornwall and Krock 1992) and repetitive exposures to high +Gz lead to muscle fatigue (Oksa et al. 1999). It has therefore been suggested that the accumulation of +Gz exposure increases the risk of musculoskeletal disorders, particularly in the cervical and lumbar spine (Kikukawa et al. 1995).

It has been measured that excessive +Gz loading during 40 min of air combat maneuvering reduces a pilot's total body height by 5 mm (Hämäläinen et al. 1996). A similar reduction would be caused if a person were standing while bearing a static shoulder load of 10 kg for 20 min (Hämäläinen et al. 1996). This indicates that the spinal column in general, and the intervertebral discs in particular, are under a high stress during air combat. +Gz exposure also leads to fatigue (Oksa et al. 1999), and it has been reported that muscular strain as measured by electromyography (EMG) increases in line with increasing G-forces (Hämäläinen & Vanharanta 1992, Oksa et al. 1996, Netto & Burnett 2006a). Magnetic resonance imaging (MRI) studies have shown that fighter pilots may have earlier degenerative changes than their counterparts, particularly in the cervical spine (Hämäläinen et al. 1993c, Petren-Malmin and Linder 2001). Exposure to high +Gz combined with a high Gz onset rate has been associated with musculoskeletal injuries, in particular in the neck and back (Kikukawa et al. 1995). It has been reported that one year of intense Gz loading has an osteogenic effect on bone, and these effects have been site-specific. Effects on bone mineral density have been found in the cervical and thoracic spine, while there were no significant changes in the lumbar spine or limbs (Nauman et al. 2001 and 2004).

Burton et al. (1987) examined fatigue after Gz exposure in a centrifuge at three levels designated low sustained G (LSG), high sustained G (HSG), and simulated air combat maneuvering (SACM). The mean maximum heart rate (HR) was 141 (±7) bpm at LSG, 171 (±4) at HSG, and 154 (±9) bpm during SACM. The mean maximum HR of 159 bpm was reported by Balldin et al. (2003) during simulated high-G sorties in a centrifuge. Burton (1980) measured HR, oxygen saturation, expired gases, lactate, pyruvate, glucose and creatine kinase, and isoenzymes of subjects who were exposed to five repeated simulated air combat maneuvers (all including 6, 8, and 10 Gz peaks of 10 s duration). High acceleration exposure affected all measured physiologic-metabolic parameters significantly. For example, lactate levels increased more than six-fold from 4.9 (±1.4) mg% to 33.0 (±7.6) mg% after the first SACM run; after the second run they increased to 38.6 (±8.2) mg%, and to 43 (±6.9) mg% after the third. After the fourth and fifth run, they remained the same. Changes in pyruvate and glucose were similar to lactate level responses. HR changes were also significantly affected. Although all metabolic parameters were affected, only HR changes appeared to correlate with developing subjective fatigue. The mean pre-SACM HRs before each run were: 72 (±2), 87 (±8), 93 (±7), 97 (±8), and 98 (±7) bpm. The mean maximum HRs during each SACM run were 153 (±5), 160 (±7), 161 (±6), 163 (±6), and 165 (±6) bpm. Post-SACM (after 30 s of rest) HRs increased from 109 (±14) to 126 (±10) between the first and the last SACM run, and from 104 (±11) to 111 (±8) after a rest of 150 s. Bain et al. (1997) conducted EMG measurements on the respiratory muscles. They discovered that respiratory muscle fatigue coincides with the termination of SACM in a centrifuge. An examination of fighter pilots' HR in a simulator showed that the mean rest HR increased from 75 to 95 bpm in groups performing sub- or low-performance level instrument approaches (Mansikka et al. 2016). However, the aim of the study was to determine mental rather than physical workload and it was performed in a simulator that did not emulate G-forces.

2.1.3 Fitness demands of high-G environment

Physical fitness is a vital component in performing military tasks such as HPA flying. It seems that, even though modern aircraft are increasingly complex technically, physical requirements for a military pilot remain as stringent as ever (Thoolen & van der Oord 2015). According to Baldin (1984), the sufficient level of muscular strength and endurance is important in view of potential physical demands during high Gz exposure and AGSM. Tesch et al. (1983) observed a G-tolerance increase of about 39 % in pilots subjected to 11 weeks of a moderately intense strength training program. The mean G-tolerance (in seconds) increased from 245 (±110) to 338 (±129) by the completion of the program. Fighter pilots are therefore commonly recommended to do strength training. This recommendation is based on a need to condition them for AGSM, G-LOC prevention, and G-tolerance (Epperson et al. 1982, Tesch et al. 1983), and in particular for G-tolerance by means of G-endurance (G-duration tolerance, i.e., the duration an individual can tolerate sustained high and variable G-loads) (Burton and Whinnery 1985). It has also been reported that repeated air combat maneuvering exercises result in the fatigue of the muscles of the upper body and neck (Oksa et al. 1999). Oksa et al. (1999) compared the results of muscle strength measurements carried out before flight and after three repeated sorties involving high +G exposure during 1 vs 1 air combat. They found that that the maximal muscle strength of the neck muscles had decreased (8-10%) between the first and last measurement. During the encounters, the mean muscular strain increased significantly only in the neck muscles (Oksa et al. 1999).

Little has been published on the physical performance level (i.e., fitness test results) of fighter pilots. Comprehensive cross-sectional studies conducted in the United States Air Force (USAF) have investigated the aerobic capacity test results (Giovannetti et al. 2012) and physical activity level (Tvaryanas et al. 2018) of active-duty USAF members, but these studies included all service personnel, not only fighter pilots. The aerobic capacity of USAF members has been measured either with a submaximal cycle ergometer test (Williford et al. 1994, Giovannetti et al. 2012) or with the "Fit to Fight" program's 1.5 mile run (Giovannetti et al. 2012).

The performance level of fighter pilots has been looked at in four studies. Tomczak et al. (2016) reported the muscular fitness level and aerobic capacity of

120 Polish Air Force (PAF) fighter pilots, while Rintala et al. (2015) reported the muscular fitness level and aerobic capacity of 195 FINAF fixed-wing aircraft pilots. Both studies reported the results of obligatory annual aerobic capacity and muscular fitness tests. The Polish study presented the results of a fitness test battery that included seven tests (zigzag run, 10 x 10 m run, pull-ups, push-ups, sit-ups, standing long jump, and 50 m swim) and of an aerobic capacity test (submaximal bicycle ergometer test). Rintala et al. (2015) investigated physical fitness level measured by four obligatory muscular strength tests (push-ups, sit-ups, squats, and hand grip) and one aerobic capacity test (maximal indirect bicycle ergometer test). Both the aerobic capacity and physical fitness of the PAF pilots were considered medium-level. When their aerobic capacity was compared to that of special forces members, their levels were found significantly lower (Tomczak et al. 2016). The physical fitness of the FINAF pilots was considered good in average but only satisfactory when compared to athlete-level performance required in "combat-flying-like" sports (Rintala et al. 2015).

The mean maximal oxygen uptake (VO_2max) was 33.7 (±5.6) mL/kg/min among the PAF pilots (Tomczak et al. 2016) and 52.1 (±5.1) mL/kg/min among the FINAF pilots (Rintala et al. 2015). The mean VO_2max of male USAF members was 35.8 (±7.1) mL/kg/min when obtained from the submaximal ergometer test and 41.9 (±5.8) mL/kg/min when obtained from the 1.5-mile run. The mean maximal aerobic capacity of Royal Australian Air Force (RAAF) pilots has also been determined. Their mean VO_2max was 50 (±6) mL, but it should be noted that since only eight subjects took part in the study (Newman et al. 1999), reliable conclusions of the physical fitness of RAAF pilots could not be drawn.

2.2 Cervical and lumbar loading of fighter pilot

2.2.1 Occurrence of flight-related spinal disorders

Flight-related spinal disorders are commonly classified as cervical, lumbar, and thoracic pain. However, there are studies that report (Kikukawa et al. 1995) all spinal disorders together. The lifetime prevalence rate of reported overall spinal (including cervical, thoracic, and lumbar) disorders among fighter pilots has been found to range from 89% (Kikukawa et al. 1995) to 93% (Rintala et al. 2015). When the quantity of acute musculoskeletal pain episodes was investigated (Kikukawa et al. 1995), it was found that nearly one third of fighter pilots (of the average age of 33 years) had had more than 10 episodes of musculoskeletal pain during their career, and the mean recovery time from a single episode had been eight days. Some studies classify disorders as multiple region disorders when pilots have reported pain in different regions (Grossman et al. 2012). According to Grossman et al. (2012), fighter pilots (25%) reported more pain in multiple regions than transport pilots (9%).

Low back pain (LBP) is exceptionally common among the adult working population (Deyo & Weinstein 2001, Ehrlich 2003), and fighter pilots are no exception (Kikukawa et al. 1995). Rintala et al. (2015) reported the LBP prevalence rate of 45% among FINAF fighter pilots. Prevalence rates among Israeli Air Force (IAF) (Grossman et al. 2012) and PAF (Truszczynska 2014) fighter pilots were between 64 and 60%, respectively. Transport aircraft pilots have reported lower and rotary-wing pilots higher prevalence of spinal disorders when compared to fighter pilots (Grossman et al. 2012).

The prevalence of cervical pain among fighter pilots (Jones et al. 2000, Lange et al 2011) is high compared to the general population (Fejer et al. 2006). It has been reported that fighter pilots have a higher prevalence of flight-related neck injuries than the pilots of other fixed-wing aircraft (Grossman et al. 2012). Furthermore, the primary aircraft type has been reported to be an independent predictor for clinically significant neck pain (Lawson et al. 2014). Higher aircraft performance (G-capability) has been associated with increased neck injury prevalence (Vanderbeek 1988, Knudson et al. 1988). Cervical pain prevalence among fighter pilots has been studied more widely than LBP prevalence. Its symptoms vary depending on the aircraft type, the age of the pilot, and the survey period (Shiri 2015).

Rintala et al. (2015) reported that flight-induced neck pain prevalence among FINAF fighter pilots was 61% over the preceding six-month period, whereas Newman (1997a) found that this prevalence among RAAF F/A-18 pilots was 85% over the lifetime. However, Newman (1997a) reported that half of the respondents had experienced neck pain only rarely. Newman's (1997a) study revealed that, despite high lifetime prevalence, only 12 % of the respondents had reported neck pain during high-G flight (i.e., air combat) and only 4% had reported neck pain on every flight. The prevalence of flight-induced neck pain among RAAF F/A-18 pilots is comparable to prevalence among United States Navy (USN) F/A-18 aviators (Knudson et al. 1988). The reported lifetime prevalence among the latter was 74% according to Knudson et al. (1988) and 86% according to Jones et al. (2000).

The prevalence of any neck injury among USAF F-16, F-15, and F-5 pilots was 64% during the past year, 51% during the past three months, and 30% during the past month (Vanderbeek 1988). The prevalence of major neck injuries was 11, 9, and 4% (Vanderbeek 1988). However, neck pain prevalence rate among F-16 pilots varies widely. For example, the one-year prevalence of self-reported neck pain among Belgian Air Force (BAF) and Royal Netherlands Air Force (RNLAF) pilots is 18.9% (De Loose et al. 2008). A study conducted among IAF pilots flying mostly equivalent aircraft (F-16, F-15, and A-4) reported lower lifetime prevalence of neck pain (47%) than among USAF pilots (Grossman et al. 2012 and Jones et al. 2000).

Neck pain is more common during training than in operational flying (Vanderbeek 1988). Occupying the rear seat (flight instructor's position) of a two-seat jet trainer has also been found to be linked with the higher severity of neck pain (Kang et al. 2011). When all neck disorders among BAF and RNLAF F-16 pilots were divided into non-flight-related and flight-related neck pain, it was found that 77% of the pilots who had experienced neck pain indicated that their complaints started when flying fighters (De Loose et al. 2008). Among these pilots, 46% of the complaints were about direct inflight pain and 54% of the complaints had started (between 10 min and 3 h) after a flight (De Loose et al. 2008).

2.2.2 Severity and intensity of spinal disorders

The severity of flight-related pain has commonly been studied with pain scales based on respondents' subjective assessment. In these scales, 0 represents no pain and 10 the most severe pain (Grossman et al. 2012, Knudson et al. 1988, Lange et al. 2013, Newman 1997a). A visual analogue scale (VAS) from 0 to 100 mm has also been used to measure the degree of spinal disorder -induced disability among fighter pilots (Rintala et al. 2015). Some studies (Grossman et al. 2012, Newman 1997a) have classified flight-related pain into four categories: none (0), mild (1–3), moderate (4–7), and severe (8–10). Acute flight-induced neck injuries have commonly been divided into major and minor injuries (Vanderbeek 1988). Minor neck injuries have been found to be more common than major injuries (Vanderbeek 1988).

Knudson et al. (1988) used a 0–10 pain scale to investigate the severity of pain among USN aviators. F/A-18 (which had the highest G-capability among the aircraft used in the study) aviators showed the highest rate (6.4), whereas A-7 (5.2) and A-4 (5.5) aviators showed a lower rate. When the researchers (Knudson et al 1988) asked whether the pain had interfered with the current or a subsequent mission, they found that 50% of the reported neck pain had had an impact on aviator performance, and the impact had been more profound in aircraft with a higher G-capability. In Finland, VAS has been used to measure the degree of spinal disorder -induced disability (Rintala et al. 2015). The median VAS-measured degree of experienced disability due to on-duty musculoskeletal pain among all FINAF fixed-wing aircraft pilots was 12 mm. However, one third of the subjects had suffered from major disability (VAS > 30 mm).

Among IAF fighter pilots currently experiencing spinal pain, the most common categories were mild or moderate pain, both in the form of LBP and cervical pain. According to Newman (1997a), mild to moderate pain (3–6 out of 10) was by far the most common result of flight-related neck injury among RAAF fighter pilots.

The frequency of flight-induced pain has been determined by asking pilots how many pain episodes (Kikukawa et al. 1995) they had had or how often, i.e., on how many days during the follow-up period they had felt the pain bothersome (Lang et al. 2013). Kikukawa et al. (1995) found that pilots had experienced on average 7.6 episodes of acute muscle pain, and 30% of the pilots had experienced more than 10 episodes during their career.

2.2.3 Classification of spinal disorders

G-related disorders are often divided into acute and chronic flight-related neck pain. It has been suggested that the most common causes of acute injuries are ligamentous injury or muscle strain. Disc protrusions and annular tears in the intervertebral discs due to intense high-performance flying have also been observed (Hämäläinen 1994b). It has been reported that inflight neck injuries lead not only to acute soft tissue injuries but also to fractures (compression fractures and the fracture of the spinous process) in the cervical spine (Schall 1989). Acute inflight neck traumas (fractures and soft tissue injuries) occur in particular in the lower part of the cervical spine (C4-7) or in the associated discs (Hämäläinen 1993c, Schall 1989, Andersen 1988). A typical acute muscle or ligament injury is the result of an unexpected high-Gz maneuver initiated by another crew member (i.e., student pilot).

Hermes et al. (2010) searched the Aeromedical Information Management Waiver Tracking System (AIMWTS) database for spinal disorders among military pilots and found that intervertebral disc disorders are the most common spinal disorders. The database produced a total of 103 cervical and 249 lumbar cases, of which 15 were diagnosed as both cervical and lumbar disorders. Most common disorder groups were spondylosis and allied disorders, other (unspecific) disorders (of the cervical region and the back), and intervertebral disc disorders. Of these disorders, 226 were classified as lumbar and 87 as cervical intervertebral disc disorders being the most common disorder groups.

2.2.4 Radiological findings

Chronic flight-related pain is usually associated with the degeneration of the spine, particularly of the cervical spine (Petren-Malmin and Linder 2001, Hämäläinen et al 1993c). The rate of spondylolysis (Hendriksen and Holewin 1999) and spinal stenosis (Hämäläinen et al. 1999) in the cervical spine is reported to be high among fighter pilots. The studies of Petren-Malmin and Linder (1999) and Hämäläinen (1993c) suggested that there is increased prevalence of degenerative changes among high-performance aircraft pilots when their MRI is compared with their age-matched controls. However, a recent meta-analysis (Shiri et al. 2015) showed no differences in the prevalence of cervical or lumbar radiological disc degeneration between fighter pilots and the pilots of non-ejection seat aircraft (transport category airplanes and helicopters) or non-flying personnel. The meta-analysis consisted of seven studies in which fighter pilots were compared to the pilots of non-ejection seat aircraft and four studies in which fighter pilots were compared to non-flying personnel to determine the prevalence of cervical disc degeneration. Four studies in which fighter pilots were compared to the pilots of non-ejection seat aircraft and two studies in which fighter pilots were compared to non-flying personnel were included in the meta-analyses to determine the prevalence of lumbar disc degeneration (Shiri et al. 2015).

2.2.5 Disqualification due to spinal disorders

Pilots may be permanently or temporarily disqualified for several medical reasons. Musculoskeletal disorders are the third most common reason for permanent medical flight disqualification among USAF pilots and navigators after cardiovascular and neurological disorders (McCrary & Van Syoc 2002). In the Royal Canadian Air Force (RCAF), 17% of the groundings were found to be due to orthopedic disorders, mainly LBP (Van Leusden et al. 1991). The study of McCrary & Van Syoc (2002) revealed a total of 157 permanent disqualifications among USAF pilots and navigators in 1995–1999. This represented a 0.18% disqualification rate per year in the service that had 17,194 rated aircrew members in 2001 (McCrary & Van Syoc 2002). The most common diagnostic categories in the group of musculoskeletal disorders were chronic (neck or back) pain or discus-related (herniated nucleus pulposus) problems. The number of medical disqualification cases due to musculoskeletal disorders was found to increase progressively with age (McCrary & Van Syoc 2002).

Kikukawa et al. (1995) and Newman (1997a) have reported the number of non-permanent disqualifications, i.e., temporary grounding, but there is no study on temporary grounding among the total population of rated aircrew members. Kikukawa (1995) found that only 16 pilots of 115, who had suffered from flight-related spinal disorders, had been temporarily taken off flying duties as a result of disorders. Newman (1997a) reported that 17% of RAAF F/A-18 pilots, who had reported neck injury, had been subject to restrictions in flying duties. The average duration of restriction had been two weeks, but the time of temporary restriction had ranged from three days to three months. Of 37 USN pilots who had reported neck injury, 11 had been temporarily restricted from flying for an average period of three days (Knudson et al. 1988).

2.3 Factors contributing to spinal loading

2.3.1 Gz exposure determined by flight hours and aircraft

Flight hours have been used as a determinant of +Gz exposure. Several studies report that inflight neck pain is without doubt associated with flight hours in high-performance aircraft (Tucker et al. 2012, Kang et al. 2011, and Hämäläinen et al. 1994a). However, no clear association has been found between LBP and flight hours among fighter pilots (Shiri et al. 2015). The largest cross-sectional study available used a USAF medical and personnel database of nearly 20,000 service pilots to calculate the odds for cervical and lumbar disorders (Hermes et al. 2010). A conclusion was that the risk produced by exposure (determined by flight hours) may be overshadowed by age. Yet flight hours displayed statistically significant positive association with LBP and cervical pain among fighter pilots in the univariate analysis, but after an adjustment for birth year in a stratified multivariate analysis, associations were no longer statistically significant.

Comparison between aircraft types has also been used as a determinant of +Gz exposure. Fighter pilots have been compared to the pilots of other non-high performance fixed-wing aircraft or helicopters to study the effects of +Gz exposure (Shiri et al. 2015). The results have indicated that LBP is more common among helicopter pilots, whereas neck pain is more common among fighter pilots (Grossman et al. 2012). The G-capability of aircraft has also been used as a predictor of cervical pain. According to the meta-analysis of Shiri et al. (2015), neck pain was more common among F/A-18, F-16, and F-15 pilots than among their counterparts who flew less G-capable aircraft (including F-5, A-7, A-4, and F1). Jones et al. (2000) found similar results in their study where 78% of F/A-18, F-16, and F-15 pilots had experienced inflight or postflight pain. Low-G aircraft (C-26, KC-135, and Shuttle Training Aircraft) pilots had not reported pain episodes. Among intermediate-G aircraft (T-38) pilots, pain episodes were uncommon (27%).

A study involving FINAF fixed-wing aircraft pilots divided the subjects into three groups designated high-G group, low-G group, and headquarters (HQ) group, based on flight intensity. Statistically significant difference was found in the prevalence of musculoskeletal symptoms between the groups as 85% of the high-G group, 72% of the low-G group, and 49% of the HQ group had experienced symptoms over the past six months (Rintala et al. 2015).

Instead of reporting only the prevalence of pain, some studies have used NDI questionnaires to reveal the degree, severity, quality, and character of occupation-related neck pain. Lawson et al. (2014) used a neck disability index (NDI), where neck pain scores greater than 8.0 were considered clinically significant. They reported that the mean score of small (trainer category), large (transport category), and high-performance (fighter category) aircraft pilots was 5.0, 7.8, and 9.2, respectively. A statistically significant risk with the odds ratio of 3.91 was found when fighter pilots were compared to small aircraft pilots. However, an overall analysis, in which all aviators where compared to a non-aviator (control) group, revealed that pilot profession regardless of an aircraft type was predictive for higher NDI scores (Lawson et al. 2014).

2.3.2 High-risk head movements

The neck is vulnerable in air combat due to high +Gz loading and awkward head positions. Even though the cervical spine can support high external loads in the neutral position, it is vulnerable when subjected to high-risk movements. These movements are described in literature (Coackwell et al. 2004, Snidjers et al. 1991). They include extensions exceeding 30 degrees and rotations exceeding 35 degrees. Neck extension combined with rotation is common in air combat (Newman 1997a), and it is associated with high levels of muscle activation (Oksa et al. 1996). The "check six" procedure, which is used to observe other aircraft directly behind the own aircraft, requires maximal neck rotation combined with extension, often accompanied by lateral bending (Newman 1997a). It has been reported that the head is out of the neutral position for 68% of an air combat maneuvering sortie (Green & Brown 2004). Newman et al. (1997a) concluded that "check six was a causal factor in most neck injuries among RAAF F/A-18 pilots. Similarly, Knudson et al. (1988) found that it was the most common head position to cause pain among USN aviators, regardless of aircraft type (F/A-18, F-4, or A-7).

It has been suggested that load caused by neck movement and head position may have a greater influence on muscle activity than increased mass of a helmet (Thuresson 2003). This suggestion is, however, based on a study conducted among rotary-wing military pilots. Among fighter pilots, the most typical mission type being flown at the time of neck injuries is air combat involving repeated head movements. These missions have accounted for 82% of neck injuries (Knudson et al. (1988).

High-risk head movements affecting the cervical spine have been studied extensively, whereas high-risk movements affecting the thoracic / upper back or the lumbar / lower back region have been less reported. The most common reported high-risk movement affecting the upper back is “check six”; for the lower back, forward bent is the most common high-risk movement. However, Kikukawa et al. (1995) concluded that of all body parts, the neck sustains most of the injuries regardless of the posture, and it is the body part most prone to an injury during “check six” and forward bent.

2.3.3 Environmental factors

When environmental factors affecting a fighter pilot are discussed, cockpit ergonomics, flight gear (i.e., helmet), and ambient temperature must be taken into account. The size and layout of fighter cockpits are determined by performance requirements (speed, maneuverability, and low observability), and these are compromised by the requirement for pilots’ ability to have an unobstructed outside field of view. The ejection seat angle and sitting posture in particular may have an effect on high G-force loading on the spine (Truszczynska ska et al. 2014). Moreover, the efficiency of the helmet-mounted devices (HMD) of modern aircraft depends on an unobstructed field of view.

Truszczynska et al (2014) found a significant relationship between LBP and a sitting posture among fighter pilots. They also found out that 43% of the pilots complained that LBP was due to a bad posture. Since the LBP frequency among PAF F-16 pilots was lower than among Su-22 and MiG-29 pilots, it was suggested that one reason for flight-related back pain was the uncomfortable sitting posture offered by the K-36 seat of the latter aircraft types compared to the ACES II seat of the F-16. The seat of the F-16 has better lumbar support and it enables a more comfortable sitting posture. Evidence has also shown that correcting sitting position with an individually adjusted lumbar support may diminish strain in the lumbar and cervical muscles (Sovelius et al. 2008b). The benefits of the lumbar support are discussed later in this chapter.

Biomechanical calculations have shown that increasing helmet weight will increase load on the neck muscles and other neck (bone, joint, and cartilage) structures significantly during +Gz exposure (Lee et al. 1991). Hämäläinen’s (1993c) inflight study also indicated that helmet weight alone is an important contributing factor to muscle fatigue and it increases muscle activity by 15% during high +Gz exposure. Night vision goggles (NVG) increase the activity of the cervical muscles further during +Gz exposure when compared to muscle activity caused by non-NVG helmet weight. It has been reported that counterweights used by helicopter pilots while flying with NVG installed have the same effect (Thuresson et al. 2003).

Even though much effort has been put into developing lighter helmets to reduce cervical loading, it seems that the introduction of more advanced equipment (NVG and HMD) has led to the opposite effect. The implementation of modern HMD equipment has increased the mass of a helmet and shift of its center of gravity (Lange et al. 2011). These factors have an effect on neck torque, and they increase the workload of neck muscles (Newman 2002). Furthermore, in order to maximize the advantages of modern HMD, the system encourages the pilot to move his head during +Gz exposure (Lange et al. 2011), and HMDs therefore increase the time when the head is deflected from its anatomical neutral position (Lange et al 2011). According to Lee et al. (1991), this has a significant effect on head-neck torques and neck flexion angles, which might increase the risk of a neck injury.

Fighter pilots who operate at high latitudes are often exposed to low ambient temperatures. It has been reported that skin temperature decreases significantly during a walkout to the aircraft and during preflight checks when ambient temperature is -14 °C (Sovelius et al. 2007). There is association among the general population between cold exposure and musculoskeletal complaints during work in low temperatures (Jin et al. 2000, Pienimäki 2002). There is also evidence of repetitive work in a cold environment causing higher muscle strain (EMG activity) than in thermoneutral conditions (Oksa et al. 2002). Therefore, cold exposure is suggested to present a risk of occupation-related neck disorders among fighter pilots (Sovelius et al. 2007). It has been hypothesized that pilots who are frequently exposed to low ambient temperatures have higher risk for neck disorders. When upper back, neck, and shoulder muscle EMG activity during simulated +Gz exposure was compared in two different ambient temperatures (+21 and -2 °C), it was found that muscle loading in low temperature caused higher EMG activity (Sovelius et al. 2007). Major increase in muscle strain was seen in the cervical muscles in particular (Sovelius et al. 2007).

2.3.4 Anthropometric factors

All air services have specified anthropometry requirements due to the space constraints of fighter cockpits and the weight and dimension requirements imposed by ejection seats. Anthropometry requirements are checked during pilot selection. The FINAF pilot selection process includes the measurement of height, weight, sitting height, and thigh length. Each measure has a maximum limit and minimum limit based on the cockpit dimensions of the primary trainer, jet trainer, and fighter. The height and weight requirements have been (until 2017) 165–190 cm and 55–92 kg, respectively. The thigh length and sitting height requirements are 55–67 cm and 81–100 cm, respectively. These requirements vary between air services; for example, the height range for RAAF pilots is 172–195 cm and the average pilot height is 181 cm (Newman 1997a).

Little research has been published of the anthropometrics and body composition of fighter pilots. Most studies do not report descriptive background information such as mean weight, body mass index (BMI), height, or the other body dimensions. Truszczynska et al. (2014) reported that mean BMI of study subjects (94 active PAF fighter pilots) was 26.9, and their BMI ranged from 21.6 to 33.9. Tomczack et al. (2016) reported that 65% of the PAF fighter pilots were overweight and 15% were obese in accordance with the World Health Organization (WHO) classification. A study of FINAF pilots (n = 267) found that the mean BMI of fighter pilots was 24.0 and that of other fixed-wing aircraft pilots was 25.2 (Rintala et al. 2015). RAAF fighter pilots' average weight was 81 kg, but their average BMI was not reported (Newman 1997a).

The relationship among military pilots between LBP or neck pain on one hand and height and weight on the other is unclear. While taller individuals report LBP symptoms more often than their shorter counterparts among the general population (Hershkovich et al. 2013), although results concerning association between anthropometrics and spinal disorders among pilots are conflicting. While pilot height has been reported as a risk indicator for LBP among helicopter pilots (Orsello et al. 2013), there is no association between height and future or current LBP among fighter pilots. Neither has a relationship between neck pain and height been reported. Tucker et al. (2012), trying to identify different personal characteristics predicting neck pain, did not find association between height and neck pain. However, one study (Parr et al. 2013) found association between neck loading and sitting height among fighter pilots. These findings are conflicting; sitting height has significant effect on neck loading under high +Gz exposure (1.6 kg helmet at +8 Gz) but this effect is not significant at lower +Gz level (+6 Gz).

It has been reported that people with LBP or neck pain have significantly higher BMI than their symptomless counterparts (Hershkovich et al. 2013, Viikari-Juntura et al. 2001). It has also been reported that overweight and obesity increase the risk of LBP (Shiri et al. 2010a) among general population. This is in line with the results of the study of Truszczynska et al. (2014) that was conducted among fighter pilots. However, there are also conflicting results; for example, Rintala et al. (2015) were unable to draw the same conclusions. In addition to reported pain episodes, association has been found between high BMI and increased sickness absence among Finnish soldiers (Kyröläinen et al. 2008).

2.3.5 Relationship between desk job and spinal disorders

When the etiology of cervical or lumbar disorders among fighter pilots is discussed comprehensively other work-related factors must also be taken into account. Fighter pilots not only fly; their duties include desk jobs as well. It has been reported that among the general population the use of the keyboard over 4–6 h per day increases the risk of neck pain (Korhonen et al. 2003). The duration of RAAF aircrew's worst neck pain episode was predicted not only by flight hours but also by weekly desktop work hours (Tucker et al. 2012). The same study also concluded that desktop hours predict neck pain -induced flight duty limitations of short (<1 week) duration. De Loose et al. (2008) reported that work-related factors, such as physical and mental fatigue at the end of a working day, spending a prolonged time in a sitting position, and annoyance caused by others in the workplace contributed to neck pain among F-16 pilots. They therefore suggest that a flight may only be a trigger while other physical, psychosocial, and work-related factors could have contributed to the development or maintenance of neck pain (De Loose et al. 2008). However, Lis et al. (2007) report in a review that sitting itself (without co-exposure factors) does not increase the risk of LBP, but sitting for more than half a workday, combined with whole body vibration and/or awkward postures, increases the risk of LBP among general population.

2.3.6 Smoking and spinal disorders

Smoking has been associated with discus degeneration (Battie et al. 1991) and higher prevalence and incidence of LBP (Shiri et al. 2010b, Battie et al. 1989). There is also evidence that smoking may increase the risk of neck pain among working age population (Viikari-Juntura et al. 2001). Among military populations, it has been found out that smoking is associated with LBP and overall injury risk (Heir & Eide 1997, Taanila et al. 2012). It has been found that, among Norwegian infantry soldiers, smokers (of more than 10 cigarettes a day) and snuff-takers suffered more overall injuries (Heir & Eide 1997), and smoking has been associated with LBP (Taanila et al. 2012) among Finnish conscripts. There is no study that would show the same association between military pilots' spinal or any musculoskeletal issues and smoking or snuff-taking. Studies indicate a wide variation in the smoking habits of military pilots: 24% of USAF pilots smoked in 1989 (Oxford & Silberman 2008), whereas 61% of Spanish pilots reported smoking (Rios-Tejada et al. 1993). A study conducted among USN aviators revealed that 13% of responders used snuff, and it was suggested that the use of smokeless tobacco products is more common among military pilots than among general adult population in the United States (McClellan et al. 2010).

2.4 Methods of protection against flight-induced spinal disorders

2.4.1 Muscle strength training and stretching

As the fundamental problem of flight-induced neck injuries and LBP stems from loading, it has been logical to assume that increased muscle strength would give more support, particularly in the neck. USN F/A-18 aviators who participate consistently in strength training exercises for neck muscles report a lower number of cervical pain episodes than those who do not exercise (Jones et al. 2000). It has also been reported that frequent muscle endurance training is associated with the reduced likelihood of inflight spinal pain (Hämäläinen 1993b). A study conducted by Ang et al. (2005) using EMG measurements suggests that fighter pilots who have neck pain have lower extensor muscle strength and, consequently, strength training might prevent G-induced neck injuries. Various fitness training programs have been recommended for fighter pilots (Coakwell et al. 2004, Kikukawa et al. 1995, Seng et al. 2003). However, these studies have limitations due to small sample sizes and compliance, and they lack information on whether pain causes lower muscle strength or vice versa. Further studies are needed to prove the protective role of adequate muscle strength against flight-induced spinal disorders.

When active neck pain prevention strategies were studied among BAF and RNLAF F-16 pilots, preflight stretching was found to be the most common active strategy (De Loose et al. 2008). When pilots were assigned to a healthy group (HG) and neck pain group (NPG), it was found that 56.9% of HG and 76.5% of NPG performed preflight stretching. The second most common strategy was strength training and the third common was postflight stretching. Both were performed by less than 10% of HG and 18% of NPG.

Tucker et al (2012) listed 12 preventive actions that are in use among fighter pilots. These included active strategies such as preflight and postflight stretching, inflight Gz warm-up and strategies involving the use of the upper body and shoulder region in order to help move the head/neck and assist in the movement of the head/neck only in one plane. Other actions included restricting movement under Gz, moving only under low Gz, and various head bracing techniques. Interestingly, Tucker et al. (2012) found that an increase in the number of preventive methods was associated with an increase in the length of average postflight pain. A study conducted by Newman (Newman 1997a) among RAAF fighter pilots revealed that 63% of the respondents performed some form of preflight exercise, which was generally described as warm-up immediately prior to a high-G sortie.

2.4.2 Flight gear and ergonomics

The current operational flight gear in FINAF includes an anti-G suit with bladders and positive pressure breathing for G-protection (PBG) and a helmet integrated with a Boeing-supplied joint helmet-mounted cueing system (JHMCS). However, the suit and PBG are designed to protect against G-LOG, not to reduce cervical or lumbar loading. The former improves G-tolerance by increasing peripheral vascular resistance and by preventing the normal descent of the diaphragm (Lindberg et al. 1960), while the latter supports the respiratory system by reducing breathing resistance and increasing breathing volume (Harding and Bomar 1990). Modern helmets are fitted with an inflatable neck bladder that supports the neck, although its main purpose is to prevent the helmet from slipping under high Gz. According to Sovelius (2014), there seems to be no published data on the effects of the bladder on neck injury protection. However, FINAF pilots have given positive feedback about the support provided by the bladder (Siitonen 2000). As discussed earlier, the effects of the JHMCS on neck disorders remain controversial.

2.4.2.1 Head and neck support

Various methods to provide head fixation to prevent cervical injury have been demonstrated in literature. These include air bags, cervical collars and various supports. Formula 1 drivers use the Head and Neck Support (HANS) system (Gramling et al. 1998), whereas a head restraint device known as Concept of a Neck Protective Device (CNPD) has been introduced for use by the occupants of military-operated high-mobility vehicles (HMV) (Panin & Prusov 2001). Both HANS and CNPD are designed to reduce the movement of the driver's head and thereby force on the neck (Gramling et al. 1998, Panin & Prusov 2001). Panin & Prusov (2001) suggested that CNPD might be useful for individuals who are under the risk of a sudden acceleration injury, including 5th generation fighter aircraft pilots. However, these devices restrict the range of movement, which renders them useless to fighter pilots who will need an unobstructed outside field of view. Due to the foregoing reason, a quality lightweight helmet is considered the most beneficial means of reducing +Gz-related neck pain (Hämäläinen 1993a).

2.4.2.2 Lumbar support

Sovelius et al. (2008b) suggested that a lumbar support could diminish muscle strain in the lower back and neck under Gz. It is hypothesized that if the seat fails to support the lower back adequately, the pilot will slump into the seat under high Gz, which will increase lumbar kyphosis and posterior pelvic tilt. In order to maintain an optimal eye position in the cockpit, this may be compensated by increasing the cervical lordosis. FINAF F/A-18 and Hawk pilots suffering from LBP have been offered the opportunity of using the lumbar support since 2014. Nearly 15% of pilots have ordered the support, but not all of them use it on a regular basis (unpublished observations 2018). According to Winfield (1999), a lumbar support has been available for Royal Air Force (RAF) Tornado, Jaguar, Harrier, and Hawk pilots suffering from LBP since 1973. However, it has been reported that, among RAF aircrew, a minority (27%) of support users are fighter pilots while the majority (73%) are rotary-wing pilots (Winfield 1999). Oksa et al. (2003) reported that a lumbar support enhances the effectiveness of muscular work during AGSM. This is explained by a more upright position of the spine, which is conducive to a more optimal length of the torso muscles; this, in turn, may enhance the muscle's ability to generate force during AGSM.

2.4.2.3 Head bracing

In addition to various supporting devices, head bracing techniques aimed at the alleviation of +Gz loads have been discussed. The most typical means of reducing cervical load has been a technique in which the pilot supports the head against the aircraft structure (Albano & Stanford 1988). An Australian study (Newman 1997b) reports that wedging or bracing the head against aircraft structures prior to +Gz application will reduce cervical load. Green and Brown (2004) concluded that using the canopy as a head support reduces the strain of the neck extensor muscles by 50%. A study on the use of preventive strategies among BAF and RNLAF F-16 pilots found that prepositioning (where the pilot supports the head against aircraft structures) was the most common method. Prepositioning was performed by 71% of the healthy (no neck pain) pilot group and by 82% of the neck pain group (De Loose et al. 2008).

2.4.3 Pilot selection

According to Sovelius (2014), there is a lack of published studies on pilot selection procedures, although careful selection procedures have been recommended as an important preventive method against future health problems among military pilots. The importance of spinal screening during a selection process has therefore been highlighted (Van Leusden et al. 1991). However, the only reported screening methods are radiological (Andersen et al. 1991, Kikukawa et al. 1995). Although various functional and movement control tests are widely used in the screening of athletes, literature contains no reports of implementing these tests in pilot selection. The absence of published information does not, mean an absence of these tests, however. In FINAF, a physical therapist's assessment that includes functional screening tests has been performed during pilot selection since 2006 (unpublished observations 2018).

The most common physical fitness tests in military pilot selection are running tests to measure cardiorespiratory fitness and muscular fitness tests to measure muscular endurance. These are used by all services. USAF pilots have to meet physical conditioning requirements in a 1.5-mile run (Smith 2018). RAAF's pre-entry assessment (PFA) includes a multistage fitness test (MSFT), also known as the shuttle run, or beep tests (DefenseJobs 2018). RAF uses both the 1.5-mile run and MSFT for fitness testing during selection (RAF 2018). The Swedish Air Force (SWEAF) and FINAF use a maximal bicycle ergometer test, instead of a running test, to evaluate candidates' cardiorespiratory fitness (Rintala 2012, Swedish Air Force 2018). Muscular fitness tests in USAF (Smith 2018), RAF (RAF 2018), and RAAF (DefenseJobs 2018) include one-minute push-ups and one-minute sit-ups. FINAF uses the same tests, to which is added a standing long jump test.

Candidates also undergo medical tests during selection. In many countries a screening test includes X-ray and/or MRI testing (Andersen et al. 1991, Kikukawa et al 1995). It is reported that, among other armed services, the Japan Air Self-Defense Force (JASDF) has rejected candidates with abnormalities such as spondylosis, spondylolisthesis, and spina bifida occulta discovered in an X-ray examination (Kikukawa et al. 1995). Andersen et al. (1991) reported that 1/10 of Royal Norwegian Air Force (RNoAF) applicants were rejected from flight training due to radiological findings. It appeared that there were 527 findings deviating from "normal" among 232 X-rayed applicants. Comparison of spinal X-ray findings revealed that the most common site for abnormal findings was the lumbar spine with a total of 213 findings, whereas 173 findings were reported in the thoracic spine and 141 in the cervical spine. The findings were divided into three groups: anomalies, degenerative conditions, and aberrations of posture. The most common diagnostic group was the aberrations of posture (370 findings), while there was 76 findings in the anomalies group and 81 in the degenerative conditions group. (Andersen et al. 1991)

2.5 Other factors predicting spinal disorders

2.5.1 Relationship between physical activity and spinal disorders

The predictors and risk factors of LBP, such as physical inactivity or poor muscle endurance, have been reported in many populations (Rissanen et al. 2002), and there is evidence that LBP can be prevented by effective exercising (Henchoz and Kai-Lik So 2008). It has been suggested that leisure time physical activity may reduce the risk of chronic LBP by 11–16% (Shiri et al. 2017). Steffens et al. (2016) reported in their review of randomized controlled trials that physical exercise alone can reduce the risk of LBP, and when combined with educational programs, it would prevent LBP. It has also been found out that low sedentary activity in leisure time is associated with higher prevalence rates of low back symptoms and resulting sick leave (Hildebrant et al. 2000). Relationship between neck disorders and physical activity has been studied less. However, the results are similar: leisure time physical activity has been found to protect against neck pain as well (Kim et al. 2018).

Fighter pilots are physically rather active; for example, 85% of the RAAF fighter pilots participated regularly in some form of exercise three times per week on average (Newman 1997a). Fighter pilots also consider muscular strength training an important protective method against flight-induced spinal disorders (Kikukawa 1995). FINAF fighter pilots have been reported to exercise 6 h per week. Training consists of endurance training for 2 h/week, strength exercise for 2 h/week, and other physical activity for 2 h/week (hours reported as median IQR). When fighter pilots were compared to pilots of fixed-wing non-high-performance aircraft (NHPA), it was found out that the number of weekly hours spent for strength exercises differed between the pilots. Pilots who flew NHPA actively spent 1.5 h per week for strength exercises, while pilots who did no fly actively used only 0.5 hours per week for the purpose. There was no difference in the hours of endurance training or other physical activity (Rintala et al. 2015).

2.5.2 Relationship between functional and fitness test results and spinal disorders

Relationship between the functional measurements of the trunk muscles and the presence of spinal disorders has been investigated widely (Hammarberg Van Reenen et al. 2006) among general working-age populations. Weak trunk muscles appear to be associated with persistent LBP, while the good isometric endurance of the back muscles seems to prevent LBP (Biering-Sorensen 1984, Suni et al. 1998). It has been reported that the risk of LBP among blue-collar and white-collar working populations is three times greater in subjects who perform poorly in the isometric back endurance test than in subjects with medium or good performance (Alaranta et al. 1995). It has also been reported that the reduced mobility of the spine (Biering-Sorensen 1984, Suni et al. 1998, Feldman et al. 2001) and/or the elasticity of the hamstring muscles (Alaranta et al. 1995) have been related to LBP among the general population. Several studies have investigated the use of movement-competency-based test batteries (Dorrel et al. 2015) for the purpose of identifying deficits in neuromuscular ability associated with increased injury risk. Of these tests, the Functional Movement Screen (FMS) is widely by military services and athletes (Moran et al. 2017). However, the review by Moran et al. (2017) does not support the use of FMS as an injury prediction tool.

There is little or no information in literature on functional assessments or mobility tests among military pilots – neither fixed-wing nor rotary-wing. A comparison between pilots with and without neck pain has indicated that NPG pilots have a significantly lower cervical range of movement (CROM), both in the sagittal and transversal plane, than their symptomless counterparts (De Loose et al. 2009). This is in line with the observations of Armstrong et al. (2005) who found significantly decreased CROM among whiplash patients compared to healthy individuals among the general population. A measurement of maximum isometric neck muscle strength (flexion, extension, and lateral bending) of F-16 pilots revealed no significant differences between healthy pilots and pilots with neck pain (De Loose et al. 2009). However, another study suggests that fighter pilots with neck disorders have lower maximal voluntary contraction (MVC) of the neck extensor muscles during strength testing (Ang et al. 2005).

2.6 Treatment of flight-induced spinal disorders

Fighter pilots do not consult a physician easily. De Loose et al. (2008) found that only 24% of pilots who had reported neck pain had consulted a physician. This finding was similar to the findings of the study of Newman (1997a), in which 27% of the pilots had sought medical attention during their entire career, whereas Drew et al. (2000) found out that 43% of their subjects had sought medical attention. Treatment for LBP or cervical pain among fighter pilots is not widely discussed. Common treatments mentioned in published studies (Drew et al. 2000, Newman 1997a) are rest, medication, and/or physiotherapy.

Studies conducted among the general population (Ylinen et al. 2003), including helicopter pilots (Ang et al. 2009), report that neck muscle strengthening is an effective method of treating neck pain, but no similar reports are available on fighter pilots. A meta-analysis of the effects of workplace exercise on controlling neck pain and LBP supported the hypothesis that workplace exercise reduces the pain (Coury et al. 2009). Loose et al. (2008) mentioned strength training as a strategy for coping and preventing further neck pain episodes. However, only 18% of pilots suffering from neck pain reported to perform strength training. A randomized controlled study among USAF pilots showed that regularly performed specific core exercises may reduce LBP when compared to controls who do not perform these exercises; however, the study included only rotary-wing pilots (Brand et al. 2015). Nevertheless, the increased performance level of physical ability was not tested.

Only two studies (Alricsson & Harms-Ringdahl 2004, Lange et al. 2013) have investigated the effect of training on neck pain among fighter pilots in a randomized-controlled setting. The first was conducted among 40 SWEAF pilots who performed the same training program, either supervised or individually (Alricsson & Harms-Ringdahl 2004). Neck muscle strength among the supervised group increased markedly but no significant changes in the frequency of neck complaints were reported in either group during the study period. However, the study did not include the training of the deep neck muscles. In the second study (Lange et al. 2013), 55 Royal Danish Air Force (RDAF) F-16 pilots were randomized to a training group and a control group. The training group performed strengthening and coordination training of deep muscles. Neck pain among the training group decreased significantly during the 3-month follow-up when compared to the control group.

A recent study (Truszczynska et al. 2014) conducted among PAF fighter pilots reports that only 4% of the subjects used specific physiotherapy programs for treating LBP. Furthermore, only 26% of the pilots applied strengthening-stabilizing exercises to cure LBP. Other treatment methods consisted of passive treatments including massage and passive stretching. These methods were reported only in individual cases, however. None of the pilots reported using analgesics, which is interesting.

Different air services use a variety of methods for the treating spinal of pain. While European air services use strengthening exercises or physiotherapy, a study conducted among JASDF pilots reports that they rely more on oriental medical therapy than orthodox western-style medical therapy (Kikukawa et al. 1995). 43% of JASDF pilots had received oriental medicine including acupuncture, moxa cautery, and muscle massage (Kikukawa et al. 1995). However, 62% of JASDF pilots considered also muscle training an effective method to protect against spinal disorders.

As stated earlier, preflight stretching is a common strategy to prevent injury of neck muscles among fighter pilots. However, there are contradictory results of the benefits of pre-exercise stretching in injury prevention among athletes (Andersen JC 2005). Among fighter pilots, the results are conflicting. Jones et al. (2000) recommended preflight stretching as a part of a potentially effective prevention strategy. Loose et al. (2008) revealed that fighter pilots who performed preflight stretching had no less neck complaints than those who did not. Similarly, Newman (1997a) discussed that stretching may not prevent +G exposure -related neck injuries.

3 AIMS OF STUDY

The beneficial effects of physical activity and performance on health as well as the preventive role of adequate physical activity level and muscular strength in guarding against spinal disorders have been well studied among the general population. However, there is almost no documented scientific work that would provide information on association between physical performance and flight-induced spinal disorders among military pilots. This study was designed to examine these associations. It consisted of five separate studies.

The specific aims of the studies (1–5) were:

1) To examine relationship between the results of functional tests conducted during annual aeromedical examinations and LBP reported five years later.

   <u>Hypothesis:</u> Reduced lower limb elasticity or spinal mobility or trunk muscle strength is a risk for future LBP.

2) To study cervical muscle loading with EMG under controlled +Gz exposure with groups of inexperienced and experienced pilots.

   <u>Hypothesis:</u> Pilots without experience of +Gz exposure have higher cervical muscle loading during the same controlled +Gz exposure in a centrifuge.

3) To investigate the associations of cumulative +Gz exposure during the first five years of a military pilot's career and future spinal disorder -induced permanent FDL.

   <u>Hypothesis:</u> Pilots under permanent spinal disorder -induced FDL have been subjected to higher +Gz exposure before limitation than their non-limited counterparts.

4) To investigate the associations of fitness test results measured during military pilot selection and future spinal disorder -induced FDL.

   Hypothesis: Pilots under permanent spinal disorder -induced FDL have shown lower strength and endurance during the selection phase than their non-limited counterparts.

5) To find out whether psoas and paraspinal muscle cross-sectional area (CSA) and composition could have predicted LBP among fighter pilots, and to investigate possible changes in psoas and paraspinal muscle CSA and composition during a five-year follow up among FINAF fighter pilots during their early flight career.

   Hypothesis: Pilots with smaller total CSA and more fatty infiltration will more likely experience LBP during the five-year follow-up.

4 MATERIALS AND METHODS

4.1 Subjects and ethical considerations

In study 1, the study group consisted of 104 male HPA and NHPA pilots of FINAF. All FINAF pilots undergoing an obligatory annual aeromedical examination in the Aeromedical Centre (AeMC) were chosen for this study. The selection criteria included that the pilots must remain in active duty throughout the five-year period of the study, and that they should consent to the use of their personal records in the study. Data for this cohort was collected from the AeMC database. Pilots in the NHPA group were not exposed to acceleration higher than 2.5 Gz. All fighter and/or jet trainer pilots were assigned to the HPA group. The maximum Gz exposure that the HPA pilots were subjected to was 8 Gz.

In study 2, the subjects were 30 volunteer pilots. The study group consisted of 15 lieutenants with one-year experience of HPA (experienced pilots) and 15 Air Force Academy (AFA) cadets without HPA flying history (inexperienced pilots). The experienced pilots had flown +8 G -capable jet trainers, while the inexperienced pilots had flown only a piston-engine primary trainer.

In studies 3 and 4, the study group consisted of 23 pilots who were under a Gz limitation (+2, +4, or +5 Gz) due to spinal disorders and 50 experienced (+ 1,000 flight hours) symptomless controls who flew actively on operative missions. The FDL group consisted of all fighter pilots who had entered pilot training in 1995–2004 and had received permanent aeromedical limitations. The non-FDL group consisted of five pilots with the highest number of flight hours and without FDL from each AFA course started in 1995–2004. This selection method was chosen to ensure that the subjects and controls had carried out the same syllabus and flight training during the early stage of their career. Only pilots with over 150 flight hours in HPA before limitation were selected to the FDL group to increase the probability of the limitation being due to flight-induced spinal disorders. In the non-FDL group, each of the top-5 pilots had Gz exposed flight experience of 1,000–4,000 hours without any spinal complaints leading to limitations in their medical history.

In study 4, the subjects were 26 volunteer fighter pilots. Only male pilots were included in studies 1–4 due to the limited number of female fighter pilots serving with FINAF. The basic descriptive determinants of the subjects at the baseline of each study are shown in Table 1.

TABLE 1 Characteristics of subjects in studies. Figures are means with standard deviations (± SD).

Study	Subgroups	n	Age (yrs)	Height (cm)	Body mass (kg)
I	HPA	70	31.0 ± 4.3	178.7 ± 4.8	77.9 ± 6.8
	NHPA	34	31.6 ± 4.0	179.0 ± 5.0	80.9 ± 8.5
II	Experienced	15	23.0 ± 0.4	178.4 ± 5.8	75.6 ± 9.7
	Non-experienced	14	22.3 ± 0.6	180.3 ± 2.9	77.6 ± 6.7
III & IV	Non-FDL	50	36.1 ± 3.0	178.7 ± 5.5	71.7 ± 7.1
	FDL	23	36.8 ± 2.2	178.4 ± 5.8	69.7 ± 5.4
V		26	20.6 ± 0.6	179.5 ± 4.7	76.8 ± 5.7

HPA = high-performance aircraft pilots; NHPA = non-high-performance aircraft pilots; FDL = flight duty limited pilots (i.e., pilots flying under permanent limitation)

Ethical approvals for studies 1 and 5 were obtained from The Ethical Committee of the Central Finland Health Care District, whereas ethical approval for study 2 was obtained from the The Ethics Committee of the National Defence University. Authorization for studies 3 and 4 was obtained from the Finnish Defense Forces review board of research permits. All four studies were conducted in accordance with the guidelines of the Helsinki Declaration. All subjects were voluntary, and before any data was collected, the participants were informed of the purpose and methods of the study, and they signed a written informed consent.

4.2 Research design

In study 1, the functional tests were conducted only at the baseline of the study for each pilot. The results of these tests were used as independent variables. A self-administrated questionnaire was carried out at the baseline and five years after the functional tests. The initial questionnaire was used as an independent variable and the second as a dependent variable. The questionnaire elicited information on previous (past year) and present symptoms of LBP as well as on pain and disorders in the neck and the thoracic back.

Study 2 compared EMG activity among the inexperienced and experienced pilots undergoing their first training in a modern dynamic flight simulator centrifuge. During the centrifuge run, EMG activity was recorded from the left and right shoulder and the neck flexor and neck extensor muscles during a standardized gradual onset (GO) where the subject was supposed to apply +8 Gz at 0.1 Gz per second onset rate. The results were expressed as the percentage of the maximal voluntary contraction of the measured muscle (%MVC). MVC was tested prior to the centrifuge run using the same electrodes and their placements.

In studies 3 and 4, early-career G-exposure was compared between the pilots who were under spinal disorder -induced FDL and the control group of experienced non-FDL pilots who flew on operative missions. The results of the physical fitness tests conducted during the application phase were also compared between the two groups. Data for this retrospective study was collected from two databases. The results of the anthropometric measurements, physical fitness tests and physical activity questionnaire conducted at the selection phase were collected from an AeMC (an agency responsible for FINAF pilot selection) database. FDL information was collected from the database of the medical section of Air Force Command Finland (AFCOMFIN).

In study 5, baseline MRI results were collected at the beginning of the study and for a follow-up five years later to reveal any changes in the psoas and paraspinal muscles CSA and composition among fighter pilots during their early flight career. The aim was to find out whether muscle CSA and composition could have predicted LBP. The CSA and composition of the paraspinal and psoas muscles were obtained at levels of 3–4 and 4–5 of the lumbar spine. Strength tests were performed within two months from the baseline MRI.

4.3 Methods

4.3.1 Functional tests (study 1)

Seven functional tests were conducted during the annual aeromedical examination. These included three spinal mobility tests, two lower limb flexibility tests, and two core strength tests. The spinal mobility tests were a Schober's test (Clarkson 1989) for lumbar flexion, a Stibor test for thoracolumbar flexion and standing lateral flexion (Clarkson 1989), all tape-measured tests which were rounded to the nearest 0.1 cm. The lower limb flexibility tests included a straight leg raise test (Clarkson 1989) to measure the flexibility of the hamstring muscles (semitendinosus, semimembranosus, biceps femoris) and a Thomas test (Clarkson 1989) to measure the flexibility of the iliopsoas muscles (psoas major and iliacus). A modified isometric back endurance test (also known as the Sorensen test) was used to measure the fatigue of the back muscles, and a modified isometric abdominal test measured the fatigability of the abdominal muscles.

In the Sorensen test (Biering-Sorensen 1984), the subject was lying in the prone position in a roman chair, fixed at the ankle and hip joint regions and with the upper limbs resting at the sides. The upper trunk was unsupported horizontally in the maximum extension with the inguinal region at the edge of the test table. This body position was maintained for 180 s, and the angle of the trunk was simultaneously measured with an inclinometer. The outcome was the degree of the measured angle after 180 s. The test was terminated after 180 s, or earlier if the subject exhibited extreme fatigue, severe pain, or cramps. The closer the angle remained the starting position the better was the result. An excellent result was achieved when the angle was maintained for 180 s.

In the modified isometric abdominal test, the knees and hip were placed at a 90-degree angle with the feet on the ground without fixation. The hands were positioned straight in the front of the body with the palms on the knees. The subject was asked to curl up with the arms extended towards the knees. The hands were kept on the knees, and this body position was maintained until exhaustion or for the maximum duration of 180 s. The outcome was the total time spent in a predetermined posture, which was verified throughout the test. The test was terminated if the subject lost the desired posture. The time of 180 s was considered an excellent result, while 120–179 s was good, 60–119 s was average, and below 60 s was poor.

The mobility tests used in the study are in common use in physiotherapy and are therefore described in detail in textbooks (e.g. Clarkson 1989). Their reliability is generally found good. For example, the intraobserver correlation of Schober's test has been reported to be 0.88, and that of the side bending tests between 0.82 and 0.87 (Hyytiäinen et al. 1991). Interobserver correlation has been reported as 0.87 for Schober's test and between 0.84 and 0.88 for the side bending tests (Hyytiäinen et al. 1991).

Both isometric strength tests used in the study have been found reliable in several studies (Hyytiäinen et al. 1991, Suni et. al. 1996, Latimer et al. 1999). Latimer et al. (1999) examined the interobserver reproducibility of the Sorensen test and could not find any differences between the observers. Hyytiäinen et al. (1991) examined the intraobserver reproducibility of the same test and could not find any differences between the measurements. The latter study (Hyytiäinen et al. 1991) found no significant intraobserver differences in the isometric abdominal test either.

4.3.2 Self-administered questionnaire (study 1)

All pilots answered a questionnaire, the purpose of which was to elicit information about previous (past year) and present symptoms of LBP and about pain and disorders in the neck and the thoracic back. The questionnaire is regularly used in annual aeromedical examinations, and it was not re-developed or edited for the present study. In the questionnaire, the causes of LBP are classified as leisure-time causes and work-related causes. Work-related causes are further classified as flight-related pain and non-flight-related (i.e., desk job -related) pain. Leisure-time causes are also classified further. In order to determine the incidence of LBP, the following question is asked: “Have you had LBP during the past year?” If a pilot answers in the affirmative, he is asked to name and specify the cause of the pain. Pain intensity is assessed using a VAS where 0 is no pain and 10 is the maximum imaginable pain. Information about age, weight, height, and tobacco use is also collected. The initial (baseline) questionnaire (baseline) was completed upon the completion of the functional tests and the second questionnaire was completed five years after the functional tests.

4.3.3 Electromyography (study 2)

Muscle activity was recorded with a portable eight-channel surface EMG device (ME6000, Muscle tester, Mega Electronics Ltd., Kuopio Finland). The electrodes were Norotrode™ dual electrodes (Myotronics, Inc., Kent WA) with an interelectrode distance of 22 ± 1 mm. They were placed in accordance with the recommendations of SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles), the concerted action in the Biomedical Health and Research Program of the European Union (Hermens et al. 2000).

EMG activity was recorded at six locations: the right and left sternocleidomastoid (SCM), right and left trapezius (TRA), and right and left cervical erector spinae (CES) muscles. The bipolar surface electrodes were placed on SCM bilaterally over the SCM muscle belly, and on CES over the splenius capitis muscle. For TRA activity measurement, they were placed over the anterolateral margin midway between the acromion and occiput. The electrode locations were prepared by shaving, sandpapering, and skin cleaning. Measured signals were preamplified 1000 times. The signal band varied between 20 and 500 Hz. The signal was full-wave rectified and averaged with a 100 ms time constant during the whole exposure.

EMG recorded at the centrifuge were normalized to EMG recorded during isometric MVC. MVC was performed as isometric contraction for cervical flexion (for SCM), shoulder rise (for TRA), and cervical extension (for CES). The results are expressed as the percentage of MVC of the measured muscle (% MVC). Each muscle group was tested separately three times; there was a one-minute rest between the tests, and the best performance according to the highest force value was taken into further analysis.

EMG is a valid method for measuring muscular activity. The relationship between EMG amplitude and tension for short-duration isometric contractions has been reported to be nearly linear (Petrofsky & Laymon 2005, Swaminathan et al. 2016). The reproducibility of EMG has been reported to be high (r=0.88, Komi and Buskrik 1970; r=0.88-0.91, Viitasalo and Komi 1975). Netto and Burnet (2006b), in their study of the reliability of EMG analysis of the neck muscles in particular, also reported a high reliability of MVC measurements within a day and between days.

4.3.4 Centrifuge (study 2)

+Gz exposure was emulated in a modern dynamic flight simulator centrifuge (Wyle Laboratories Inc., El Segundo CA) in Linköping, Sweden. The centrifuge has the radius of 9.14 m and it is capable of generating 15 G maximum and accelerations of up to 10 G/s. The gondola has two degrees of freedom and its layout is based on the controls of the JAS 39 (Saab Ltd., Linköping, Sweden) aircraft. It is fitted with a Martin-Baker ejection seat (Martin-Baker Aircraft Co. Ltd., Middlesex, UK) of the same type as installed in the real aircraft. The seat-back angle is 28 degrees. EMG was recorded from a standardized GO run where the subject was supposed to apply +8 Gz at 0.1 Gz per second onset rate. After the subject had positioned in the gondola, the centrifuge was started to idle at 1.4 Gz.

Measurements were recorded during a GO run where the subject was supposed to apply +8 Gz at the onset rate of +0.1 Gz * s^{-1}. Passive G-tolerance (PGT) was also examined during the run. PGT, determined by the centrifuge instructor, is an individual Gz level when a pilot starts AGSM (due to tunnel vision) during the standardised GO run. All subjects in the study had identical experience of centrifuge runs (two prior test runs) and the same AGSM training with the same instructors.

4.3.5 Fatigue index (study 3)

Cumulative +Gz exposure levels were measured using the fatigue index (FI) of the aircraft. FI is determined by the number of times the levels of +0.25, +2.5, +3.5, +4.5, +5.5, +7.0, and +8.0 Gz are exceeded during sorties or respectively, are declined in the conditions of -0.5, and -1.5 Gz. These values are recorded by the aircraft's accelerometer and stored in the flight data recorder. FI values from each sortie are given a figure that represents cumulative Gz exposure. Cumulative Gz exposure is then determined per 1000 flight hours. The suggested maximum for the follow-up of a pilot's annual exposure is 13 FI /1000 flight hours. This figure is based on specific values for the structural fatigue follow-up of a fighter aircraft (unpublished observation: AFCOMFIN directive CK9720). However, 13 FI is not a constant maximum that a pilot must not exceed. The system is introduced to increase pilots' and squadron commanders' awareness of individual pilots who may be at risk due to intensive loading. It is also intended to serve as a tool for smart scheduling in order to manage occupational loading.

4.3.6 Physical fitness and anthropometry tests in application phase (study 4)

FINAF pilot application tests included aerobic and muscular fitness tests. Each applicant's anthropometrics were also analyzed. Maximal aerobic capacity was evaluated with a maximal bicycle ergometer test. The initial workload of the test was 20 W, and it was increased by 20 W at one-minute intervals until volitional exhaustion. Work capacity was measured as the average load (watts per body mass) during the last minute (W max^1/kg). The minimum requirement observed during selection was 3.5 W/kg.

Muscular fitness was determined by a standing long jump and repetitive dynamic pull-ups, sit-ups, back-extensions, and push-ups. For all repetitive dynamic tests, the subjects were instructed to perform as many repetitions as they could over a 60 s period. Supervisors taught and demonstrated the correct techniques before the test. Repetitions done with an incorrect technique were disregarded. Each test was graded with a scale from 0 (poor) to 3 (excellent) (Table 2). All applicants must have reached at least 8 points (from a maximum of 15) in total to pass the selection.

The pull-up test measured the endurance of the arm, shoulder and upper back muscles. In the initial position, the subject was hanging from a horizontal bar, gripping it with the hands. He was then asked to raise the chin over the bar by flexing the arms and then return to the initial position with the elbows fully extended (Schmidt 1995).

The sit-up test is a measure of the hip flexor and abdominal muscles (Tsigilis et al. 2002, Viitasalo et al. 1980). For this test, the subject was lying supine on the floor with the knees flexed at a 90-degree angle and the assistant supported the feet to the ground. Then he raised the upper body (with the hands behind the neck) until the elbows touched the knees, and then returned to the initial position, in which both scapulas touched the floor.

The push-ups test measures, primarily, the endurance of the extensor muscles of arms and shoulders, but it also requires trunk muscle endurance to stabilize the trunk during the performance (Freeman et al. 2006). For the test, the subject is required to extend the arms fully while keeping the body straight, and then lower the body into a position in which the elbow angle is 90 degrees.

For the back lift, the subject is supported from the ankle joints. The upper body is lifted until the scapulas are raised 30 cm, and then lowered back to the initial position. Detailed information on the muscular fitness tests can be found in the studies by Santtila et al. (2006) and Taanila et al. (2010). The test retest reliability of push-up and sit-ups has been reported to be high among young adults. According to Augutsson et al. (2009), intraclass correlation values for sit-ups and push-ups were, respectively, 0.92 and 0.95.

The standing long jump test measures the explosive force production of the lower limbs (Bosco et al. 1983). For this test, the subject was allowed to swing the arms and the upper body to assist the bilateral takeoff phase. The distance between the bilateral landing and the starting point was measured and expressed in meters.

Anthropometry measures and questionnaires of physical activity were also recorded in the application phase. The anthropometry measures, taken during pilot selection, included height, weight, sitting height, and thigh length. Each measure has a maximum and minimum limit, which are based on the dimensions of the cockpits of the primary trainer and advanced trainer that the pilots fly before converting to the F/A-18. Physical activity level was studied by asking the applicants whether they had participated in sports for regular fitness benefits or as a competitive athlete (i.e., as a member of a sports team or in the form of high-level junior sports participation) at the time of applying for FINAF service.

TABLE 2 Fitness categories and scoring of muscular fitness tests.

	Poor 0 points	Satisfactory 1 point	Good 2 points	Excellent 3 points
Pull-ups (reps/min)	<6	6-9	10-13	14 ≤
Push-ups (reps/min)	<22	22-29	30-37	38 ≤
Sit-ups (reps/min)	<32	32-39	40-47	48 ≤
Back extensions (reps/min)	<40	40-59	50-59	60 ≤
Standing long jump (cm)	<200	200-219	220-239	240 ≤

4.3.7 Magnetic resonance imaging (study 4)

Axial T2-weighted MRI were obtained at the levels of the 3-4 and 4-5 lumbar intervertebral discs using a 1.5T GE Signa HDxt (Milwaukee, WI, USA) with a phased-array surface coil. The CSA of both sides of the paraspinal and psoas muscles were measured with Agfa Impax workstation software (Mortsel, Belgium) by tracing the borders of these muscles. The results were expressed as cm^2. Each muscle structure was circumscribed, and the average value was calculated from these measures. The multifidus and erector spinae muscles were measured (including the non-muscular tissue between them) together and named as the paraspinal muscles (PS). The outcomes for the left and right side are reported separately because side-to-side paraspinal muscle asymmetry has been found to be common (Niemeläinen et al. 2011).

In addition to CSA, qualitative muscle composition was measured. The atrophy of a muscle was rated qualitatively for the paraspinal muscles and psoas muscles at the L3–L4 and L4–L5 levels for all subjects, based on visual evaluation using a 3-point visual scale (0 = significant muscle atrophy; 1 = minor deposits of non-muscle tissue (e.g., fat), 2 = normal muscle, no apparent non-muscle tissue). Both the quantitative (CSA) and qualitative measurements of muscle composition were performed by two well-experienced musculoskeletal radiologists.

The reliability of MRI in quantifying the paraspinal muscles has been investigated in several studies and the method has been found reliable (Gille et al 2007, Ranson et al. 2006). The intraclass correlation coefficients (ICC) for intrarater reliability for CSA measurements at the level of the 3–4 and 4–5 lumbar intervertebral discs has been reported excellent for psoas (ICC 0.97-0.99), erector spinae (ICC 0.97-0.99), and multifidus muscles (ICC 0.97-0.98).

4.3.8 Maximal isometric strength measurement during early career (study 4)

Maximal isometric trunk flexion and extension were performed in a standing position. The extension test is shown in Figure 3, while the flexion test was done in the same aperture standing the opposite way. The measurement was recorded by an isometric strain-gauge dynamometer (Rantanen et al. 1994). The hips were fixed at the level of the anterior superior iliac spine. The strap was tightened around the shoulders just below the armpit and connected horizontally to the dynamometer (Digitest LTD, Oulu, Finland) by a steel chain. A minimum of two trials was performed for each subject and the best result was selected for analysis.

Maximal isometric bilateral leg extension force (Figure 4) was measured with an electromechanical dynamometer. The subject sat on a bench with the back firmly fixed against the backrest and the hands on the handles. He placed the feet on the resistance stand at the base of the sledge. The knee angle was set at 90 degrees using a goniometer. Maximum push toward the leg stand was held for 3–5 s and performed twice with 30–60 s rest between the sets. The measurement was recorded with an isometric strain-gauge dynamometer. A minimum of two trials were performed for each subject and the best result was selected for analysis. The test method is well documented and has been used in previous studies (Häkkinen et al. 1998, Santtila et al 2008). The reproducibility of the measurements of maximal isometric muscle force has been reported to be high (r=0.98, C.V.=4.1%) (Viitasalo et al. 1980).

FIGURE 3 Maximal isometric trunk extension.

FIGURE 4 Maximal isometric bilateral leg extension.

4.3.9 Physical activity, pain and disability questionnaire (study 4)

All subjects answered questions regarding sport and exercise participation and LBP symptoms during the follow-up period. The structured questionnaire included questions on musculoskeletal disorders during the past year and over the entire follow-up period. There was a section for each (lumbar, thoracic, and cervical) region accompanied by illustrations for the validation of localized symptoms. If pain was ongoing or the subject had experienced pain during the past seven days prior to filling-in the questionnaire, VAS value was also questioned. Physical activity level was probed with the question: "How many days have you been physically active (exhaustive exercise that included increased ventilation and sweating for at least 30 min) during the past week?" Annual activity level was asked separately for aerobic exercises (running, cross-country skiing, etc.), muscular strength (cross fit, weight lifting, martial arts, etc.), and racket (tennis, etc.) and ball games (soccer, basketball, ice hockey, etc.). The subject was asked to name the sports in which he had participated.

4.4 Statistical analysis

Means with standard deviations (SD) or standard errors (SE) were given as descriptive statistics in every study and the significance threshold in each test was set at 0.05 (studies 1–5). In study 1, logistic regression and Chi-Square tests were used to determine association between functional test results and LBP. Association between demographic factors and LBP was also analyzed with logistic regression and Chi-Square tests. The subjects in the HPA and NHPA groups were compared with Student's t-test. The change of LBP intensity over time was analyzed with a non-parametric McNemar's test.

In study 2, Student's t-test and analysis of variance (ANOVA) for repeated measures were used to compare the levels of the measured variables between the groups.

In studies 3 and 4, Student's t-test was used for comparison between the groups. Levene's test was used for testing the normality of variances. The Chi-Square test was used to compare dichotomous variables of sports background between the groups. Pearson's correlation coefficient (r) was used to determine statistical dependence between the variables.

In study 5, relationships between muscle CSA, composition and strength test results were evaluated using Pearson's correlation coefficient (r). A one-way repeated measured ANOVA was conducted to identify any changes in the subjects' CSA during the five-year follow-up. A further Student's t-test was used for comparison between LBP and non-LBP.

All analyses were conducted using the SPSS Statistics for Windows V.21.0 software (SPSS, Inc., IBM Company) (studies 1–5).

5 RESULTS

5.1 Functional test measures

There was no statistically significant difference between the functional test results or the demographic factors of the HPA and NHPA pilots at the baseline (Table 3). Isometric low back endurance test results were associated ($p = 0.029$) with leisure-time sport-related LBP experienced five years after the examination among the HPA and NHPA pilots. Neither reduced lower limb flexibility or passive range of movement (ROM) tests results nor isometric abdominal muscle endurance test result were associated with LBP under any circumstances.

TABLE 3 Comparison between functional test measurement among HPA and NHPA pilots. Figures are means with standard deviations (± SD).

	HPA	NHPA	p
Hamstring flexibility			
Left (deg)	87±11	89±8	0.34
Right (deg)	87±11	89±9	0.20
Spinal ranges of movement			
Lumbar flexion (cm)	5.0±0.9	5.6±0.9	0.50
Thoracolumbar flexion (cm)	12.0±1.3	12.1±1.4	0.65
Lateral flexion, left (cm)	23.1±2.9	23.1±3.6	0.21
Lateral flexion, right (cm)	23.6±3.0	23.6±3.3	0.75
Isometric strength tests			
Back test (deg)	10.5±10.6	10.8±11.5	0.28
Abdominal test (s)	129±44	123±50	0.81

HPA = high-performance aircraft; NHPA = non-high-performance aircraft

5.2 Demographic information and LBP

The HPA pilots had experienced more flight-related LBP than the NHPA pilots (p = 0.013). Aircraft type was not associated with any other type of LBP incidents other than flight-related pain. Demographic information (age, weight, height, BMI, and tobacco use) was not associated with LBP in the baseline questionnaire or in the questionnaire conducted 5 years later. LBP (in any situation) reported in the baseline questionnaire was associated with LBP in the questionnaire conducted 5 years later. Neck pain and pain in the level of the thoracic spine at baseline were not associated with future LBP. LBP intensity described with a VAS at baseline was not associated with LBP after 5 years. LBP was most commonly related to flight duty and leisure-time sports. Both flight-related and sports-related LBP decreased significantly in the five-year follow-up (Table 4).

TABLE 4 Prevalence and cause of LBP among all fixed-wing aircraft pilots at baseline and after 5 years.

LBP during last year, n (%)	Q1	Q2	p
Overall LBP	77 (71)	62 (59)	0.04*
Leisure-time sports-related LBP	33 (31)	20 (19)	0.02*
Flight-related LBP	33 (31)	17 (16)	0.01*
Other (non-flying) work-related LBP	21 (19)	23 (22)	0.59
LBP under other circumstances	13 (13)	12 (12)	1.00

* Indicates significance (non-parametric McNemar test)

5.3 Neck and shoulder muscle EMG and PGT

The pilots without HPA experience showed significantly higher muscle activity in the neck flexor (F = 4.8, df = 23, p = 0.04) and extensor muscles (F = 4.7, df = 23, p = 0.04) on the left side during last 5 s of the recorded period at G-levels exceeding 7.4. The combined (left and right side) mean EMG was significantly higher among these pilots. The combined mean (SD) EMG was 29.5% (±29.0) in the neck flexor muscles and 45.7% (24.7) in the neck extensor muscles among the inexperienced pilots and 21.6% (±12.7) and 32.7% (±11.4) among the experienced pilots (Figure 5).

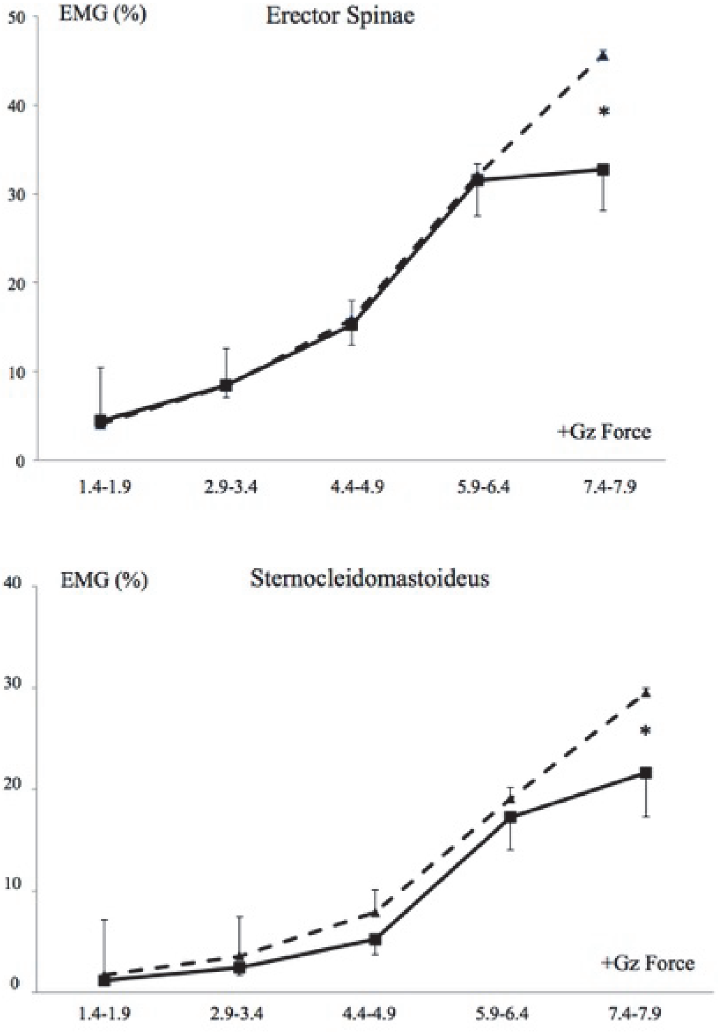

FIGURE 5 Mean EMG (%) among experienced (solid line) and inexperienced (dotted line) pilots under increasing G-exposures.

The pilots without HPA experience showed significantly lower PGT (F = 6.5, df = 24, p = 0.03). The mean PGT level was +4.6 Gz (±0.6) among inexperienced and +5.0 Gz (±0.2) among the experienced pilots (Figure 6).

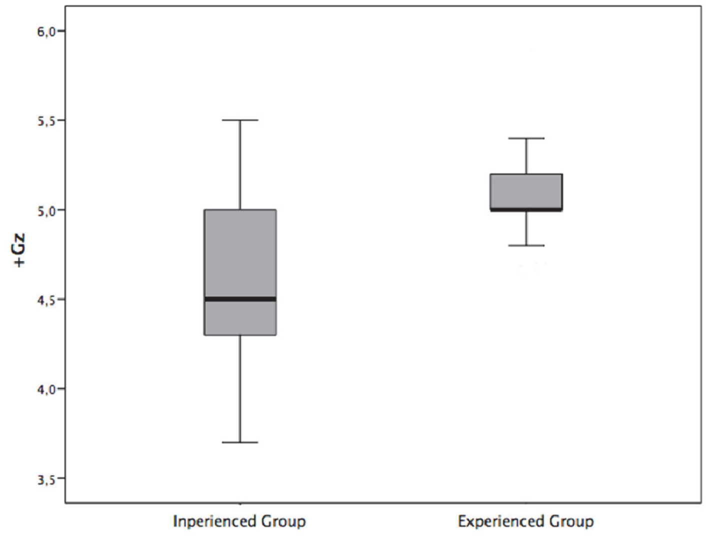

FIGURE 6 Mean passive G-tolerance among experienced and inexperienced pilots.

5.4 G-exposure and spinal injury -induced flight duty limitations

Mean (±SD) flight hours under +Gz exposure of the FDL group was 1354 ± 451 h, ranging from 167 to 2280 h during the entire career. The average flight hours of the non-FDL pilots are classified and therefore not presented. The +Gz-exposed flight hours of the non-FDL group ranged between 1000 and 4000 h. There was no statistically significant difference in flight hours during the first five years of HPA flying between the FDL and non-FDL groups ($p = 0.18$). The mean (±SD) FI accumulation during the first five years of HPA flying was 8.0 ± 1.8 among the FDL group and 7.7 ± 1.7 among the non-FDL group. Comparison of total FI accumulation between the two groups showed no statistically significant difference ($p = 0.57$).

5.5 Application phase results and flight duty limitations

There was statistically significant difference between the FDL and non-FDL groups in the total score of the muscular fitness tests performed in the selection phase. All selection phase results are shown in Table 5. The non-FDL group had a better mean ± SE total score of the muscular fitness tests (13.7 ± 1.7) than the FDL group (12.4 ± 1.62). This difference (1.38, BCa 95% CI [0.386, 2.266]) was statistically significant ($t(49) = 2.80$, $p = 0.007$). When the test results were further analyzed test by test it was found that the non-FDL group had better results in the pull-ups (14.4 ± 4.2) than the FDL group (11.5 ± 2.0). This difference (2.90, BCa 95% CI [1.128, 4.729]) was statistically significant ($t(49) = 3.37$, $p =$

0.001). The non-FDL group had better results in the back extension test (71.1 ± 14.1) than the FDL group (60.0 ± 12.2). This difference (11.08, BCa 95% CI [2.924, 18.585]) was statistically significant (t(37), $p = 0.007$). The maximal aerobic capacity results were not statistically different between the groups in the selection phase. The analyzed anthropometric measures showed no statistical difference between the two groups.

The non-FDL pilots had participated in competitive sports significantly ($p = 0.012$) more than their FDL counterparts. At the time of selection, 54% of the pilots in the non-FDL group had reported a background in competitive sports while only 22% of the FDL group pilots had reported this background.

TABLE 5 Mean (±SD) physical fitness test results of non-FDL and FDL groups.

	Non-FDL	FDL	p-value
Aerobic capacity (W/kg)	4.5 ±0.5	4.3 ±0.4	0.13
Muscular fitness (pts of 15)	14 ±2	12 ±2	0.01 **
Pull-ups (reps/min)	14 ±4	12 ±2	0.01 **
Push-ups (reps/min)	44 ±12	41 ±14	0.41
Sit-ups (reps/min)	50 ±5	47 ±5	0.55
Back lifts (reps/min)	71 ±14	60 ±12	0.01 **
Standing long jump (cm)	243 ±9	236 ±15	0.68

** Indicates significance (Students t-test, with Levene's test for equality of variances)

5.6 MRI findings

The mean (±SD) CSA of the paraspinal muscles among the study group was 31.0 (±3.8) cm^2 at the L3–4 level and 28.6 (±3.8) cm^2 at the L4–5 level. The mean CSA of the psoas muscle was 25.7 (±3.4) cm^2 the L3–4 level and 21.3 (±3.2) cm^2 at the L4–5 level. All subjects were ranked in category 2 (normal) in the 3-point (0–2) visual scale used to measure muscle composition. The mean self-reported sport participation was 3.2 times per week for overall sports participation and 1.9 for strength training.

The follow-up comparisons (ANOVA) showed statistically significant ($p < 0.01$) increase in the CSA of the paraspinal muscles over the five-year follow-up period. The mean CSA of the paraspinal muscles (left and right side combined) had increased by 8% and 7% at the L3–4 and L4–5 levels, respectively. However, the CSA increase of the psoas muscles (2% at L3–4 and 3% at L4–5) was statistically not significant. CSA in all measurement points are shown in Table 6. The comparison of CSA changes between the pilots in the LBP group and their symptomless counterparts during the follow-up period showed no statistically significant differences.

TABLE 6 Longitudinal changes of paraspinal and psoas muscle (n = 26) during five-year follow-up.

	Baseline CSA (cm^2)	Follow-up CSA (cm^2)	P^a
PS 3–4 (R)	31.29 ± 4.04	33.68 ± 4.30	<0.01**
PS 3–4 (L)	30.69 ± 3.26	33.20 ± 3.53	<0.01**
PS 4–5 (R)	28.67 ± 3.79	30.12 ± 4.17	<0.01**
PS 4–5 (L)	28.49 ± 4.28	30.86 ± 4.70	<0.01**
Psoas 3–4 (R)	16.91 ± 3.36	17.40 ± 3.32	0.02*
Psoas 3–4 (L)	17.39 ± 3.60	17.70± 3.48	0.27
Psoas 4–5 (R)	21.04± 3.20	21.81± 3.91	0.07
Psoas 4–5 (L)	21.53± 3.21	22.16± 3.36	0.05

CSA = cross-sectional area; PS = paraspinal muscles; [a] ANOVA for repeated measures, (Wilks' Lambda) was used to obtain *P values; *p <0.05; **p <0.01*

There was a statistically significant correlation with the leg extension test results and the CSA of the psoas (r=0.60, p<0.01) and the paraspinal muscles (r=0.60, p<0.01) at the L3–4 level. Table 7 also shows statistically significant correlations between the trunk flexion and extension test results and paraspinal muscle CSA at the L3–4 and L4–5 levels and psoas muscle CSA at the L4–5 level. The correlation coefficients at each CSA measuring point are shown in Table 8.

A further CSA analysis between the pilots who had experienced LBP and their symptomless counterparts during the follow-up revealed no statistically significant difference between the LBP group (n = 8) and the symptomless (n = 18) group. Neither was there any difference in side-to-side asymmetry between the two groups.

TABLE 7 Correlation coefficients between CSA measurement and strength test results.

	Leg extension	Trunk flexion	Trunk extension
PS 3–4 [a]	0.60**	0.50**	0.50**
PS 4–5 [a]	0.23	0.44*	0.43*
Psoas 3–4 [a]	0.60**	0.38	0.36
Psoas 4–5 [a]	0.54**	0.48*	0.45*

PS = paraspinal muscles; a = Pearson coefficient; *p <0.05; **p <0.01;

TABLE 8 Correlation coefficients between each CSA measurement and strength test results.

PS 3–4 (R)	0.59**	<0.01	0.47*	0.02	0.52**	0.01
PS 3–4 (L)	0.60**	<0.01	0.53**	0.01	0.46*	0.02
PS 4–5 (R)	0.29	0.15	0.36	0.08	0.42*	0.03
PS 4–5 (L)	0.15	0.47	0.47*	0.02	0.40*	0.04
Pso 3–4 (R)	0.68**	<0.01	0.39*	0.04	0.39	0.05
Psoas 3–4 (L)	0.51**	0.01	0.35	0.08	0.32	0.11
Psoas 4–5 (R)	0.60**	<0.01	0.48*	0.01	0.48**	0.01
Psoas 4–5 (L)	0.47*	0.02	0.47*	0.02	0.40*	0.04

PS = paraspinal muscles; CC = correlation coefficient (Spearman); *p <0.05; **p <0.01

6 DISCUSSION

The aim of this thesis was to study the effects of +Gz forces on fighter pilots' spinal disorders, cervical loading, and FDL and to determine the predictive role of physical fitness during early career and in the selection phase in disorders and limitations. Results from seven functional fitness tests conducted during aeromedical examination, the outcome of an isometric strength test during early career, and the results of aerobic and muscular fitness tests administered in the selection phase were compared to spinal disorders and flight-duty limitations due to those disorders. Cervical muscle loading was compared between inexperienced and experienced pilots, and finally, relationships with muscular CSA in the paraspinal and psoas muscles were compared to disorders observed during a five-year follow-up.

The main finding was that none of the functional tests used in FINAF pilots' annual aeromedical examination were able to identify pilots who had a risk of developing flight-induced or work-related LBP in the five-year follow-up. However, muscular fitness test results obtained in the selection phase and overall physical activity seem to have predictive role in spinal disorder -induced FDL. Even though paraspinal and psoas muscle CSA cannot predict spinal disorders it was found to correlate well with isometric strength. It was also found that muscle activity is relatively high in the neck and shoulder area under increasing +Gz, even with the head stationary, particularly among non-experienced pilots. Although it was found that LBP is more common with HPA than non-HPA pilots, LBP is also commonly related to other tasks than HPA flying. Furthermore, there was no relationship between direct FI-measured early-career +Gz exposure and spinal disorder -induced FDL. These results indicate that +Gz exposure during early career (the first five years of flying under G-exposure) is not an independent FDL risk factor. To the best of our knowledge, this is the first study to investigate the relationship between Gz-exposure and disorders based on direct G-exposure measurement, and therefore its results in comparing G-exposure and disorders may be considered unique.

6.1 Functional test results as risk indicators for low back pain among fixed-wing pilots

It was hypothesized that reduced lower limb elasticity, spinal mobility or trunk muscle strength is a risk for future LBP. The primary aim was to find out whether any of the functional test results assessing lower limb elasticity, spinal mobility, and the isometric strength of the trunk muscles are associated with future LBP and could therefore be used to predict the development of LBP in different situations. Overall, the study produced few and minor findings showing that only isometric back endurance was related to LBP. Leisure-time physical activity in particular was related to LBP after five years. None of the functional test results could reveal the risk for flight-related LBP in the future.

The finding that reduced isometric back endurance is related to LBP (caused in leisure time physical activities) among military pilots is in line with previous studies (Biering-Sorensen 1984, Suni et al. 1998, Alaranta et al. 1995) conducted among the general population. However, it seems that adequate isometric strength does not have protective role in flight-related or overall LBP. Moreover, there is evidence that limited spine mobility and the reduced flexibility of the lower limb muscles may be conducive to LBP (Suni et al. 1998). However, no association between LBP and any spinal mobility or lower limb flexibility tests have been observed.

The secondary aim was to investigate association between background information (such as the primary aircraft type, anthropometrics, BMI, and tobacco use) collected at the baseline and LBP reported five years later. The present five-year follow-up produced a significant association with the aircraft type and flight-related LBP but did not associate with any other types of LBP. Interestingly, only 5% of the non-HPA pilots reported to have experienced flight-related LBP in the past year, while one fourth (23%) of the HPA pilots reported having flight-related LBP in the past year. This finding supports the hypothesis that cumulative loading on the low back in a Gz environment may have a causal effect on LBP. The finding is also in line with the study of Rintala et al. (2015) who investigated association between demographics (age, BMI, fitness test scores, and flight hours) and the degree of disability among FINAF pilots. They also reported that the percentage of high-performance flight hours of total flight hours was the only independent predictor of disability.

Although there is evidence that height (Orsello et al. 2013) and tobacco use (Battie et al. 1991) are risk factors for LBP, no association between LBP and height, weight or tobacco use was found. Non-published observations indicate that discus degeneration is one of the leading diagnostic reasons for spinal-induced FDL among FINAF fighter pilots. Smoking is known to promote the degeneration of lumbar discs (Battie et al. 1991), and therefore relationship between tobacco use and LBP was investigated carefully. 25% of the pilots reported smoking at least occasionally and 7% reported smoking daily. This percentage is clearly higher than the 3% share reported among the pilots of United

States armed services (Drew et al. 2000), but it is not higher than the percentage reported among the general population in Finland (in 2016, 15% of the Finns reported smoking daily). 10% of the pilots used snuff daily, which is less than among male coscripts (12%) but more than among the general population (5%) in Finland (Mattila et al. 2012).

After five years of follow-up, the reported percentage of overall LBP was 59%, with 16% of the pilots reporting flight-related LBP and 22% reporting desk job -related LBP. Even though overall LBP prevalence among the study population was relatively high, the prevalence of work-related LBP, and in particular flight-related LBP, was lower than among many other populations (Bridger et al. 2002, Chen et al. 2005, Miyamoto et al. 2000). Reported LBP prevalence among taxi and truck drivers is between 50 and 51% (Chen et al. 2005, Miyamoto et al. 2000), while rotary-wing military pilots have reported rates as high as 80% of the population (Bridger et al. 2002). It is not clear why military pilots subjected to cumulative low back loading experience less occupation-related LBP than other populations, and the findings of this study do not shed any light on the matter. They highlight the fact that the causes of pain are not related to HPA flying alone; LBP related to leisure-time sports and desk jobs was as common as LBP related to flying itself. There was a statistically significant decrease in reported LBP rate in the five-year follow-up, but the study cannot explain the reason for this drop.

In summary, this study has revealed that LBP is a common problem among military pilots but it is also associated with tasks other than flying. None of the seven functional tests could identify pilots who had flight-induced or work-related LBP five years later. However, adequate isometric back endurance may have a protective role in LBP caused by physical activities.

6.2 Neck and shoulder muscle activation among experienced and inexperienced pilots

EMG-measured neck and shoulder muscle loading was compared between the groups of inexperienced and experienced pilots during Gz exposure in a centrifuge. The hypothesis was that EMG recordings obtained from pilots without any experience in high-performance flying would show higher muscle activity than those of their counterparts with one-year fighter experience. This hypothesis was partly verified. There was no statistically significant difference in muscle activation under low – that is, less than +6.4 Gz – G-exposure, but above that range the results between the groups differed significantly. The activity of the neck flexor (sternocleidomastoid) and extensor (erector spinae) muscles was significantly higher among the inexperienced pilots.

When the mean muscle activity among the entire study population was compared to ergonomic recommendations (Jonsson 1982) for static work (5% MVC) it was found that the recommendations were exceeded even under relatively low Gz forces. When the results were compared to the study of Ang and Kristoffersson (2013), conducted in the same centrifuge using similar EMG normalizations, this study found higher relative EMG activities in the neck flexor and extensor muscles. This divergence could be explained by the fact that the subjects of Ang and Kristoffersson (2013) were very experienced (mean flight experience 2570 h) compared to those of this study. The comparison of the results with those of previous inflight studies (Oksa et al. 1999, Oksa et al. 1996) shows that peak values were much higher in the inflight studies than in this centrifuge study. It has been reported that peak values of over 50% MVC are common during actual missions. A reason for these differences may be the lack of head motion and helmet weight in this study when compared to inflight studies (Oksa et al. 1999, Oksa et al. 1996).

It has to be kept in mind that the activity of the cervical muscles increases both during head movements and under increasing +Gz (Hämäläinen & Vanharanta 1992). When the results of this study are examined it should be noted that the study was conducted with the head practically immobile. Head movements during actual missions are conductive to neck injuries (Coackwell et al. 2004). Particularly, the common "check six" movement (involving significant neck rotation and extension) has been reported as a high-risk movement (Coackwell et al. 2004, Snijders et al. 1991). Major head movements were avoided and the effects of head movements were therefore not measured in this study to ensure safety.

It has also been documented that helmet weight alone increases the loading and activity of the cervical muscles in a high +Gz environment (Phillips & Petrofsky 1983), whereas lighter helmets have been reported to reduce the mean activity of the cervical muscles (Hämäläinen 1993a). The absence of a helmet should therefore be taken into account when comparing the results of this study and inflight studies. In addition, previous studies (Ang & Kristoffersson 2013, Sovelius et al. 2008a) have reported that the adding of NVG to a standard helmet causes even higher muscle activity. On the basis of the foregoing, it can be assumed that increased loading would increase muscle activity further.

This study also compared individual PGT between the groups. The mean PGT level among the inexperienced and experienced pilots was +4.6 and +5.0 Gz, respectively. The difference between the groups was significantly different (P = 0.018). The lower PGT level and higher muscle activation level among the inexperienced pilots may lead to earlier fatigue during a mission. It can be speculated further that during a real flight sortie which involves common head movements the difference between experienced and inexperienced pilots may even increase because inexperienced pilots are known to move the head more than their experienced counterparts (unpublished observations). Because the sample was representative of the FINAF pilot community and the groups were similar in demographics and fitness level, the results may be considered well comparable to the entire FINAF pilot community.

In conclusion, the results showed that surface EMG -measured muscle activity under increasing +Gz is relatively high in the neck and shoulder area even without the additional weight of a helmet and with the head held immobile. The pilots without any fighter experience had higher muscle activity at high +G levels and consequently showed lower PGT than their experienced counterparts. Therefore, the same flight mission might lead to increased fatigue among pilots who have less experience in +Gz flight.

6.3 Physical fitness test results, +Gz exposure and spinal disorder -induced flight duty limitations

The main objective was to investigate whether +Gz exposure levels or physical fitness during early career could predict permanent spinal disorder –induced FDL over a military pilots' career. The study hypothesized that high +Gz exposure during first five years of flying career could predict later FDL. It was also hypothesized that lower muscular and aerobic fitness test results in the pilot selection phase are associated with future spinal disorder -induced FDL. The hypothesis was partly verified. The muscular fitness test battery results, in particular the results of the pull-up and back extension test, were significantly lower among the pilots who were subject to FDL than among the non-FDL pilots, but no statistically significant difference in the aerobic fitness test results between the groups was noticed.

The study suggests that good trunk extensor muscle endurance seems to prevent from flight-related spinal issues. This is well in line with the results of previous studies (Biering-Sorensen 1984, Suni et al. 1998) conducted among the general population, which concluded that adequate level of trunk extensor muscle strength may guard against LBP. The finding that trunk extensor strength is related to spinal disorder -induced FDL is logical. However, the role of the pull-up test, which measures the strength of the upper back and the biceps muscles, is not clear. Since the subjects found attaining the maximum score of 3 points in the pull-up test, the most demanding task in FINAF's five-test battery, it can be assumed that the test measures well the overall athletic ability. Although the results of the other tests (standing long jump, push-ups, and sit-ups) were not statistically different, the non-FDL pilots showed a tendency to obtain better results than their FDL counterparts.

The results of the aerobic fitness test (bicycle ergometer) conducted in the selection phase were not statistically different between the FDL group and non-FDL group. The minimum requirement in the selection phase is 3.5 W/kg, and reaching the required level may therefore be sufficient to prevent future FDL. The finding that only muscular endurance has predictive role in future spinal disorders is supported by several studies (Biering-Sorensen 1984, Alaranta et al. 1995, Rissanen et al. 2002) that have reported poor trunk muscle endurance as an LBP risk factor. However, according to the review of Hamberg van Reenen et al. (2007), there are also conflicting results, and it can therefore be concluded that, due to inconsistent results from multiple studies, there is no evidence of a relationship between trunk muscle endurance and LBP. In addition, anthropometrics (height, weight, sitting height, and thigh length) measured in the selection phase were not statistically different between the groups. However, strict anthropometric requirements are observed in FINAF pilot selection. They limit a pilot's height to 190 cm and sitting length (measured from the buttocks to the head) to 100 cm. Thigh length is limited to 67 cm. Consequently, these requirements may cause a small deviation among the results which might lead to statistical insignificance.

In addition to taking the physical fitness tests, all pilot candidates are interviewed and questioned about their sports activity background. Interestingly, when this background of the FDL and non-FDL groups was compared, it was found that the pilots in the FDL group had participated in competitive and guided sports programs significantly less than their non-FDL counterparts. The finding highlights the common opinion that active sport participation has a beneficial overall effect on health and it may prevent many disorders, including spinal disorders. In a further analysis, sports were divided into four categories in order to find out whether a certain type of sport would be more beneficial than others. However, no difference between the categories was found among the groups, which might be due to relatively small sample size of the study.

Neither were there statistical differences in flight hours or FI data among the groups. According to these findings, it seems justified to conclude that the accumulation of +Gz exposure during the early career is not an independent risk factor in the development of subsequent spinal disorder -induced FDL. This outcome differs from the review of Shiri et al. (2015), which investigated relationship with G-forces and neck pain. However, they (Shiri et al. 2015) characterized +Gz exposure only on the basis of aircraft type and flight years or hours. Nonetheless, pilots flying the same aircraft type may be subjected to totally different +Gz exposure due to different mission profiles and flight syllabi and the results of this study may therefore be conflicting. Furthermore, it has to be kept in mind that a symptom of pain alone will not impose FDL on a FINAF pilot, and other signs and symptoms of an illness or injury (such as discus degeneration) will be needed. For this reason, comparisons to previous studies that have involved pain questionnaires is not possible. Overall, the comparison of the results of this study to the previous studies has to be done with caution because there are no studies reporting direct accumulation of Gz in military aviation.

It is not possible to determine whether FINAF pilots are subjected to higher +Gz exposure than their counterparts elsewhere. However, this study showed that +Gz exposure during the first five years of fast jet training with the Hawk and the first years of F/A-18 training did not differ between the study groups. The original hypothesis that pilots who are subject to spinal disorder -induced FDL would have been under higher Gz exposure in the early years of their career than their non-FDL counterparts was therefore rejected. Several factors that may influence the development of spinal disorders were not measured or controlled in the study. These factors include the accumulation of Gz loading over the entire career, the individual control of head and trunk position during G-loading, and injuries sustained in leisure-time activities. An awkward neck posture in particular may play a significant role in cervical pain. The small number of the subjects (23) in the FDL group was a weakness of this study. In contrast, the lineup of non-FDL group, which represented the most experienced fighter pilots with 1000–3000 G-exposure flight hours without spinal disorders leading to FDL, may be considered a strength from a data collection point of view.

In summary, pilots who demonstrated lower muscular fitness in the selection phase may be under an increased FDL risk later in their career. In particular, low results in the trunk extension and pull-up tests were associated with future spinal disorder -induced FDL. The aerobic fitness test results and anthropometrics measured in the selection phase were not associated with future FDL. Active sport participation may also guard against subsequent FDL. Differences in early-career (the first 5 years) +Gz exposure did not have a predictive value in view of future spinal disorder -induced FDL.

6.4 Cross-sectional area of paraspinal muscles and its association with muscle strength: five-year follow-up

Changes in psoas and paraspinal muscle CSA and composition during the five-year follow up were investigated during the pilots' early flight career. In addition, muscle CSA and composition were evaluated to find out whether they could predict LBP. The follow-up revealed that the CSA of the paraspinal muscles increases significantly during the early career. However, CSA or muscle composition of the evaluated muscles did not have predictive role in LBP in the follow-up.

According to literature (Farthing et al. 2003), increased muscle CSA is generally expected as the result of resistance training of sufficient duration and workload. Psoas and paraspinal muscle CSA is known to correlate with maximal trunk flexion and extension (Peltonen et al 1998). It has also been reported that intense bodybuilders have 27% greater paraspinal muscle CSA than their non-bodybuilding twins (Gibbons et al. 1998). Therefore, some of the CSA increase among the subjects may be a result of regular resistance training. However, this study was unable to draw a direct conclusion of whether or not the subjects' muscular strength increased since only baseline strength test results were available, unfortunately.

The finding that CSA or muscle composition did not predict LBP is in line with prior studies (Hebert et al. 2014, Fortin et al. 2014). However, some results suggest that muscle composition (Kjaer et al. 2007) and CSA (Danneels et al. 2000) are associated with LBP. Relationships between muscle composition and CSA and LBP have been found with middle-aged (mean age from 37 to 40 years) subjects, and these results are therefore not well comparable with the present results conducted with younger subjects (Danneels et al. 2000, Kjaer 2007). Previous studies on muscle CSA's predictive role in the development of LBP also had design limitations. They were conducted with a cross-sectional design and, therefore, they were unable to reveal, whether the abnormal muscle is the cause of LBP or vice versa. Moreover, the role of psoas muscle CSA should be used with caution in LBP prediction because the increase of the psoas CSA may be a result of a pathological hip flexion and contraction.

Although the increase of muscle CSA was statistically significant and the body weight of the subjects increased over the follow-up period, the composition of the evaluated muscles did not change at all. This does not support the findings of a previous longitudinal study (Fortin et al. 2014), which reported that age affects the composition of the paraspinal muscles over time, but was not surprising due to the subjects' young age and the relatively short (5 years) follow-up period. It has been long known that an increase in the amount of fat is usually the first inactivity-induced change in the muscles of the low back (Kjaer et al. 2007). However, the subjects were physically active individuals who participated in sports an average amount of more than three times per week. This might have contributed to the consistently low fatty infiltration and increased CSA of the muscles. It should be noted in particular that nearly two out of three subjects reported doing strength training at least twice a week regularly throughout the year, which may also have contributed to CSA increase and unchanged muscle composition.

The comparison of the baseline MRI and isometric strength tests showed that all tests (leg extension, trunk extension, and trunk flexion) had an association with the CSA of the paraspinal muscles. The results of the isometric trunk flexion and extension strength tests in particular correlated significantly with paraspinal muscle CSA at both measured levels (L3–4 and L4–5) and psoas CSA at the L4–5 level. The results of the leg extension test also correlated significantly with psoas CSA at both levels (L3–4 and L4–5) and paraspinal muscle CSA at L3–4 level. These results indicate that muscles with larger CSA are also capable of producing more power in isometric strength tests.

The finding that trunk extension and flexion strength correlates with paraspinal CSA are well in line with previous studies (Peltonen et al. 1998, Gibbons et al. 1997) that associated CSA of the paraspinal and psoas muscles with the isokinetic and isometric strength of core muscles. However, there are no studies that would directly discuss association between the strength of the lower limb muscles and CSA and composition of the lumbar paraspinal or psoas muscles. The reason for CSA of the psoas muscles not correlating with the maximal force production of the leg extensors is not clear. It has been reported that psoas CSA correlates with sprint velocity (Tottori et al. 2017) and that high-intensity training increases the hypertrophy of not only the lower limb but also the trunk muscles (Osawa et al. 2014). Consequently, the findings of this study may indicate that the subjects who were capable of producing more force with the lower limb extensors (rectus femoris and gluteus) also have bigger psoas muscles.

In summary, CSA of the paraspinal muscles of FINAF fighter pilots seems to increase during the first 5 years in service. This might be explained by a physically demanding work and regular exercise. Paraspinal and psoas muscle CSA is also elated to overall maximal isometric strength. No association between muscle composition or CSA and LBP was found, however.

6.5 Methodological considerations and limitations

The functional and physical fitness tests (including a muscular endurance and strength test and an aerobic fitness tests) used in this study have all been found reliable. The functional test (Clarkson 1989) and the muscular fitness test (Taanila et al. 2010) are described in detail in literature. The functional tests are used commonly in physiotherapy, while the muscular fitness tests are widely used by armed forces. The bicycle ergometer test used for assessing aerobic fitness is used in many sports and described in detail in literature (Santtila et al. 2010). The ergometer test was continued until exhaustion and the results were presented in W/kg (instead of commonly used submaximal tests and predicted VO_2max) to ensure the validity of the test. Isometric strength tests have been used in several studies (Häkkinen et al. 1998, Santtila et al. 2008) and their reproducibility is high (Viitasalo et al. 1980). The muscular and aerobic tests have been part of the pilot selection process in which all tests have been administered precisely and with care, and the subjects have been motivated and performed with maximal effort in order to pass the selection. All these can be considered to strengthen the reliability and validity of the tests.

EMG is a valid method for measuring muscle activity, but electrode placement is critical for the reliability of measurements. The coefficient of correlation between force and an EMG signal may vary significantly depending on electrode placement (van Dieen et al. 1991). The official recommendations of SENIAM (Hermens et al. 2000) were adhered to in order to ensure the validity and reliability of the measurements. The simulation setup in which the EMG measurements were conducted may be considered to be as close to real aircraft flight as possible, and it used real-aircraft hardware such as the Martin-Baker seat and a realistic stick and throttle. Furthermore, the rapid onset profile made possible by the centrifuge provided +Gz exposure identical to that encountered in a real aircraft. However, there are limitations in the setup compared to real flying; for example, head immobility and the lack of helmet weight render this comparison difficult.

Magnetic resonance scans are more accurate than conventional radiographs and they can screen soft tissues such as intervertebral discs and muscles and their composition. The reliability of MRI measurements of muscle CSA is well studied (Gille et al. 2007; Ranson et al. 2006). The intrarater reliability for CSA measurements of psoas (ICC 0.97–0.99), erector spinae (ICC 0.97–0.99), and multifidus muscles (ICC 0.97–0.98) is excellent. To ensure the validity of the measurements, two well-experienced musculoskeletal radiologists were hired to do the analysis, and the average value was calculated from their measurements. A weakness in the MRI study was the relatively short five-year follow-up period of the young fighter pilots. This appears to be too short for the evaluation of relationship between muscle CSA and spinal disorders, particularly flight-related LBP.

The greatest strength when compared with previous studies on +Gz-induced spinal disorders was the use of FI as a measure of exact individual G-exposure. De facto, fighter pilots who fly the same aircraft type may be subjected to totally different +Gz exposure due to different mission profiles and flight syllabi. Different +Gz exposures may be experienced even during the same mission due to pilots' skills, situational awareness, and the maneuvering of other own and opponent aircraft. The use of FI made it possible to avoid a bias that would have resulted from characterizing +Gz exposure only by aircraft type and years or hours flown. Data on real G-accumulation could now be gathered instead.

In contrast to the objective measurements obtained in the physical fitness tests, EMG, FI, and MRI, information on LBP and physical activity background was based on subjective self-administered questionnaires in which the subjects reported any occurrence of LBP and the intensity and duration of the pain. Information on the type and level of sports that the subjects practiced was also gathered. Self-administered questionnaires assessing physical activity may lead to a reporting bias, such as over-reporting by sedentary individuals, as presented by Fogelholm et al. (2006). In contrast to subjective ratings, the effects of spinal disorders on a military pilot's work were also measured with a tangible marker in the form of permanent FDL, which, when imposed on a pilot, will end or severely hamper his or her career.

It must also be noted that observational studies are always influenced by confounding factors. Therefore, the limitations described above are only the main limitations to the study, and several other, minor limitations may exist despite the author's attempts to control them.

7 MAIN FINDINGS AND CONCLUSIONS

The main findings of this thesis can be summarized as follows:

1. Functional tests conducted during a physiotherapist's appointment in the annual aeromedical examination could not identify pilots who had flight-related LBP at baseline or 5 years later. However, the results of isometric back endurance test were associated with LBP resulting from leisure-time physical activities in the five-year follow-up. This indicates that adequate isometric back endurance may protect against LBP.
2. The pilots with no experience of HPA flight showed significantly higher muscle activity during high +Gz exposure (+7.4 G and over) than their HPA-experienced counterparts. PGT was also lower among the pilots who had no HPA experience. These findings suggest that the same mission involving high +Gz exposure could be more fatiguing for pilots who have less HPA experience.
3. Early-career +Gz exposure level measured with FI or flight hours cannot predict future FDL. This finding may indicate that the amount of +Gz exposure is not an independent risk factor for spinal disorders and that the causes of spinal disorder -induced FDL are multifactorial.
4. Pilot candidates who have better muscular endurance, particularly axial strength, and candidates who have participated actively in sports before selection (in high school) are less likely to become subject to future FDL due to neck and back problems. This indicates that good results in muscular fitness tests during selection and an active sports background may protect from FDL-inducing spinal disorders during a fighter pilot's subsequent career.
5. Paraspinal and psoas muscle CSA was found to be related to overall maximal isometric strength. The CSA of paraspinal muscles increases among FINAF fighter pilots during the first 5 years in service. This might be explained by a physically demanding work and regular exercise.

To sum up, this study shows that pilot candidates who have better muscular endurance and background in competitive sports are less likely to become under FDL due to neck and back problems in the future. Similarly, adequate isometric back endurance can protect from future LBP caused by leisure-time physical activities. Secondly, fighter aircraft pilots seem to suffer more from flight-related LBP, but +Gz exposure is not an independent risk factor for a limitation to fly. Risk factors of spinal disorder -induced FDL should be investigated further. More sensitive, accurate and flight duty -related physical fitness tests along with relationships between head movements and FDL should be studied in particular.

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ORIGINAL PAPERS

I

FUNCTIONAL TEST MEASURES AS RISK INDICATORS FOR LOW BACK PAIN AMONG FIXED-WING MILITARY PILOTS

by

Honkanen T, Kyröläinen H, Avela J, Mäntysaari M. 2017.

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II

NECK AND SHOULDER MUSCLE ACTIVATION AMONG EXPERIENCED AND INEXPERIENCED PILOTS IN +GZ EXPOSURE

by

Honkanen T, Oksa J, Mäntysaari MJ, Kyröläinen H, Avela J. 2017.

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III

+GZ EXPOSURE AND SPINAL INJURY-INDUCED FLIGHT DUTY LIMITATIONS

by

Honkanen T, Sovelius R, Mäntysaari M, Kyröläinen H, Avela J, Leino T. 2018.

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IV

ASSESSMENT OF MUSCULAR FITNESS AS A PREDICTOR OF FLIGHT DUTY LIMITATION

by

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V

CROSS-SECTIONAL AREA OF THE PARASPINAL MUSCLES AND ITS ASSOCIATION WITH MUSCLE STRENGTH AMONG FIGHTER PILOTS: A 5-YEAR FOLLOW-UP

by

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RESEARCH ARTICLE

Open Access

Cross-sectional area of the paraspinal muscles and its association with muscle strength among fighter pilots: a 5-year follow-up

Tuomas Honkanen[1*], Matti Mäntysaari[1], Tuomo Leino[2,5], Janne Avela[3], Liisa Kerttula[4], Ville Haapamäki[4] and Heikki Kyröläinen[3,5]

Abstract

Background: A small cross sectional area (CSA) of the paraspinal muscles may be related to low back pain among military aviators but previous studies have mainly concentrated on spinal disc degeneration. Therefore, the primary aim of the study was to investigate the changes in muscle CSA and composition of the psoas and paraspinal muscles during a 5-year follow up among Finnish Air Force (FINAF) fighter pilots.

Methods: Study population consisted of 26 volunteered FINAF male fighter pilots (age: 20.6 (±0.6) at the baseline). The magnetic resonance imaging (MRI) examinations were collected at baseline and after 5 years of follow-up. CSA and composition of the paraspinal and psoas muscles were obtained at the levels of 3–4 and 4–5 lumbar spine. Maximal isometric strength tests were only performed on one occasion at baseline.

Results: The follow-up comparisons indicated that the mean CSA of the paraspinal muscles increased ($p < 0.01$) by 8% at L3–4 level and 7% at L4–5 level during the 5-year period. There was no change in muscle composition during the follow-up period. The paraspinal and psoas muscles' CSA was positively related to overall maximal isometric strength at the baseline. However, there was no association between LBP and muscle composition or CSA.

Conclusions: The paraspinal muscles' CSA increased among FINAF fighter pilots during the first 5 years of service. This might be explained by physically demanding work and regular physical activity. However, no associations between muscle composition or CSA and low back pain (LBP) experienced were observed after the five-year follow-up.

Keywords: Low back pain, MRI, Muscle composition, Isometric strength, Military aviation, G-force

Background

Low back pain (LBP) is a common disorder throughout Western society [1] and fighter pilots are no exception to that [2, 3]. The reported LBP prevalence among Finnish Air Force (FINAF) fighter pilots is 71% [4], and it is not uncommon that pilots are limited to fly due to spinal disorders [unpublished observations, 2017]. Fighter pilots report higher prevalence of back pain compared to transport or cargo pilots [4, 5]. Therefore, the high acceleration forces have been suggested as an underlying factor for LBP among fighter pilots [3]. Furthermore, it has been found out that the FINAF fighter pilots, who have passed their fast jet flight training, have already experienced flight-induced musculoskeletal pain in their early flight career [3].

Lumbar paraspinal muscle size, asymmetry and composition assessed with Magnetic Resonance Imaging (MRI) have been associated with LBP [6–8]. The paraspinal muscles are smaller in patients with chronic LBP than in their control counterparts [7, 9]. Furthermore, the cross-sectional area (CSA) of the paraspinal muscles, especially at the lowest level of the lumbar spine, has been found to be smaller in LBP patients compared to their healthy counterparts [10]. It has also been suggested that the side-to-side CSA asymmetries of the

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lumbar paraspinal muscles associate with LBP [10–12]. According to literature, it is, however, conflicting when asymmetries are diagnosed as an abnormality. Hides et al. [11] suggested that asymmetries of greater than 10% should be regarded as an abnormality, whereas Niemeläinen et al. [13] found that the side-to-side paraspinal muscle asymmetries of greater than 10% is common among men without a history of LBP.

The predictive role of paraspinal muscle CSA, asymmetry and composition on LBP is not clear. Some studies [8] have suggested that greater paraspinal fatty infiltration is associated with a higher risk of having LBP, while other studies [10, 14] have not been able to make the same conclusion. According to Lee et al. [7], CSA of the paraspinal muscles at the lower lumbar level can be considered to be a prognostic factor of chronicity of LBP. However, atrophy of the paraspinal muscles may be a consequence of LBP. It is suggested that disc or nerve root damage could cause selective atrophy of the multifidus muscles [15]. Therefore, it has to be carefully considered whether the reduced muscle CSA predicts LBP or vice versa.

It has been suggested that regular (2–3 times per week) resistance training enhances hypertrophy in the paraspinal and psoas muscles [16]. Respectively, it has been found that the paraspinal and psoas muscle CSA correlates with maximal trunk extension and flexion forces [17] and with isokinetic strength [18]. When CSA of the paraspinal and psoas muscles has been compared between athletes and non-athletes, the athletes have had significantly greater CSA in both muscles [17]. There are also conflicting results of a relationship between paraspinal muscle CSA and strength of the lower back muscles. Ropponen et al. [19] found only low associations between the erector ($r = 0.21$) and psoas ($r = 0.31$) muscles' CSA and isokinetic force. On the contrary, Parkkola et al. [16] were not able to find an association between the back muscles' size and maximal isometric extension strength of the trunk.

Despite the high incidence of LBP among fighter pilots and the physically demanding high acceleration environment, no previous studies have assessed lumbar paraspinal muscle composition and CSA among fighter pilots. Furthermore, there are no studies investigating the relationship between the isometric muscular strength and muscle CSA and composition among fighter pilots. Previous research, assessing the relationship between muscle composition or CSA and LBP or muscle strength, have focused on patients with LBP or patients and their matched controls [16] or cohorts drawn from population-based samples of working age people [14, 19, 20]. Some studies have also only concentrated on healthy individuals [13, 21], while only two studies have used subjects under middle age [17, 21]. The changes in the psoas and paraspinal muscles of young adults (age ranging from 20 to 26 years) are not documented in any longitudinal follow-up studies.

The main objective of the present study was to investigate the possible changes in CSA and composition of the psoas and paraspinal muscles in the 5-year follow up among the FINAF fighter pilots during their early flight career and, thus to determine whether muscle CSA and composition could have a predictive role for LBP. In addition, the secondary aim was to examine a possible relationship between the overall isometric strength test results and muscle CSA at the baseline. Prevention of pilots' LBP induced flight duty limitations has enormous operational and economic importance, in addition to protecting pilots' health. Early identification of pilots susceptible to severe LBP would allow directing the preventive interventions to the risk group. Measurement of low back mobility and muscular function has not been very successful in predicting LBP in (fighter) pilots. Therefore, new methods are needed for this purpose, like the MRI measurement of lumbar paraspinal muscle composition and CSA used in the present study.

Methods

Subjects

Study subjects ($n = 26$) were Finnish Air Force (FINAF) fighter pilot volunteers. Their mean (±SD) age was 20.6 (0.6) years at the baseline. All subjects were male pilots. Subject characteristics including weight, physical test results and LBP history are presented in Table 1.

The magnetic resonance imaging (MRI) examinations were collected as a part of a larger study investigating relationships between the high +Gz acceleration exposure in high performance fighter flying and degenerative changes in intervertebral discs. At the beginning of the study, the baseline MRI was obtained and its follow-up five years later. The strength tests were performed within two months after the baseline MRI as a part of regular fitness testing among fighter pilots. The research was approved by the ethics committee of the Central

Table 1 Baseline and follow-up characteristics of the subjects ($n = 26$), mean (± SD)

	Baseline	Follow-up
Age (yrs.)	20.6 ± 0.6	25.8 (0.7)
Body mass (kg)^a	76.8 ± 5.7	78.5 (5.6)*
Leg Extension (kg)	221.0 ± 37.9	N/A
Trunk Flexion (kg)	16.9 ± 3.4	N/A
Trunk Extension (kg)	17.4 ± 3.6	N/A
12-min running test (m)	2999 ± 228	N/A
LBP (no. subjects)	0	8

LBP low back pain experienced; ^{a}ANOVA for repeated measures, (Wilks' Lambda) was used to obtain *P values*; *$p < 0.05$

Finland Health Care District, and written informed consent was obtained from all subjects.

Axial T2-weighted MRI were obtained at the levels of the 3–4 and 4–5 lumbar intervertebral discs using a 1.5 T GE Signa HDxt (Milwaukee, WI, USA) with a phased-array surface coil. CSA of both sides of the paraspinal and psoas muscles were measured with Agfa Impax workstation software (Mortsel, Belgium) by tracing the borders of these muscles and were expressed as cm^2. Each muscle structure was circumscribed by two well-experienced radiologists (both specialized to musculoskeletal radiology) and the average value was calculated from these measures.

It has been found out that the borders between the multifidus and the erector spinae muscles (iliocostalis lumborum and longissimus thoracis pars lumborum) are often difficult to distinguish [22]. Therefore, the multifidus and erector spinae muscles were measured including the non-muscular tissue between them, together as one muscle mass, and considered as the paraspinal muscles. L3-L4 and L4-L5 were selected for the analysis because both of these levels have been used in previous studies [13, 22] and because CSA of the paraspinal muscles has previously been found to be the largest overall at the L3-L4 level [22].

The reliability of MRI in quantifying the paraspinal muscles has been investigated in several studies and the method has constantly been found to be reliable [23, 24]. The ICCs for intrarater reliability for CSA measurements at the level of the 3–4 and 4–5 lumbar intervertebral discs has been reported to be excellent in the psoas (ICC 0.97–0.99), erector spinae (ICC 0.97–0.99) and multifidus muscles (ICC 0.97–0.98). Outcomes for the left and right side are reported separately because the side-to-side paraspinal muscle asymmetry has been found to be common [13].

In addition to the CSA measures, a qualitative muscle composition measurement was conducted by two well-experienced musculoskeletal radiologists. The atrophy of muscle was rated qualitatively for the paraspinal muscles and psoas muscles at the L3–L4 and L4-L5 levels for all subjects based on visual evaluation using a 3-point visual scale (0 = significant muscle atrophy; 1 = minor deposits of non-muscle tissue (e.g. fat), atrophy 2 = normal muscle, no apparent non-muscle tissue). The average value was calculated from these measures. The MRI measurements of muscle morphology and CSA offer valid assessment of muscularity [24], as compared to muscle function tests that may be influenced by such factors as pain and motivation.

Muscle strength measures

Prior to all muscle strength tests, the pilots performed a standardized 20 min warm-up. It included light jogging for the first five minutes followed by core and mobility exercises guided by a physiotherapist. The tests were carefully introduced to the subjects and in all tests verbal encouragement was given to each subject.

Maximal isometric trunk flexion and extension were performed in the standing position. The extension test is shown on the Fig. 1, while the flexion test is done in the same aperture standing the opposite way (face away from the wall). The measurement was recorded by an isometric strain-gauge dynamometer [25]. The hips were fixed at the level of the anterior superior iliac spine. The strap was tightened around the shoulders just below the armpit and horizontally connected to the dynamometer (Digitest LTD, Oulu, Finland) by a steel chain. A minimum of two trials was performed for each subject and the best result was selected for further analysis. The duration of maximal pull against the strap was held for 3–5 s and performed twice with 30–60 s rest between the sets.

Maximal isometric bilateral leg extension force (Fig. 2) was measured on an electromechanical dynamometer. The subject was positioned sitting on the bench with their back firmly fixed into the backrest and hands on the handles. The subjects placed their feet on the resistance stand at the base of the sledge. The knee angle was set to 90 degrees using a goniometer. The maximal push towards the leg stand was held for 3–5 s and performed twice with 30–60 s rest between the sets. The


[redacted]

Fig. 1 Maximal isometric trunk extension

Fig. 2 Maximal isometric bilateral leg extension

measurement was recorded by an isometric strain-gauge dynamometer. A minimum of two trials were performed for each subject and the best result was selected for further analysis. This method is well documented and used in many previous studies [26, 27]. The reproducibility of measurements of maximal isometric muscle force is high ($r = 0.98$, C.V. =4.1%) [28]. Finally, overall maximal muscle strength in the present study refers to the results of these three measurements (leg extension and trunk flexion and extension).

Physical activity, pain and disability questionnaire

Each participant was questioned about their history of sport and exercise participation and LBP symptoms during the follow-up period. The structured questionnaire included questions of musculoskeletal disorders during the last year and for the whole follow-up period. There was a section for each (lumbar, thoracic and cervical) region which all was pictured in a questionnaire to validate the localized symptoms. If the pain was ongoing or the subject had experienced pain during the last seven days prior to filling in the questionnaire, the value of the visual analogic scale (VAS) was also questioned. Questions related to physical activity level were: "How many days had the subject had been physically active (exhaustive exercise which includes both increased ventilation and sweating for at least 30 min) during the last week as well as during the last days?" The annual activity level was asked separately for aerobic exercises (i.e. running, cross country skiing, etc.), muscular strength (i.e. cross fit, resistance training and martial arts, etc.) and racket (i.e. tennis) and ball games (i.e. soccer, basketball, ice-hockey, etc.). The subject was asked to name the sports he had participated in.

Statistical analysis

Means with standard deviations (± SD) are given as descriptive statistics. Shaprio-Wilk's test was used to test the assumption of normality. Relationships between muscle CSA, composition and strength test results were evaluated using Pearson's correlation coefficient (r). A one-way repeated measured analysis of variance (ANOVA) was conducted to evaluate the null hypothesis that there is no change in subjects' CSA during the 5-year follow-up. Further analysis to explore the predictive value of the CSA measurements were performed, and the subjects were divided into LBP and non-LBP groups. The student's t-test was used for comparison between the groups. The level of significance was set at 0.05. All analyses were conducted using SPSS Statistics for Windows V.21.0 software.

Results

The mean (±SD) CSA of the paraspinal muscles among the study group was 31.0 (3.8) cm^2 at the L3–4 and 28.6 (3.8) cm^2 at L4–5 levels. The mean CSA of the psoas muscle was 25.7 (3.4) cm^2 and 21.3 (3.2) cm^2, respectively. All the subjects were ranked in category 2 (normal) in the 3-point (0–2) visual scale measuring muscle composition. The descriptive values of the maximal isometric strength test results are presented in Table 1. The mean self-reported sport participation was 3.2 times per week for overall sports participation and 1.9 for strength training, respectively.

The follow-up comparisons indicated that there was a statistically significant ($p < 0.01$) increase in CSA of the paraspinal muscles over the 5-year follow-up period. The mean CSA of the paraspinal muscles (left and right side combined) increased by 8 and 7% at the L3–4 and L4–5 levels, respectively, during the 5-year follow-up. However, the increase in CSA of the psoas muscles (2% at L3–4 and 3% at L4–5) was statistically not significant. CSAs in all measurement points are described in Table 2.

The mean (±SD) combined CSA of psoas was 15.9 (3.0) cm^2 at L 3–4 and 20.1 (3.0) at L4–5, respectively among the pilots who not experienced LBP. The CSAs of psoas among the symptomless counterparts were 17.7 (3.5) cm^2 at the L 3–4 and 21.8 (3.2) at L4–5 level, respectively. The difference was statistically not significant in either at L3–4 ($p = 0.21$) or at L4–5 ($p = 0.21$). There

Table 2 Longitudinal changes of CSA (cm^2) of the paraspinal and psoas muscles (mean ± SD)

	Baseline	Follow-up	P^a	95% CI
PS 3–4 (R)	31.3 (4.0)	33.7 (4.3)	< 0.01**	1.6 to 3.2
PS 3–4 (L)	30.7 (3.3)	33.2 (3.5)	< 0.01**	1.6 to 3.4
PS 4–5 (R)	28. 7 (3.8)	30.1 (4.2)	< 0.01**	0.7 to 2.2
PS 4–5 (L)	28.5 (4.3)	30.9 (4.7)	< 0.01**	1.5 to 3.3
Psoas 3–4 (R)	16.9 (3.4)	17.4 (3.3)	0.02*	0.1 to 0.9
Psoas 3–4 (L)	17.4 (3.6)	17.7 (3.5)	0.27	0.3 to 0.9
Psoas 4–5 (R)	21.0 (3.2)	21.8 (3.9)	0.07	0.1 to 1.6
Psoas 4–5 (L)	21.5 (3.2)	22.2 (3.4)	0.05	0.1 to 1.3

CSA Cross-sectional area, *PS* Paraspinal muscles, *R* right, *L* left; ^{a}ANOVA for repeated measures, (Wilks' Lambda) was used to obtain *P values*; $*p < 0.05$; $**p < 0.01$

was also no statistically significant difference in CSA of the paraspinal muscle. At the L3–4 level it was 31.2 cm^2 (4.0) among pilots who had experienced LBP and 30.9 cm^2 (3.7) among the symptomless counterparts. The results at the level of L4–5 were 29.1 (5.6) and 28.3 (2.9), cm^2, respectively. The difference was statistically not significant in either at L3–4 (p 0.89) or at L4–5 (p 0.64).

There was a statistically significant correlation with the leg extension test results and the combined (left and right side) CSA of the psoas ($r = 0.60$, $p < 0.01$) and paraspinal muscles ($r = 0.60$, $p < 0.01$) at the L3–4 level. Table 3 shows that there were also statistically significant correlations between the trunk flexion and extension test results and side to side paraspinal muscle CSA at the L3–4 and L4–5 levels and CSA of the psoas muscles at the L4–5 level. The correlation coefficients at each CSA measuring point are presented in Table 4.

In further analysis, CSA between pilots who had experienced LBP and their symptomless pilots during the follow-up revealed that there was no statistically significant difference between the LBP group ($n = 8$) and symptomless ($n = 18$) group. Furthermore, there was no statistical difference between the side-to-side asymmetry between the pilots who had experienced LBP and the pilots who had been symptomless.

Table 3 Correlations coefficients (r) between combined (left and right side) CSA measurement and strength test

	Leg Extension		Trunk Flexion		Trunk Extension	
	r	P	r	P	r	P
PS 3–4	0.60**	<.01	0.50**	<.01	0.50**	<.01
PS 4–5	0.23	.26	0.44*	.03	0.43*	.03
Pso 3–4	0.60**	<.01	0.38	.06	0.36	.07
Pso 4–5	0.54**	<.01	0.48*	.01	0.45*	.02

PS Paraspinal Muscles, *Pso* Psoas Muscles, *CC* Correlation Coefficient (Spearman); $*p < 0.05$; $**p < 0.01$

Table 4 Correlations coefficients (r) between side to side CSA measurement and strength test results

	Leg Extension		Trunk Flexion		Trunk Extension	
	r	P	r	P	r	P
PS 3–4 (R)	0.59**	< 0.01	0.47*	0.02	0.52**	0.01
PS 3–4 (L)	0.60**	< 0.01	0.53**	0.01	0.46*	0.02
PS 4–5 (R)	0.29	0.15	0.36	0.08	0.42*	0.03
PS 4–5 (L)	0.15	0.47	0.47*	0.02	0.40*	0.04
Pso 3–4 (R)	0.68**	< 0.01	0.39*	0.04	0.39	0.05
Pso 3–4 (L)	0.51**	0.01	0.35	0.08	032	0.11
Pso 4–5 (R)	0.60**	< 0.01	0.48*	0.01	0.48*	0.01
Pso 4–5 (L)	0.47*	0.02	0.47*	0.02	0.40*	0.04

PS Paraspinal Muscles, *Pso* Psoas Muscles, *CC* Correlation Coefficient (Spearman); $*p < 0.05$; $**p < 0.01$

Discussion

The present study demonstrated that the muscle CSA increased in all measured segments (L3 - L4 and L4 - L5) both in the psoas and paraspinal muscles during the 5-year follow-up. However, the increase in CSA was statistically significant in both sides of the paraspinal muscles in L3 - L4 and L4 - L5 but only at the right side of the psoas muscle at the L3–4 level. At the baseline, it was further found out that the maximal leg extension force correlated with the psoas and paraspinal muscles' CSA, with the exception of psoas CSA at the L3–4 level. In addition, both maximal trunk extension and flexion forces correlated with paraspinal muscles CSA in L3 - L4 and L4 - L5 and psoas CSA in L4–5 at the baseline.

Increased muscle CSA is generally expected following a resistance training intervention of sufficient duration and workload [29, 30]. It has been suggested that maximal trunk extension and flexion forces correlate with CSA of the paraspinal and psoas muscles [17]. Furthermore, Gibbons et al. [31] found out in their twin study that an intensive bodybuilder had 27% greater CSA of the erector spinae muscle than that of his twin. However, it is not possible to conclude if the muscular strength had increased along with the increase of muscle CSA among the subjects of the present study because only the baseline strength test results were available. According to the results of the health questionnaire, our subjects were physically active individuals. The average amount of sports participation was more than three times per week and 15 out of 26 subjects reported doing strength training at least twice a week regularly throughout the year. Therefore, we suggest that a part of the increased CSA could be a result of regular resistance training. The anti G straining maneuver (AGSM) executed during the high-performance flying includes isometric muscle contractions which could also theoretically lead to muscle mass increase. Although, the proper AGSM is done mainly by contracting thigh, buttock and abdominal muscles, the high performance flying itself may also cause the part of the increase of CSA reported in the present study.

An increased amount of fat is normally the first change in muscles of the lower back due to inactivity. In the present study, the composition of the paraspinal or psoas muscles did not change over the follow-up period, although body weight increased. This finding was in contrast to the findings of the longitudinal (15-yr follow-up) study of Fortin et al. [20] which suggests that age is significantly associated with composition of the paraspinal muscles. Nonetheless, the finding of the present study was expected due to a relatively short follow-up period and the young age of the subjects. For example, the follow-up period of the longitudinal study of Fortin et al. [20] was three times longer and the mean age of subjects were older (47 yrs. vs. 21 yrs.) than in the present study.

Previous studies investigating CSA of the paraspinal muscles have reported a caudal increase in CSA of the multifidus and decrease of the erector spinae muscles [13]. In the present study, CSA of the multifidus and erector spinae muscles were measured together as one muscle mass (paraspinal muscles). Therefore, it is not possible to define if there was caudal increase in the multifidus muscle only. In accordance with previous literature investigating the multifidus and erector spinae muscles together, we also found out that CSA was larger at L3-L4 than at L-4 - L5 [22]. The results of this study showed only a little side to side asymmetry of CSA between the measured muscles. The mean CSA measurements of the paraspinal muscles were slightly larger on the right side as compared to the left side in the baseline measurements. The difference between the mean CSA of the paraspinal muscles was 0.60 cm^2 (31.29–30.69 cm^2) at L3 - L4 and 0.18 cm^2 (28.67–28.49 cm^2) at L4 - L5, and the difference was not statistically significant.

In this study, a statistically significant correlation was found between isometric strength test results and CSA of the measured muscles at the baseline. It indicates that muscles with larger CSA are capable of producing more power in isometric strength tests. The trunk flexion and extension test results had significant correlation in both levels (L3–4 and L4–5) of the CSA measurements of the paraspinal muscles. Furthermore, both test results correlated with psoas CSA measurement at the L4–5 level. These findings support previous research [17, 18] where CSA of the paraspinal and psoas muscles have been associated with isokinetic and isometric strength test results. Nonetheless, there are conflicting results. Parkkola et al. [16] could not find association between maximum isometric extension strength and CSA of the lumbar muscles among medical students aged between 21 and 27 years. This contradictory finding could be explained with differences in sex and physical training. Furthermore, the subjects in the current study were active males, whereas Parkkola et al. [16] studied sedentary women.

The leg extension test results showed a significant correlation between CSA of the psoas muscle at levels L3–4 and L4–5. Furthermore, the leg extension test correlated with the paraspinal CSA measurement at L3–4 level. The investigators were not able to find research discussing directly the association between the strength of lower limb muscles and CSA and composition of the lumbar paraspinal or psoas muscles. Therefore, this finding can be considered as novel. The explanation to why the CSA of the psoas muscles correlated with the maximal force production of the leg extensors is not clear. It has been reported that the psoas muscles' CSA as well as lower limb (quadriceps and adductor) muscles' CSA correlates with sprint velocity [32]. Furthermore, it has been found that high intensity training improves not only lower limb but also trunk muscle hypertrophy [33]. Therefore, it is possible to speculate that those subjects who are capable of producing greater force with the lower limb extensors (i.e. rectus femoris and gluteus) may also have larger psoas muscles.

CSA or muscle composition of the studied muscles did not have predictive role on LBP in the 5-year follow-up and supports previous research [14, 20].There are also conflicting results suggesting that muscle composition [6] and CSA [10] of the multifidus muscle is associated with LBP and self-reported disability [34]. Thus, the relationships between muscle composition and CSA and LBP have been found with subjects with a mean age of between 37 and 40 years [6, 10]. When discussing the predictive role of muscle CSA and composition, the most important limitation with these previous studies is the cross-sectional design. The direction, whether the abnormal muscle is the cause of LBP or vice versa, should be investigated in longitudinal studies. Moreover, because the association between muscle strength and LBP was not found in the present 5-year follow-up, it is suggested that longer follow-up studies should be done to investigate the relationship between LBP and muscle strength. However, unless there is no other evidence, it is also justified to say that muscle CSA may not be important in dealing with LBP or risk for pain.

The use of reliable/valid methods in this investigation enhances the quality of the study. The reliability of muscle CSA measurements performed with an MRI is well supported [23, 24]. In addition to high reliability of muscle measurements with MRI scanning, also physical fitness measurements used in this study have been used in several previous studies [26, 27] and their reproducibility is high [28]. A limitation to this study is that there were only strength measurements during baseline.

The 5-year follow-up period of the young fighter pilots may be too short when discussing the relationship between CSA of muscles and LBP and the flight related pain in particular. The subjects only had a few years of the +Gz exposure (flying with fighter jets), which may be the reason that only eight of 26 subjects reported of any kind of LBP episode in the follow-up. Conversely, Rintala et al. [3] found that 9 out of 10 FINAF pilots have experienced musculoskeletal disorders already during their fighter training. The reason for conflicting results might be due to different kind of questionnaires and the subjective nature of these investigations. Furthermore, musculoskeletal disorders studied in the study of Rintala et al. [3] included disorders in both cervical and lumbar areas.

Conclusions

In summary, this was the first study to evaluate lumbar paraspinal muscle composition and CSA among fighter pilots. The present 5-year follow up study suggests that over the first five years of flight service, paraspinal muscles' CSA increases and associates well with the baseline strength test results among the FINAF fighter pilots. Therefore, it could be concluded that in spite of the fact the strength levels of FINAF fighter pilots might increase during the first five years of their career, no association between future LBP and MRI findings of paraspinal or psoas muscles' CSA was observed. Nevertheless, the LBP occurrence was low among the study population, and therefore, we recommend future studies to investigate this association with longer follow-up periods.

Abbreviations

CSA: Cross sectional area; FINAF: Finnish Air Force; LBP: Low back pain; MRI: Magnetic resonance imaging; VAS: Visual analogic scale

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Availability of data and materials

The data supporting our findings is not applicable. All information, including physical fitness tests and MRI-scanning results, of FINAF military pilots are confidential and therefore, it is not possible to deposit the data in publically available repositories.

Authors' contributions

TH took part in all elements of the study and drafted the manuscript. TH and MM contributed to the design of study and data interpretation and statistical analyses. LK and VH (both specialized to musculoskeletal radiology) contributed to the MRI analyses. HK, JA and TL contributed to the study design, participated in the revision of the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

This research has been performed in accordance with the Declaration of Helsinki. The ethical approval was provided by the Central Finland Health Care District. A written informed consent was obtained from all subjects of the study.

Consent for publication

A written informed consent was obtained from the subject in the figures (Figs. 1 and 2) and a copy of the written consent is available for review by the Editor in Chief of this journal.

Competing interests

The authors declare that they have no competing interests.

Publisher's Note

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