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Human factors issues related to man-portable air defence systems (MANPADS)

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ABSTRACT

This study was conducted for the Defence Research and Development Canada (DRDC) Toronto Research Centre (TRC) under Task 13 of Contract W7719-185397/001/TOR in support of DRDC's modelling and simulation (M&S) capabilities within the Advanced Platforms and Weapons (APW) Strategic Focus Area (SFA). The current study examined human factors issues related to man-portable air defence systems (MANPADS).

An open-source literature search augmented by documentation provided by DRDC was performed to identify relevant publications for a literature review. A data collection framework was developed for compilation and evaluation. A refined documentation (N=21) set was selected based on extent to which the literature was focussed on MANPADS and human issues. The study team reviewed and summarized the documentation. The review addressed the role of human factors related to the MANPADS concept of use, system, training approaches, test and evaluation (T&E), automation, biomechanics, target tracking and human performance models. Several human factors engineering (HFE) knowledge gaps were identified in the domain.

Based on these findings, a small set of future research topics was proposed for execution within DRDC's simulated environments. Recommended next steps for advancing research within DRDC's simulated environments and/or employing prototyping tools were also outlined. The research topic areas are listed below and require validation to ensure alignment with DRDC's priorities.

- Anthropometric analysis - Develop an accurate human performance database that represents a full range of human size (i.e., 5^{th}-95^{th} percentile) in accordance with MIL-STD-1472H;
- Environmental clothing and protective equipment - Investigate human performance associated with cold weather clothing and the impact of wearing protective equipment on accuracy and to determine if MANPADS can reasonably be used within cold weather environments;
- Operational training procedures associated with the Target Engagement Sequence (TES) - Training and practice for operational procedures to ensure target acquisition and engagement can be completed within the battery life of the Battery Coolant Unit (BCU);
- Terrain - Team leader's selection of optimal position attacking aerial threats and ensuring adequate protection for the team;
- Mission length - Impact of long missions on human performance that are performed under stressful conditions which required quick movements while load carrying; and
- Visual search patterns - Investigate optimal search patterns (horizontal, vertical) within small and large sector sizes.

Résumé

Cette étude a été menée pour le Centre de recherche de Toronto (CRT) de Recherche et développement pour la défense Canada (RDDC) dans le cadre de la tâche 13 du contrat W7719-185397/001/TOR à l'appui des capacités de modélisation et de simulation (M&S) de RDDC au sein du Domaine d'intervention stratégique (SFA) sur les plates-formes et armes avancées (APW). La présente étude a examiné les problèmes de facteurs humains liés aux systèmes portables de défense aérienne (MANPADS).

Une recherche documentaire de sources ouverte au public, complétée par la documentation fournie par RDDC, a été effectuée pour identifier les publications pertinentes pour une revue de la littérature. Un cadre de collecte de données a été élaboré pour la compilation et l'évaluation. Un ensemble de documentation raffinée (N = 21) a été sélectionné en fonction de la mesure dans laquelle la littérature était axée sur les MANPADS et les problèmes humains. L'équipe de l'étude a examiné et résumé la documentation. L'examen a porté sur le rôle des facteurs humains liés au concept d'utilisation des MANPADS, au système, aux approches de formation, aux tests et à l'évaluation (T&E), à l'automatisation, à la biomécanique, au suivi des cibles et aux modèles de performance humaine. Plusieurs lacunes dans les connaissances en ingénierie des facteurs humains (HFE) ont été identifiées dans le domaine.

Sur la base de ces résultats, un petit ensemble de sujets de recherche futurs a été proposé pour exécution dans les environnements simulés de RDDC. Les prochaines étapes recommandées pour faire avancer la recherche dans les environnements simulés de RDDC et/ou l'utilisation d'outils de prototypage ont également été décrites. Les domaines de recherche sont énumérés ci-dessous et doivent être validés pour assurer l'alignement avec les priorités de RDDC.

- Analyse anthropométrique - Développer une base de données précise des performances humaines qui représente une gamme complète de taille humaine (c.-à-d., 5e-95e centile) conformément à la norme MIL-STD-1472H;
- Vêtements et équipement de protection environmentale - Étudier le rendement humain associé aux vêtements pour temps froid et l'impact du port d'un équipement de protection sur la précision et déterminer si les MANPADS peuvent raisonnablement être utilisés dans des environnements par temps froid;
- Procédures de formation opérationnelle associées à la séquence d'engagement de la cible (TES) - Formation et pratique des procédures opérationnelles pour garantir que l'acquisition et l'engagement de la cible peuvent être effectués pendant la durée de vie de la batterie de l'unité de refroidissement de la batterie;
- Terrain - Sélection par le chef d'équipe de la position optimale pour attaquer les menaces aériennes et assurer une protection adéquate pour l'équipe;
- Durée de la mission - Impact des longues missions sur le rendement humain qui sont effectuées dans des conditions stressantes nécessitant des mouvements rapides lors du transport de charges ; et
- Modèles de recherche visuels - Étudier les modèles de recherche optimaux (horizontaux, verticaux) dans les petites et grandes tailles de secteur.

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LIST OF ACRONYMS

3D	3-DIMENSIONAL
˚C	DEGREES CELSIUS
ACM	ASSOCIATION FOR COMPUTING MACHINERY
ADS	AIR DEFENCE SYSTEM
APW	ADVANCED PLATFORMS AND WEAPONS
ARL	ARMAMENTS RESEARCH LABORATORY
ASI	ADDITIONAL SKILL IDENTIFIER
AT	ADAPTIVE TRAINING
ATD	AUTOMATIC TARGET DETECTION
BCT	BRIGADE COMBAT TEAM
BCU	BATTERY AND COOLANT UNIT
C2	COMMAND AND CONTROL
CF	CANADIAN FORCES
cm	CENTIMETERS
CoC	CHAIN OF COMMAND
COTS	COMMERCIAL-OFF-THE-SHELF
dB	DECIBELS
DCIEM	DEFENCE AND CIVIL INSTITUTE OF ENVIRONMENTAL MEDICINE
DRDC	DEFENCE RESEARCH AND DEVELOPMENT CANADA
EA	ELECTRONIC ATTACK
EM	ELECTROMAGNETIC
EMD	ENGINEERING AND MANUFACTURING DEVELOPMENT
EMG	ELECTROMYOGRAPHIC
EPM	ELECTRONIC PROTECTION MEASURE
ESM	ELECTRONIC SUPPORT MEASURE
EW	ELECTRONIC WARFARE
FAADS	FORWARD AREA AIR DEFENSE SYSTEMS
FAASV	FIELD ARTILLERY AMMUNITION SUPPLY VEHICLE
FEA	FINITE ELEMENT ANALYSIS
FEM	FINITE ELEMENT MODEL
FHT	FIELD HANDLING TRAINER
FOE	FOLLOW-ON EVALUATION
FOR	FIELD OF REGARD
FOV	FIELD OF VIEW
ft	FEET
ft-lbs	FOOT-POUNDS
ft/sec	FEET PER SECOND
HEL	HUMAN ENGINEERING LAB

HFE	Human Factors Engineering
HFES	Human Factors & Ergonomics Society
IFF	Identification Friend or Foe
IMTS	Improved Moving Target Simulator
in	Inches
IR	Infrared
IRCCM	Improved Counter Countermeasures
ITV	Improved TOW Vehicle
IVR	Immersive Virtual Reality
kg	Kilograms
km	Kilometers
LAAD	Low Altitude Air Defense
LAW	Light Anti-tank Weapon
lbs	Pounds
lbs/sec	Pounds per Second
LCS	Load Carriage Systems
LOS-FH	Line-of-Sight Forward-Heavy
m	Meters
M&S	Modelling and Simulation
MAS	Mid-Anterior Shoulder/Deltoid Muscle
MANPADS	Man-Portable Air Defence Systems
MC	Mid-chest/pectoral Muscle
MCRP	Marine Corps Reference Publication
MDP	Mid-Deltopectoral Line
MFTA	Mission Function Task Analysis
mm	Millimeters
msec	Milliseconds
MMH	Manual Materials Handling
MOEs	Measures of Effectiveness
MOPs	Measures of Performance
MRI	Magnetic Resonance Imaging
MUA	Mid-Anterior Upper Arm
NATO	North Atlantic Treaty Organization
NIOSH	National Institute for Occupational Safety and Health
NPC	Non-Player Character
NPRS	Numerical Pain Rating Scale
OCM	Optimal Control Model
OOD	Officer of the Deck (Navy)
PET	Person-Environment-Technology
PSM	Pleural Surface Model
PTL	Primary Target Line
RCAF	Royal Canadian Air Force
RE	Recoil Energy

RH	RELATIVE HUMIDITY
RI	RECOIL IMPULSE
ROE	RULES OF ENGAGEMENT
RPG	ROCKET-PROPELLED GRENADE
RV	RECOIL VELOCITY
sec	SECONDS
SA	SITUATION AWARENESS
SAM	SURFACE-TO-AIR
SEWAT	SUBMARINE EW ADAPTIVE TRAINER
SFA	STRATEGIC FOCUS AREA
SGT	SERGEANT
SHORAD	SHORT-RANGE AIR DEFENSE
SITREP	SITUATION REPORT
SOPs	STANDARD OPERATING PROCEDURES
SOR	STATEMENT OF REQUIREMENT
SRAW	SHORT RANGE ANTI-TANK WEAPON (SRAW)
T&E	TEST AND EVALUATION
TES	TARGET ENGAGEMENT SEQUENCE
TOP	TEST OPERATING PROCEDURES
TOW	TUBE-LAUNCHED OPTICALLY GUIDED SYSTEM
TRC	TORONTO RESEARCH CENTRE
UK	UNITED KINGDOM
US	UNITED STATES
UV	ULTRAVIOLET
VA	VULNERABLE AREA
VM	VEHICLE METRIC
VP	VULNERABLE POINT

1. INTRODUCTION

This study was conducted for the Defence Research and Development Canada (DRDC) Toronto Research Centre (TRC) under Task 13 of Contract W7719-185397/001/TOR in support of DRDC's modelling and simulation (M&S) capabilities within the Advanced Platforms and Weapons (APW) Strategic Focus Area (SFA). [1]

1.1 Background

DRDC TRC is beginning to examine the role of human factors in the use of MANPADS for the Royal Canadian Air Force (RCAF) with a particular interest developing a simulation testbed system for MANPADS. DRDC has several simulation environments and prototyped tools related to air defence but so far, the human role has not been fully considered. To start this effort, DRDC TRC is first examining human factors related to man-portable air defence systems (MANPADS). To date, as far as we know, little to no human factors work examining these systems has been documented.

1.2 Objective

Three objectives of this work included:

1. Perform a literature search and review of relevant publications related to the use of MANPADs and similar such systems;

2. Identify gaps in human factors literature; and

3. Recommend research topics related to MANPADS systems that could be addressed in DRDC's simulated environments and/or that model human performance.

1.3 Scope

This literature search and review included, but was not limited to, papers directly dealing with the operations of MANPADS, human factors papers related to the use of similar devices (e.g., man-portable anti-tank rocket launchers, recoilless rifles), M&S literature related to human performance of similar systems, and academic literature on target tracking. Maintenance activities were not addressed as part of this review.

1.4 This Document

This document is organized according to the following sections:

- *Section One: Introduction*. This section provides the introduction, project scope and objective of the work;

- *Section Two: Technical Approach*. This section presents an overview of the methodology used to perform the literature search and review;

- *Section Three: Summary of Findings*. This section presents the findings identified through the conduct of the work including gaps in the research literature that were identified by the study team;

- *Section Four: Experimental Research Topics*. This section presents an overview of human centered design and presents experimental research topics relevant to MANPADS systems that could be addressed using DRDC's simulation capability;

- *Section Five: Conclusions and Next Steps*. This section reports the conclusion, and recommendations for modelling and validating human performance experiments related to MANPADS;

- *Annex A: Documents Included in Literature Review.* This Annex presents a list of the documents and abstracts that were included in the literature review;

- *Annex B: References for Future Research.* This Annex presents references identified in the literature search which may be relevant to future research topics but were excluded from the current review; and

- *References*: This section lists the references that were included in the literature review.

2. TECHNICAL APPROACH

This section describes the methodology that was executed to support the project objective.

2.1 Literature Search

A literature search on the Google database was conducted using open and subscription-based sources to collect technical documents related to man-portable systems.

2.1.1 Sources

Paid and freely available sources were used to identify relevant literature. Some references identified from paid subscription-based databases were provided to DRDC as an alternate means of accessing them since there was no time and materials budget for the project. The following sources were used:

- Google Scholar;
- Human Factors & Ergonomics Society (HFES);
- Association for Computing Machinery (ACM);
- Oxford Academic;
- SAGE Journals;
- ScienceDirect;
- SPIE;
- Taylor & Francis; and
- Springer.

2.1.2 Keywords

A set of keywords (and combinations of these keywords) was used to conduct the literature search for each domain area. The keywords associated with each domain are presented in Table 2-1.

Table 2-1: Keywords for Literature Search

Domain	Keywords
MANPADS	MANPADS, Man-portable air defence systems, MANPAD operations, operational military use of MANPADS, MANPAD human factors, man-portable shoulder launched systems.
Automation and Autonomy	MANPADS automation, Human autonomy teaming MANPADS, automated MANPAD target tracking.
Human Performance Models	MANPADS modelling and simulation, modelling shoulder-launched weapon performance.
Human Performance Metrics	MANPADS human performance, target tracking performance metrics, shoulder-launched system performance.
Human target tracking	Human factors target tracking, weapon scope target tracking, target tracking with scope, weapon scope human factors.

Domain	Keywords
Biomechanical Factors	Soldier weapon load biomechanics, anti-tank weapon load biomechanics, military shoulder load carriage, shoulder-fired weapon recoil, anti-tank weapon recoil.

2.2 Data Collection Framework

A data collection framework was developed to support the literature search. The framework was used to gather specific data associated with each of the documents identified during the literature search. The data collection framework also included the two criteria used to assess the documents for inclusion in the literature review (i.e., relevant to MANPADs and human performance). All criteria are identified and briefly described in Table 2-2.

Table 2-2: Data Collection Framework for Air-Based Defence Systems

Category	Description
Item number	The number assigned to the document.
Principal Author	The first author listed on the document.
Title	The title of the document.
Year of Publication	The year the document was published.
Citation	The full citation for the documents in APA format.
URL	The URL link to the document online.
Country of Origin	The country where the document was written/research was conducted.
North Atlantic Treaty Organization (NATO) member	Whether the country of origin is a member of NATO.
Search Engine	The search engine used to find the document.
Search Terms	The search terms used to find the document.
Abstract	The document's abstract (if present).
Summary	A summary (1-2 sentences) of the document was generated by the study team if the document was published without an abstract.
Domain	The most relevant research domain associated with the document. Domains included Human Factors Engineering (HFE) issues using MANPADS, automation/autonomy, biomechanical factors, target tracking and performance models.
Sub-Domain	Sub-domains that associated with some research domains.
MANPAD-Focused Evaluation Criteria	A criterion used to assess the relevance of the document to MANPADs-focussed issues. Ratings included High, Medium or Low.
Human-Focused Evaluation Criteria	A criterion used to assess the relevance of the document to Human-focussed issues. Ratings included High, Medium or Low.

2.3 Evaluation of Literature

The literature search yielded a large set of documentation (N=49). The relevance of each document was rated using the two evaluation criteria (see Table 2-2 for details).

The documents were assigned a rating of High, Medium or Low for each criterion. Documents assigned two ratings of 'High' or 'Medium' (or a combination thereof) were considered relevant to the current study and were included in the literature review. A subset of the documentation was included in the final set of literature (n=20). One document which did not meet the pre-established criteria was retained by the study team due to Technical Authority's interest in the topic area. [17] Thus, the documents included in the literature review (N=21) are presented in Annex A.

Documents assigned a rating of 'Low' on one or both criteria were considered to have 'low' relevance and were excluded from the subsequent literature review (N=28). Since these documents may be relevant for future research, the full references were compiled and presented in Annex B.

The qualitative approach used to evaluate the documentation is depicted in Figure 2-1.

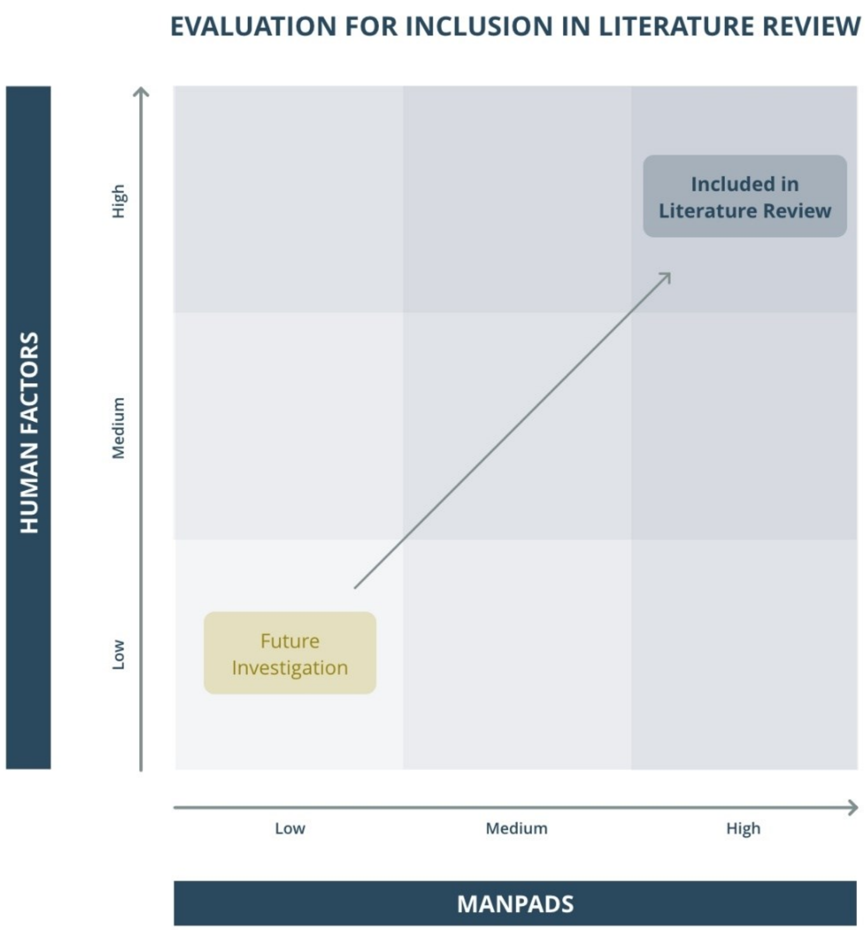

Figure 2-1: Evaluation for Inclusion in the Literature Review

3. SUMMARY OF FINDINGS

3.1 Concept of Use

MANPADS represent an air defence element that is used within a military's larger electronic air defence system (ADS) and is referred to as short-range air defense[1] (SHORAD) [2][5] and low altitude air defense (LAAD). [6] This weapon represents one of the last layers (penultimate) of air defense [2] and is intended to neutralize unfriendly forces before they can attack assets or forces. [8] MANPADS are point-defense weapons used to facilitate movement of land force units and defend vulnerable areas (VA) or vulnerable points (VP) against aerial observation and attacks. [2][5] MANPADS can be deployed in any terrain (i.e., Arctic region, tropical region) and are used against aircraft that can be spotted, either unaided or aided with binoculars, by a MANPADS team. [2][5][8] The targeted missiles counter high-speed, low-level, ground attack aircraft including fixed- and rotary-wing aircraft and unmanned aircraft.

A MANPADS is a shoulder-mounted (or shoulder-launched) weapon equipped with an infrared (IR) homing-guided/negative ultraviolet (UV) heat seeking missile system with modified proportional navigation. [2] Once the missile is launched it is not controlled by the gunner causing the weapon to be referred to as a 'fire and forget' system. The United States (US) Stinger MANPADS weapon is equipped with an identification, friend-or-foe (IFF) subsystem used to identify friendly aircraft. The surface-to-air missiles (SAM) fired from a MANPADS are steered by an electronic guidance system towards the target aircraft. [5][6]

Within the context of a hierarchical Command and Control (C2) network, the effectiveness of MANPADS is maximized when its use is coordinated with the forces. [8] MANPADS are deployed by land force units, including individual personnel or small teams, from missile posts that are located within a close range to the VA or VP being defended. [2] These weapons engage approaching aircraft within sight of the operator during or just before their final attack maneuver. High priority targets are protected from all sides by MANPADS teams positioned to provide overlapping coverage. In contrast, only the likely threat approaches are defended for low priority targets rather than providing all-around coverage.

C2 orders (i.e., fire control orders, state of readiness and air defence warning issuance) are issued from the command post to the subordinate missile post via tactical links such as voice (via a control net) or text messages. [2][5][6] The method of transmission is determined by both the data link and the display capability of devices available at the mission post. [2] The orders provide a primary target line (PTL), a sector of fire and a list of potential aircraft types that may pose a threat. The tactical situation necessitates effective decision-making capabilities and the MANPADS team's ability to maintain situation awareness (SA) of the overall exercise or battle. [2]

Due to the lack of near real-time data transmission capability and the short reaction times that must be accommodated, the authority for identification and engagement is vested in the team leader. [5] The team leader is responsible for providing updates to the

[1] The American spelling for 'defense' is used when the content refers to US documentation. Otherwise, the Canadian spelling for 'defence' is used.

chain of command (CoC), in this case the section chief, regarding the readiness state, weapon status, situation reports (SITREP) and acknowledge the receipt of orders. [2][6] The section leaders are responsible for maintaining SA across all individual MANPADS teams. The section chief may be unaware of the team's location due to their frequent movements. [6]

If direct communications to the section leader are lost during dynamic battle activity, the MANPADS team will maintain the Rules of Engagement (ROE) for hostile aircraft and assume a point defense role until communications are regained. As well, the supplemental fire control measures that were in effect (e.g., weapons tight during daylight hours or weapons hold at night) will be maintained. [5][6] In the interim, communications will be relayed to the section leader through another MANPADS team. [6]

3.2 Personnel and Roles

The MANPADS team is assigned to a specific geographical section which is defined in terms of azimuth and elevation. In addition, the terrain type influences MANPADS team's deployment; in the case of a hilly terrain MANPADS are positioned in the approach corridors used by the attacking aircraft. [2] The flexibility and mobility of the weapon and the reactivity of the MANPADS teams allows this system to support all tactical operations. The primary mission of air defense teams, including the MANPADS teams, is to provide close in, low altitude, SAM weapons fires in defence of assets by defending forward combat areas, vital areas, installations, units conducting special or independent operations. The secondary mission is to provide a task-organized, ground security force. [6]

Individual MANPADS teams work as part of a MANPADS network to protect a designated area. To ensure effective employment, the team must consider the air threat, the integrity and location of the firing team, alerting (i.e., an aircraft is approaching) and cueing (i.e., direction of aircraft travel) and target destruction. [6] Within an individual MANPADS team, both members are trained as weapon operators, radio operators and drivers. Also, both personnel are trained to perform aircraft and armour recognition and machine gun employment. In addition, each team member has a unique role as either the team leader (also referred to as the team chief) or the gunner. [5][6] The MANPADS team members react to aerial threats in a coordinated manner as depicted in Figure 3-1. The study team extracted technical details from US doctrine, training and research documentation to characterize the roles and responsibilities for MANPADS team.

Figure 3-1: Depiction of a Coordinated MANPADS Team.

Source: Adapted from Fig. 1 in [2].

3.2.1 Team Leader

Upon arrival at their location, the team leader determines the optimal firing position, field of view (FOV) and the PTL while considering factors such as terrain features that could mask the missile launch, potential obstructions, and the adequacy of the backblast area. [5] There is very little time to react to imminent aerial threats [2][5] and teams may move frequently to maintain their defence. [6]

The team leader is responsible for the following task sequence: [2][5][6]

- Conduct visual search. Systematic search methods are used to detect small objects at long ranges followed by their recognition and identification. Experienced team leaders may use non-systematic search methods. Two systematic scanning methods used by team leaders include:
    - Horizontal scanning is performed 20 degrees above the horizon; and
    - Vertical scanning is performed using the horizon as a starting point and prominent terrain features as a reference point.

  Small search areas improve detection outcomes however, the areas should not be less than 30 degrees because the accuracy of the alert warning system azimuth may be reduced. Fatigue must be managed (e.g., avoid eye muscle relaxation by focussing on distant objects) and alertness is maintained by sharing the scanning task between team members and taking regular rest periods approximately every 15 minutes. There is a direct relationship between the size of the sector assigned to the MANPADS team and the level of difficulty associated with detecting an aerial threat. [2] For example, detections are easier when the assigned sector size is small (approximately 30 degrees) compared to when the assigned sector size is large (approximately 90 degrees).

- Establish contact. Make visual contact with aircraft prior to identification. From the point at which a high-speed threat is detected, the MANPADS team has approximately 10 to 20 seconds (sec) to engage;

- Identification of aircraft. Aircraft is identified as friendly, hostile or unknown within approximately 5 to 15 sec. Identification is completed prior to engagement;

- Decision to engage. Engagement decisions are based on the ROE and criteria provided by the section leader. The team leader selects the method of engagement; and

- Order engagement. The team leader gives the gunner an order to fire the weapon.

3.2.2 Gunner

The gunner is responsible for operating the MANPADs when a threat is imminent. If the gunner is working independently and facing multiple threats, the most serious threat should be addressed first. The gunner is responsible for the following task sequence: [2][5][6]

- Position weapon. The gunner picks up the weapon and positions it on their shoulder (i.e., referred to as ‘shoulder the weapon’) and waits for the team leader’s order;

- Interrogate aircraft. The US Stinger IFF operation is an automatic function which is activated when the gunner aims the weapon at the target and presses the challenge switch. The team leader interprets the outcome of the interrogation;

- Activate weapon. The weapon is activated by the gunner via the safety and actuator switch located behind the grip assembly. Once activated, the weapon can be fired within 45 sec before the battery coolant unit (BCU) needs to be replaced;

- Continue tracking. The gunner uncages the seeker providing the signal is strong enough to lock onto the target;

- Determine range. The gunner evaluates the target to determine if it is within the weapon’s range. This does not apply to helicopters and propeller aircraft. See Section 3.3.3 for optical sight requirements;

- Super elevation and lead. Once the seeker is uncaged, the gunner views the aircraft image through the appropriate super-elevation and lead reticle (i.e., left, center or right reticle); and

- Fire weapon. The gunner initiates firing by squeezing the trigger and simultaneously holding the uncage bar. Upon firing, the gunner should hold their breath for 3 sec (See hazards in Section 3.3.7). A MANPADS team engages with incoming aerial threats based on the number, type and direction of aerial threats including: [6]
    - Shoot-look-shoot technique. The gunner prepares the MANPADS and engages a single target once the team leader has visually identified it, confirmed it is hostile and gives the order; and
    - Shoot-New Target-Shoot. Both the gunner and team leader prepare weapons to simultaneously engage separate aircraft. Multiple threats are determined when aircraft are flying in a certain formation at the same speed and within a certain distance of each other (e.g., less than 1000 feet (ft) between the aircraft).

The following aspects are considered by the gunner when evaluating a detected aerial threat:

- Aircraft direction. The gunner adopts a specific posture (i.e., step and lean toward the target leading with the left foot) and aligns the aircraft image within range ring of the weapon sight. Judgements based on the movement of the gunner's body are indicative of the aircraft's direction of movement (i.e., horizontal movement of the gunner's arms and upper body indicates the aircraft is crossing, lack of significant horizontal movement or vertical movement indicates incoming or outgoing aircraft);
- Aircraft posture. Initially, aircraft are considered as hostile, and the gunner will proceed with engagement unless it is cancelled by the team leader;
- Aircraft type. A dichotomous decision is made as quickly as possible to determine aircraft type (i.e., jet type and propeller type). The outcome of this decision determines the approach used by the gunner to align the aircraft in the weapon sight; and
- Aircraft range. The gunner determines whether the aerial target is within range of the missile. This decision is based on the type of aircraft (i.e., jet type or propeller type), direction of movement (i.e., incoming/outgoing, crossing) and the type of measurement (i.e., range ring measurement, time count rule). The gunner fires at propeller aircraft as soon as the missile is activated, and the IR lock-on is acquired.

3.2.2.1 *Gunner experience level*

The success of a MANPADS target engagement is closely linked to the gunner's experience level. A DRDC report categorized observations of gunner behaviour as a means for assessing the impact of skill level on the success (or lack thereof) of target engagement. The approach used the same letter grading system typically used in the US educational system (i.e., Grades A through F). The definitions associated with each grade were based on the study team's experience gained from attending various field trials as well as a review of formal documentation (i.e., US Stinger operator manual) and a video analysis of war zone engagements. The grades were intended to provide guidance with respect to the type of behaviour associated with each skill level and did not represent a formal, structured evaluation. [9]

For the current purposes, the study team developed a data collection framework to compile DRDC's observations using a more systematic approach. Behavioural characteristics associated with each skill level are presented in Table 3-1 below. A rudimentary coding system was developed to indicate the extent to which the skill existed within each skill level and is presented below.

- Y=Yes, highly trained and knowledgeable;
- L=Likely have good training or experience and knowledge;
- M=Maybe have some training and knowledge;
- U= Unlikely to have useful knowledge and no formal training; and
- N=No understanding of the system.

Although there was a substantial amount of missing data, the compilation of information provides a foundation that can be used to develop measures of performance (MOPs) and/or measures of effectiveness (MOEs) for the evaluation of MANPADS team skillsets. These characterizations require validation from the operational community.

Table 3-1: Proposed MANPADS Team Skill Level

Proposed Skill Level	Training				Coordination				Weapon and Site Handling							
	Received Formal MANPADS Training	Identify Aircraft Types	Simulator Experience	Live Fire Experience	Team Leader & Gunner	Coordinated Teams	Interconnected Units	Advanced Comms, Threat, Visual Systems	Terrain Knowledge for Site Selection	Visual Search Patterns	Employ IFF	Adhere to ROE	Target Acquisition Procedures	Firing Procedures	Maintenance /Storage	Employ Security Measures
A – Excellent	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
B – Above Average	Y	-	-	M	Y	-	-	-	Y	-	U	-	Y	Y	U	-
C – Average	M	-	-	-	M	-	-	-	U	-	-	-	M	Y	N	U
D – Below Average	N	-	-	-	N	-	-	-	-	-	-	-	U	U	-	U
F – Failure	N	-	-	-	-	-	-	-	-	-	-	-	N	N	-	-

3.3 System

The MANPADS have two main system components, the weapon launcher and the missile. Each of these components is described and depicted in the sub-sections below. Descriptions are generally consistent with most types of MANPADS, but specific details are based on documentation included in the literature review which tended to focus on the US Stinger system.

3.3.1 Target Engagement Sequence

Generally, there are ten steps, with some minor order variations, completed when engaging targets. [22] These steps are referred to as the Target Engagement Sequence (TES) and identified in Figure 3-2.

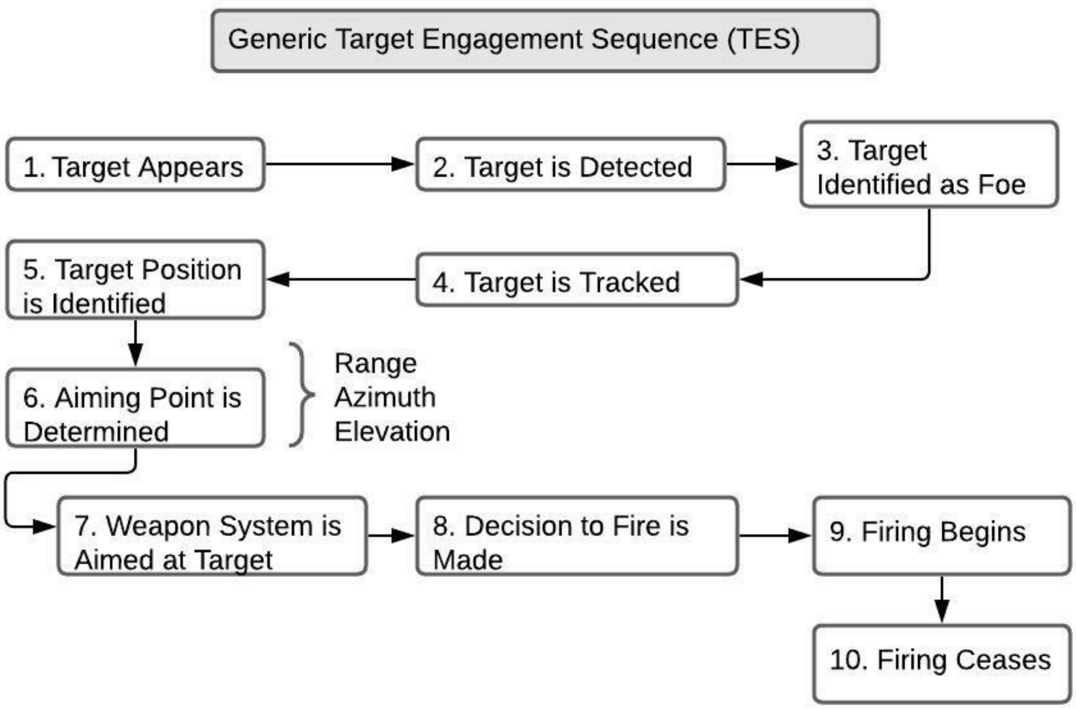

Figure 3-2: Generic Target Engagement Sequence

3.3.2 MANPADS Weapon Launcher

The MANPADS weapon launcher, depicted in Figure 3-3, is equipped with a sight assembly (A) and is comprised of three components including a detachable gripstock (B), a BCU (C) and a missile round (D). [7]

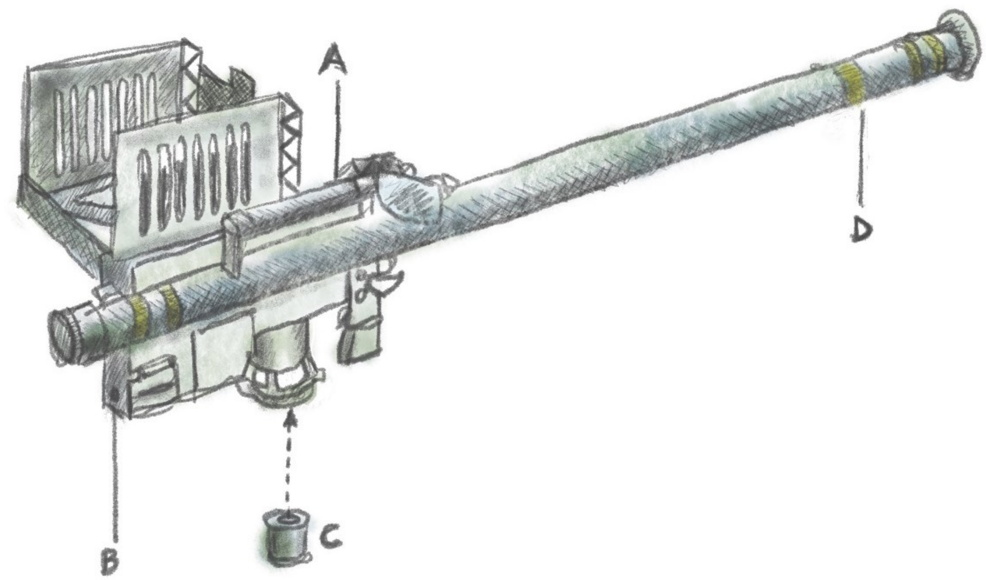

Figure 3-3: MANPADS Weapon Launcher.

Source: Adapted from Fig 2-2 in [6].

A variation of the US Stinger has improved tracking ability and improved IR counter countermeasures (IRCCM) compared to the basic system. [7] Each of the MANPADS weapon launcher components, and attachments (if appropriate), is described in Table 3-2 below. [2][5][6]

Table 3-2: Components of MANPADS Weapon Launcher

Components	Description
Sight Assembly (A)	The sight assembly is attached to the launch tube and allows the MANPADS operator to estimate range of aircraft and track movement. The sight assembly is retractable and can be manipulated (i.e., brought to its active position) by the operator once the weapon is removed from the case for operational use. Two acquisition indicators are located on the sight assembly including 1) a speaker for generating auditory tones indicative of IR acquisition and/or IFF identification and 2) a bone transducer that delivers vibrations to the MANPADS operator’s cheekbone to communicate acquisition signals. See Section 3.3.3 for information concerning the employment of the optical sight.
Detachable gripstock (B)	The gripstock is detachable and contains the materials (i.e., circuitry) needed to prepare for and launch the missile. It provides a base to attach the foldable IFF antenna assembly and can be manipulated by the operator for storage or while carrying.
BCU (C)	The single-use BCU contains a thermal battery. It powers the pre-launch system operation and provides Argon gas to cool the IR detector and the missile seeker. Once the MANPADS is fired, the BCU is removed and discarded.
Missile round (D)	The missile round is secured in a launch tube comprised of glass fiber where it is protected from environmental elements (e.g., humidity, heat, dust). The missile round is comprised of two major components, the missile and the launch tube. The MANPADS launch tube contains the missile round and provides a base for attaching the sight assembly and the IFF antenna.

3.3.3 Employment of the Optical Sight

Successful use of the MANPADS is dependent upon the gunner's effective use of the sight installed on the weapon. Specifically, three tasks must be effectively completed including acquire, identify, and track the target. The top-level design requirements that were most important for optimal sighting using a similar weapon (i.e., Short-Range Assault Weapon [SRAW]) included sight magnification, FOV and reticle pattern. [8]

The gunner is responsible for making time critical and complex judgements related to target engagement. Assessments are based on the criteria listed below.

- Visual information acquired through the magnification provided by the weapon sight (i.e., raw visual data such as aircraft type and aircraft posture);
- Tools used in conjunction with the weapon sight (i.e., range ring measurements to judge aircraft direction); and
- Their own positional data (i.e., vertical and/or horizontal body movements relative to postural stance).

3.3.4 MANPADS Missile

Typically, each team member carries a single weapon round. The supersonic, SAMs fired from the US Stinger MANPADS weapon launcher have a range of 0.2 – 4 kilometers (km) and travel at a maximum speed of Mach 2.2. [2] The MANPADS missile is depicted in Figure 3-4 below. [7] The missiles are comprised of three main sections including a guidance section (A), a warhead section (B) and a propulsion section (C and E). Each of these sections and their associated elements are described in Table 3-3 below. [2][5][6]

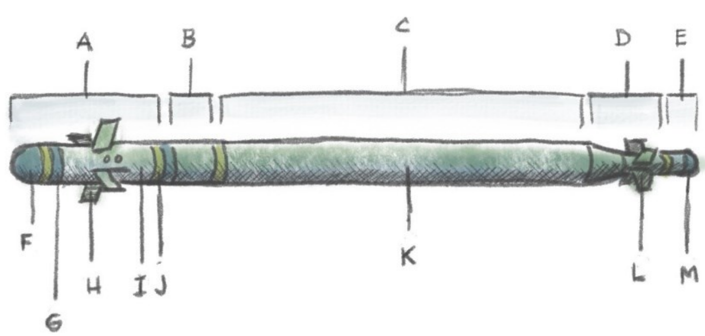

Figure 3-4: MANPADS Missile.

Source: Adapted from Fig 2-1 in [6]

There are three ways in which missiles are packaged (described below) with the main distinctions being the inclusion of gripstock and the method used to house the BCUs. [6]

- Weapon round complete. Contains the missile round, the gripstock and BCUs housed in a reusable aluminum container;
- Weapon round partial. Contains the missile round and BCUs housed in a reusable aluminum container. The gripstock is not included; and
- Missile round. Contains the missile round and BCUs housed in a fiberboard box within a wire-bound wooden container. The gripstock is not included. [5]

Table 3-3: Components of MANPADS Missile

Sections	Description
Guidance section (A)	This section contains three assemblies (described below), a battery (J) and in-flight control surfaces (H). Seeker Assembly (F): The seeker assembly tracks the IR or negative UV radiation source automatically once the gyro is uncaged and during the missile flight. The seeker can discriminate between the small (i.e., jet tailpipe) and large (i.e., clouds, terrain) radiation sources. Guidance Assembly (G): The guidance assembly processes the IR/UV radiation and provides commands to guide the missile during the flight. Control Assembly (I): The control assembly directs the missile flight through the conversion of guidance commands resulting in the movement of the control surfaces.
Warhead section (B)	This section contains a proximity type fuse assembly and high explosives stored in a cylindrical casing. The fuse detonates the warhead via a low-impact switch or a hard target sensor once it is within proximity of the target or penetrates the target. The warhead will be detonated within 15-19 sec via a self-destruct circuit if it does not intercept the target.
Propulsion section (C and E)	This section contains two motors (i.e., launch and flight boost) that enable propulsion, a tail assembly (D) and tailfins for flight control (L). The launch motor (M) ejects the missile from the tube and travels a safe distance of approximately 9 meters (m) before the flight boost motor (K) ignites to provide the thrust needed to quickly reach maximal speed and propel the missile towards the intended target.

3.3.5 Physical Parameters

Physical dimensions, including weight estimates, for the MANPADS weapon launcher and missiles are presented in Table 3-4. [2][5] These unvalidated measurements were based on the documentation included in the review and should be interpreted with caution. The measurements were included in the current review as they may be useful when representing the weapon launcher and missiles within a simulated environment and/or when analyzing lifting requirements during task analyses. Measurements were presented using the imperial and metric systems based on the available information; the study team converted the available measurements to generate a complete set of measurements. Imperial measurements were presented in inches (in), or pounds (lbs) and metric measurements were reported in meters (m), centimeters (cm), millimeters (mm) and kilograms (kg).

Table 3-4: Estimated Physical Parameters

Component	Length	Width	Height	Weight
Missile	57.9 in 1.47 m 147.0 cm	Diameter 69 mm		Missile 22.0 lbs 10.0 kg Warhead 6.0 lbs 2.7 kg
Missile round (i.e., missile round is enclosed in a glass fiber launch tube sealed at both ends and is a separate component from the gripstock and BCU))	59.5 in 151.1 cm	7.25 in 18.4 cm	7.25 in 18.4 cm	If combined with gripstock/BCU 36.1 lbs 16.4 kg
Field Handling Trainer (FHT) used in training (i.e., mock-up or imitation)	59.5 in 151.1 cm	7.25 in 18.4 cm	7.25 in 18.4 cm	If combined with gripstock/BCU 36.1 lbs 16.4 kg
BCU	3.4 in 8.6 cm	3.75 in 9.5 cm	3.75 in 9.5 cm	2.0 lbs 0.9 kg
IFF Programmer/Battery Charger	23.6 in 59.9 cm	13.3 in 33.8 cm	10.7 in 27.2 cm	41.0 lbs 18.6 kg
Shipping/Storage Container	66.0 in 167.6 cm	13.5 in 34.3 cm	18.0 in 45.7 cm	Empty 54.1 lbs 24.5 kg Full 100.0 lbs 45.5 kg
Weapon Rounds	**Boxed Dimensions**			**Weight**
FIM-92D Weapon round complete (including 5 BCUs)	66.0 in 167.6 cm	13.0 in 33.0 cm	13.25 in 33.7 cm	95.0 lbs 43.1 kg
FIM-92D Weapon round partial (including 5 BCUs)	66.0 in 167.6 cm	13.0 in 33.0 cm	13.25 in 33.7 cm	90.0 lbs 40.1 kg
FIM-92D Missile round (including 2 BCUs)	67.25 in 170.8 cm	13.8 in 35.1 cm	11.2 in 28.4 cm	79.0 lbs 35.9 kg

3.3.6 Environmental Conditions

The MANPADS must be capable of operating 'during and after exposure' to a variety of natural and induced environmental conditions. While the environmental conditions for conducting MANPADS operations were not specified in the reviewed literature, this information was available for a similar weapon system (i.e., SRAW). [8] The study team adapted the information to MANPADS operations to be used as guidance (where appropriate) for future research purposes. The relevant natural and induced environmental conditions relevant to MANPADS weapon operations (not human operational conditions) are identified and described in Table 3-5. The data requires validation if specific environmental requirements are needed. Given the technological differences between the current MANPADS and the SRAW systems, the environmental conditions associated with storage, transportation and field handling of MANPADS were not addressed.

Table 3-5: Environmental Conditions Relevant to MANPADS Weapon Operations

Environmental Condition	Capable of Operating During and After Exposure
Natural Environments	
Temperature	-32 degrees Celsius (˚C) to 63˚C
Altitude	Operational when operator is positioned within an altitude range of 0 to 3,657 m
Humidity	In accordance with paragraph 'High Relative Humidity (RH) with High Temperature' in MIL-STD-210. RH refers to the degree of saturation of the air. It is the ratio of the actual vapor pressure of the air to the saturation vapour pressure. The maximum value of 100 percent occurs as follows: • In nature up to 30-32 ˚C right over water surfaces adjacent to coastal deserts; • Quite frequently in tropical areas up to 26 ˚C and approaches 100 percent in tropical jungles; and • In fog and clouds and may also be present before fog is visible.
Sand and Dust	In accordance with paragraph 'Sand and Dust' (sub-paragraph 'Frequency of Occurrence') in the 'Worldwide Surface Environment' section of MIL-STD-210.
Icing and Freezing Rain	Capable of operating while in an environment of freezing rain and once (up to 19 mm) clear glaze ice has been removed via use of antifreeze, salt, alcohol, chipping or warming.
Salt Fog	Capable of operating following a minimum 48-hour exposure to 5 percent salt spray with a temperature of 35˚C.
Solar Radiation	In accordance with paragraph 'Daily Cycle of Temperature and Other Elements Associated with the Worldwide Hottest 1-Percent Temperature Value' Table of MIL-STD-210.
Rain	In accordance with paragraph 'Rainfall Rate' in the 'Worldwide Surface Environment' section of MIL-STD-210 for the '10-year period' and the '1-hour duration'.

Environmental Condition	Capable of Operating During and After Exposure
Natural Environments	
Winds	In accordance with paragraph 'Frequency of Occurrence' (sub-paragraph of the 'Wind Speed') in the 'Worldwide Surface Environment' section of MIL-STD-210 during and after exposure to the '1 percent extreme', 'associated gusts' and '1-minute steady'.
Induced Environments	
Acceleration	Capable of operating during and after exposure to the MANPADS launch and flight acceleration environments and in accordance with the confidence factor identified in MIL-STD-810 Environmental Test Methods Table 513.4-I and Table 513.4 II.
Missile In-Flight Vibration	In accordance with a 50 percent safety factor added and determined during flight tests in the Engineering and Manufacturing Development (EMD) effort.

3.3.7 Hazards

The literature review identified several hazards which can significantly impact the operators' health and safety. These hazards are identified and described in Table 3-6 below.

Table 3-6: Hazards Related to MANPADS Operations

Hazard	Description
Toxic fumes	Upon firing the missile, toxic fumes are released from the missile. The gunner must hold their breath from the time the trigger is pulled and until it is released to avoid inhalation of the toxic fumes. It may also be necessary for the gunner and team leader to move away from their position if an exhaust plume is visible (i.e., the fumes have not dissipated) before recommencing inhalation. [2][6]
Flying glass	Upon firing the missile, glass shatters in the front (IR window) and the back (blowout disk) of the weapon creating a hazard. Eye protection must be worn by the team leader. The gunner must use the clear plastic eye shield on the weapon sight to protect their left eye upon firing. The gunner's right eye is protected due to the firing position. [6]
Noise	Permanent hearing loss will be caused if personnel are exposed to more than two missile firings without wearing hearing protection. Personnel within 125 m (400 feet) should wear hearing protection. [6]
Posture	The MANPADS should only be fired while in a standing position. [6]
Armour	The debris from firing the MANPADS can cause injury. In addition to ear protection, personnel should wear a helmet and a body armour vest. [6]
Weapon position	Debris caused by firing the weapon presents a hazard to the gunner. The MANPADS should be fired at angles no greater than 65 degrees to prevent the missile back blast from injuring the gunner. Similarly, the MANPADS should not be fired if the launch tube is within 30 in of the ground. [6]
Burns	The BCU becomes extremely hot (400 degrees Fahrenheit) 3-5 minutes after being activated. The gunner should only handle the heat-insulated cap when removing the BCU. [6]
High Pressure	Residual argon gas is released under high pressure when the BCU is removed from the weapon by the gunner. The BCU should be removed within three minutes of firing the missile. [5][6]
Protected positions (Enclosures)	Death or injury to the gunner will occur if the weapon is fired from a protected position or from within enclosed position due to the noise, backblast and toxic exhaust that are generated upon firing. The gunner must fire the weapon in an open area which reduces the impact of these hazards. However, this requirement also reduces the weapon's effectiveness in urban terrains due to enclosures and the gunner's survivability since they are more easily located by unfriendly forces. [8]

3.4 MANPADS Training

Three training focal areas identified by the US Department of the Army (as cited in [2]) include system handling, weapon operating procedures and tactical employment. In addition, decision-making and maintaining SA are essential for ensuring effective employment of MANPADS across a range of tactical situations. Rigorous training is needed to acquire and maintain the necessary skills and to operate within a wide range of environments and terrains. Training on the following sub-set of skills is needed to ensure a high level of proficiency: target acquisition, rehearsing firing procedures and building SA of the aerial scenario. [2]

3.4.1 Skills Development

Initially, MANPADS operators are trained within a classroom setting. Subsequently, the operators develop more complex skills through a combination of practical training methods which include live training and simulation center training. For example, the US Stinger operators complete a five-week course to acquire a military occupational specialty (i.e., Additional Skill Identifier; (ASI)) and the basic skills needed to operate the weapon. However, sustainment training and certification on the system is achieved through subsequent and centralized training opportunities from the brigade combat team (BCT) and outside organizations. [5]

Once skills are acquired, a subset of the complex skills must be maintained with a level of high proficiency to enable effective decision-making and responses within extremely short timeframes for single and multi-threat (e.g., airfield under aerial attack) situations. Substantial costs, effort and infrastructure as associated with these practical training methods. [2] A brief description of the practical training methods is provided in the sub-sections below.

3.4.2 Live Training

Live training can include live field exercises and training drills. Live field exercises are intended to provide opportunities to observe and operate the MANPADS within the context of the larger aerial threat. However, these exercises typically occur only once or twice per year, due to the high costs involved, which limits the opportunities for MANPADS operators to develop practical expertise. In fact, operators may not be provided with the opportunity to fire the MANPADS during the live field training which limits their overall experience with the system in a realistic setting. Further, these exercises implement specific, pre-planned (i.e., referred to as ‘canned’) scenarios and may not represent the full-scale aerial threat (e.g., engaging air strikes during an armed conflict) which is needed to develop the operator’s full understanding of how to execute their role within a complex situation. [2]

Practical training can also be achieved through the conduct of live drills and firing procedures using dummy missiles at military airfields. Within this context, MANPADS operators can practice target acquisition and firing procedures using routine military flights and other air traffic as the simulated targets (e.g., time required to complete the task sequence and accuracy of response). In addition, supervisor feedback and timings can be monitored. There are significant limitations of this approach. First, the aircraft profiles (i.e., slow-moving) and manoeuvres are inconsistent with the profiles that would occur in actual situations. Second, there is no means to determine whether the simulated target would fit within the missile hit criteria. Finally, the drills practice does not contribute to the development of more complex skills such as maintaining SA or quick decision-making under time constraints.[2]

3.4.3 Proprietary Simulation-based training

Simulation training systems are more cost-effective than live training and can be used to support learning and train audiences in circumstances that would otherwise be unavailable, too risky or for which there is no safe alternative. In some cases, simulation-based training (e.g., flight simulators used to train emergency procedures, astronautical training) is designated as mandatory. [3] Simulation-based training has been used to acquire or practice a wide range of skills across various domains. When applied to MANPADS, simulation-based training has used to acquire, maintain and improve weapon operation skills. This training must be integrated within the MANPADS overall training program to achieve its greatest benefits. For example, simulation training intended to refresh skills should be implemented when MANPADs operators have already acquired the skills. Further, training should be delivered in accordance with procedures relevant to operational settings and with the frequency needed to reinforce knowledge and skills. [2]

Two types of proprietary simulation training are used to train MANPADS operators including part-task trainers and full-task (and high-fidelity) trainers. A brief description of the types of simulation training and the potential limitations of these systems is provided below.

- Part-task trainers. These trainers are focussed on training or refreshing a specific subset of skills. This approach could support the development and/or maintenance of specific MANPADS operator skills such as target acquisition, firing procedures and building SA of the aerial scenario; and

- Full-task trainers. These trainers are used to develop and maintain more complex skills. [2][3] Operators have few opportunities to train within a full-task or high-fidelity simulated training environment due to their lack of availability, high-costs and the limited number of training facilities which tend to be centrally-located rather than located at the air defence units. Finally, the training sessions are very short (i.e., 15-30 minutes) in comparison to the length of operation (i.e., several hours) and do not provide sufficient opportunity to develop complex skills. [3] As is the case with the live field exercises, scenarios used in the simulated training environment are usually pre-determined (i.e., canned) and there is little flexibility to train for atypical but challenging missions which could negatively impact performance when engaged in real operations. [2] Three examples of MANPADS simulation trainers focus, design and limitations are identified in Table 3-7. Importantly, these trainers are designed to accommodate members of NATO (US) as well as non-NATO countries (e.g., Russia and Israel). The information presented is not intended to be exhaustive and as well, other relevant simulation systems may exist.

Table 3-7: Proprietary Simulation Systems

Proprietary Simulation System Details
Improved Moving Target Simulator (IMTS) by Aegis Technologies Group, Inc.
Focus: • US Stinger training to engage target aircraft Design: • Operators use real Stinger launchers (i.e., dummy versions) to simulate target engagements; • Accommodates simultaneous training for up to three US Stinger teams (i.e., 2 personnel associated with each team); • Fully immersive environment including high-fidelity visual and auditory effects; • 360-degree field of regard (FOR) dome; • Weather effects; and • Terrain. Limitations: • Break in Presence: Reduced realism for missile visual effect and smoke generation upon missile launch due to dome projection which makes the launch effect appear very far away from the launcher that is being held by the operator; and • Displacement of system requires re-calibration.
Konus Igla-Type MANPADS Simulator by Joint Stock Company of Russia
Focus: • Russian MANPADS training engage target aircraft Design: • Comprised of a launcher unit, conical display system and instructor workstation; • Not fully immersive as it provides 192 x 60 degrees FOR via a conical curved screen; • Accommodates one person per session; • System features include target maneuver generation, IR decoys, simulation of weather conditions, terrain features and land platforms; • Instructor is responsible for generating aerial targets and control of environmental effects (e.g., weather, jamming, platform selection); and • Performance evaluation is enabled by system playback and automatic evaluation features. Limitations: • Displacement of the display structure or projectors requires re-calibration.
Breeze MANPADS Simulator by Breeze Simulation of Israel
Focus: • Train MANPADS gunners on various systems that are operating from mobile anti-aircraft battery units Design: • Comprised of a visual display for 3-dimensional (3D) world view, a scenario generator to create targets and tactical situations and a debriefing capability; and • Accommodates one person per session. Limitations: • Non-immersive display comprised of flat screens which provide a limited FOR.

3.4.4 An Alternative Approach to Simulation Training

A feasibility study using Commercial-Off-the-Shelf (COTS) components was performed to address some limitations and training gaps associated with current practical and simulated training. [2] A MANPADS part-task trainer was constructed using COTS-based technology and hardware components. The prototype training system simulated the US Stinger FIM-92 missile system and was comprised of a fully immersive virtual reality (IVR) system equipped with a head-mounted display, a game engine and passive (not active) haptics (i.e., visual, auditory, haptics). Active haptics (i.e., vibration delivered to gunner's cheekbone) could not be met within this prototype. However, a wide range of passive haptics (i.e., US Stinger prop) were enabled to facilitate the operator's 'presence' during the experience including physical interaction with the missile launcher (i.e., weight, vibration) and auditory and visual cues (i.e., triggers and clicks) consistent with the actual operational environment.

The following three critical MANPADS operator tasks, identified by a MANPADS task analysis[2] and consistent with US Department of the Army (as cited in [2]), were targeted by the part-task trainer:

- Target acquisition;
- Tactical decision making; and
- Maintenance of SA in a multi-threat scenario.

The study findings demonstrated that the COTS-based simulation generated the environmental and tactical conditions needed to develop the specific MANPAD skills. Although the study was limited to the use of passive haptics, these findings have several important implications for the current literature review including: [2][3]

- The use of low cost, readily available and easily maintainable COTS-based technology and equipment could improve the accessibility to and operator engagement with MANPADS training for critical tasks providing the specific subset of skills can be adequately represented within the virtual environment;
- Improved access to training supports the development of self-paced learning programs and the reinforcement of specific skills for each operator rather than supporting a generic learning program;
- A non-proprietary system provides greater flexibility for developing specific training scenarios that better reflect the complexity of emergent aerial threats; and
- The impact of training within a simulated environment for longer durations (possibly consistent with typical mission durations) on the MANPADS operator's performance and health could be assessed.

[2] A detailed description of a MANPADS task analysis is presented in [3].

3.4.5 Realism within Simulated MANPADS Environments

Simulation-based training that maintains consistency in the operator's experience between the virtual and operational environments will optimize training outcomes. Technologies that reinforce operator attitudes and opinions are more likely to be understood and ultimately adopted and judged favourably by the target audience. [3] Maintaining consistency within virtual environments is facilitated through the inclusion of elements needed to re-produce critical environmental and tactical conditions. In contrast, elements that are operationally unrealistic or technical issues that reduce realism (e.g., jitter, frame rate) should be eliminated or minimized to reduce the potential for negative transfer of knowledge. [3]

Ensuring consistency supports the cognitive processing of system cues to improve the operators' skills and performance. Further, the researchers' expectations of system performance can be refined which can identify factors beyond the operators' control that can affect performance (e.g., cybersickness) and provide a more realistic experience with respect to mission length (i.e., missions can last for several hours compared to short trials that last only 15-30 minutes). [2] Some types of consistency needed to support the transfer of learning between virtual and operational environments for MANPADS operators and improve performance for critical tasks (e.g., target acquisition and engagement) include:

- Procedures. MANPADS operators should be able to use the same procedures (i.e., steps) to perform the same task in both virtual and operational environments.

- Physical Features. An accurate representation of the physical design of the weapon (e.g., positioning the physical trigger, the gripstock assembly, optical sight and the battery and coolant unit) can support the development of procedural memory skills needed to both quickly and effectively activate the weapon. Also, an accurate launcher weight can influence the operator's posture and balance when positioning the weapon. [3]

- Cues. Auditory, visual and haptic cues indicative of target acquisition need to be properly paired by the operator to optimize the timing for engaging the target. Examples include vibration cues delivered to the operator's cheekbone and the clarity and intensity of auditory cues. [3]

3.5 Test and Evaluation (T&E)

Interactions between the users, tasks and environment are not always considered at the most critical system acquisition phases for COTS and prototypes. [4] The response times for air defence systems have become so short (i.e., less than 10 sec) that it may not be possible for the human operator to respond or react. As such automation has been introduced into the sequence (e.g., IFF to detect unfriendly aircraft) to support the human operator. Some research suggests that basic gunner and squad leader tasks have been poorly designed particularly when automation is introduced into the task sequence (Babbit, 1987 as cited in [22]) thereby limiting their potential performance.

A 'lessons learned' review of land force systems performed in the 1990s that was based on earlier Canadian Forces (CF) acquisitions, concluded that most HFE trials co-occurred with other trials rather than being dedicated evaluations. Rather, human factors should be emphasized at the early stages of system acquisition which includes the requirements definition and concept development activities. [7][8][22] The failure to identify or address design issues at these critical milestones negatively impacts performance reliability, availability, safety and habitability operators' performance. Further, the findings were consistent with a report provided by a Task Force on T&E released by the US Defense Science Board (as cited in [4]) which noted that human factors evaluations should focus on identifying problems early in the T&E process with increased efforts made during the initial design and when modifications and equipment updates are on-going. [4].

The original review was revised in the early 2000s which reinforced the original findings. For the updated review, human factors scientists from DRDC, formerly Defence and Civil Institute of Environmental Medicine (DCIEM), compiled findings from trial data associated with twelve unique land force systems (i.e., 105 mm howitzers, 155 mm howitzers, anti-tank weapons, 120 mm mortars, main battle tank, Field Artillery Ammunition Supply Vehicle (FAASV)) since human factors assessments are frequently performed during field trials. The purpose of the review was to identify common problem areas which, the authors concluded, were the result of insufficient attention having been allocated to human factors issues during the design phase. The findings were consistent with observations reported by the US Task Force on T&E (as cited in [4]). The implication of this conclusion is that operators were not considered during the design process despite being the target audience for using the weapon systems.

The review did not include trial evaluation data related to MANPADS however, given the consistency in findings observed across the various land force systems it seems reasonable to assume that some of these limitations could also apply to MANPADS systems. For this reason, the five areas of concern identified by the review were considered relevant to the current study and the key points that are most relevant to the conduct of MANPADS design and personnel training were identified in Table 3-8 below. [4]

Table 3-8: Common Human Factors Problem Areas Relevant to MANPADS

Human Factors Topic	Key Points
Inconsistent performance	Human performance, as measured by learning curves for trained and untrained operators, was inconsistent across system trials due to the inadequate time allocated to operator training and the lack of established, repeatable and routinely implemented Standard Operating Procedures (SOPs). Performance improved once SOPs were established and understood by operators. Selection of trial participants was based on availability or experience and did not necessarily represent the target audience. Training packages from the weapon supplier were not used during the assessments and therefore, the adequacy of the training that would be delivered with the system could not be assessed.
Workspace	Consistency with human factors standards (i.e., range of body sizes, impact of environmental conditions). Poor design negatively impacts the ease of access to controls and displays and the completion of fine motor tasks while wearing cold weather environmental clothing (i.e., gloves, outerwear).
Control and display configurations	The sights (i.e., the primary displays on the weapons) are incompatible with other equipment worn by personnel (i.e., helmets, glasses and environmental clothing) which can interfere with the operational activity. Ineffective design (i.e., control location, non-intuitive movement of controls) negatively impacts reliability (e.g., random failures of components, human errors).
Workload	Manual Materials Handling (MMH) resulting in high physical workload and weapon handling had a negative impact on system effectiveness. Operators were placed at a significant risk of injury (particularly lower back injuries). Subjective reports did not identify negative impacts of physical stress (e.g., awkward postures when lifting) until prolonged trials were on-going indicating that objective performance measures should also be applied to assess physical workload. Alterations to training programs will not offset the impact of MMH and changes to crew models or engineering solutions to reduce lifting requirements would address overexertion of operators. Mental workload was not identified as a problem in the review.
Noise	High noise levels resulting from weapon firing was identified as a serious health hazard due to the potential for temporary and/or permanent hearing loss. The risk was compounded by the failure to use and/or improper use of hearing protection. Noise masks important information delivered by speech and warning signals which presents a safety issue for the MANPADS team (i.e., team leader and gunner) which can be addressed by taking protective measures (e.g., limit number of exposures per day, develop a safety plan).

3.5.1 Automated Missiles

As indicated previously in Section 3.1, once fired, the MANPADS missile is autonomous and cannot be controlled by the gunner. [2] The MANPADS team is responsible for making critical decisions which will have negative impacts if the wrong decisions are made (i.e., fratricide). Such decisions are largely based on the output from the automated IFF system. For example, the team leader’s decision to engage the threat and the gunner’s assessment that the target can be hit are critically important since the impact of these actions cannot be undone. The interface between the operator and the system must support the human operator’s decision making and provide information in a readily useable format.

3.6 Biomechanical Factors

This literature will be focused on the biomechanical factors related to shoulder-launched weapons. This includes load carriage effects, impulse noise, weapon weight and lengths and recoil effects of weapon firing.

3.6.1 Weapon Recoil

Shoulder-fired weapons are used to fire weapons with large payloads. When a weapon is fired, the reactive force directed backward into the shooter’s shoulder is referred to as ‘recoil’. There are three components to recoil, referred to as a ‘kick’, including Recoil Impulse (RI) measured in pounds per second (lbs/sec), Recoil Energy (RE) measured in foot-pounds (ft-lbs) and Recoil Velocity (RV) measured in feet per second (ft/sec). Variables that determine the RE include weapon weight, propellant weight, round weight and muzzle velocity. [16]

Blankenship [15] referred to a Test Operations Procedures (TOP) 3-2-504 which identifies limitations associated with the daily number of rounds that can be fired by a soldier based on the RE (Table 3-9). The origin of these limitations and the method for determining tolerable RE levels remains unclear [14][15] and opinions differ according to which component(s) should be used to determine the recoil effects and establish standards. The Human Engineering Laboratory at Aberdeen Proving Ground has indicated that RI is most important and should be limited to 3.0 lbs-sec.

However, Burns has argued that the TOP 3-2-504 incorporates rough approximations of cartridge impulse and excludes mitigating factors. Further, Burns noted that the TOP 3-2-504 is designed for use in a testing environment rather than for use in combat. There is a need to define limitations, based on experimental design approaches, for specialized weapons that require specialized training, different firing positions and consideration of anthropometry. [14]

Table 3-9: Daily Firing Limits based on Recoil Energy

Recoil Energy	Firing Limitations
Less than 15 ft-lbs	Unlimited firing is permitted
15 to 30 ft-lbs	200 rounds per day per gunner
30 to 45 ft-lbs	100 rounds per day per gunner
45 to 60 ft-lbs	25 rounds per day per gunner
Exceed 60 ft-lbs	No shoulder firing is permitted

3.6.1.1 *Shooter Position*

The shooter’s body acts as a mechanical filter by reducing the peak force and spreading the impulse across a longer time period. [14] Parameters affecting the peak forces at the shooter’s shoulder include shoulder spring stiffness, shoulder damping coefficient, weapon impulse, effective mass of the weapon and effective mass of the shooter’s arms and hands. [15] Further, the gross reaction of the shooter’s body to the recoil impulse depends on their mass, or more specifically, the mass of the moving body part such that the recoil is experienced differently from one individual to another (i.e., heavier individuals may experience less recoil). [14] Compared to the displacement observed when firing from a prone position, the upper body can displace a lot of the recoil effect due to the rotation that occurs relative to the lower body. However, the shooter’s anticipation of the recoil and the preparation for the impact (i.e., to minimize the peak force and reduce the gross motion of the body) can cause them to flinch having a negative impact on accuracy. [14]

3.6.1.2 *Recoil Injury*

Several physical impacts from firing shoulder-fired weapons have been noted (e.g., tissue damage including contusions and lacerations, pain, soreness and stiffness, abnormal electromyographic (EMG) results at rest and a maximal effort). [14][15] Peripheral nerve injuries such as nerve palsy have been related to shoulder-fired weapons. Radial nerve palsy, however, may be related to the shooter’s position (or posture) rather than the recoil energies. These physical impacts may vary across shooters based on body dimensions. There is a latency of 150-200 milliseconds (ms) between firing the weapon and the shooter's passive physical response due to the neuromuscular system response. [15] Evidence suggests that the shooter’s anticipation of the impact is associated with preparations for the recoil (e.g., decreasing their handgrip force on the weapon and flinching) which can negatively impact performance. Further, shooters’ subjective ratings of recoil are positively correlated with recoil impulse and peak force. [15]

In the absence of a better alternative, Blankenship applied the limits identified by the TOP 3-2-504 to investigate the rate of injury amongst standing, unsupported soldiers firing 15 shots using a shoulder- fired weapon with the recoil energy at or just below 60 ft-lbs in accordance with TOP 3-2-504. Several human factors measurements were gathered by researchers to assess the physical injuries caused by weapon recoil. Detailed findings that were most relevant to the current literature review are identified and described in Table 3-10 below along with their associated findings. The following five recommendations were generated from this study:

- The TOP 3-2-504 standard of firing 25 rounds per day may be too high especially for a wide range or recoil energy of 45-60 ft-lbs without a recoil mitigating device or shoulder protection;

- Repeated exposure to high recoil energy levels should be investigated. For the present purpose, exposure while in a standing, unsupported position is the only relevant body posture for MANPADS weapon;

- Measurements of height, weight and handgrip strength should be conducted to validate their value for predicting recoil injuries. The results of the validation could contribute to personnel selection criteria and the use of protective measures;

- The use of magnetic resonance imagery (MRI) and algometry should be employed to record the presence of recoil injuries; and

- Modifications of existing weaponry should consider the human factors implications to avoid additional injuries (i.e., facial injuries due to the charging handle).

Table 3-10: Physical Injuries Caused by Weapon Recoil

Human Factors Measurement and Description	Relevant Finding
Pain Intensity. Ratings reflecting pain intensity in the shoulder area were gathered using the 11-point Numerical Pain Rating Scale (NPRS) while at rest, during tests (i.e., range of motion, strength and functional) and between shots when firing a shoulder-fired weapon.	The subjective findings revealed pain intensity ratings and reported recoil ratings increased significantly (i.e., shots 4 through 15 and shots 7 through 15, respectively) across the number of shots fired. This finding indicates the recoil had a cumulative effect on pain. Having fired 15 shots, which accounted for 60% of the permissible rounds for a single day, only 60% of participants reported they would be able to fire an additional 10 rounds to meet the total number of 25 rounds that would be permitted by TOP 3-2- 504.
Pressure pain thresholds. A digital algometer recorded pressure pain thresholds in the following four regions: mid-anterior upper arm (MUA), mid-anterior shoulder/deltoid muscle (MAS), mid-deltopectoral line (MDP) and the mid-chest/pectoral muscle (MC). Participants indicated when they first experienced painful pressure.	Pressure pain threshold measurements were a valuable tool for assessing shoulder injury. The subjective findings revealed pressure pain thresholds were significantly lower for all four regions tested immediately following firing and for 72 hours post-firing (except for the MAS region). Pain reports were directly related to vertical aiming errors. Pain intensity reports for participants' shoulder abduction range of motion were observed immediately following firing the weapon.
Bruising. Size of bruises was categorized by the study team as small (less than 4 centimeters squared (cm^2)), medium (greater than 4 cm^2 and less than 25 cm^2) or large (greater than 25 cm^2).	Large multi-colour contusions (i.e., bruising patterns) were observed on all participants immediately following firing over the anterior shoulder (i.e., lateral pectoralis to the anterior deltoid).
MRI. MRI images of the shoulder and extremity were obtained using a mobile MRI unit.	MRI analysis was the most valuable tool for assessing the presence and impact of firing a high-energy recoil weapon. Evidence of injury was observed for most participants (93%) for the anterior deltoid muscle (shoulder), proximal biceps (arm) brachii muscle and pectoralis major muscle (chest) during the immediate post-firing period. Approximately 63% of participants experienced moderate contusions and 20% acquired small lacerations to their facial area during firing. The smaller areas of inflammation suggested the bruising was most likely superficial rather than deep tissue. Subjective reports suggested the injury peaked 24 hours post-firing for most participants. Lack of injury at any point was associated with only one participant.
Range of Motion. A goniometer measured active ranges of motion and the mean score of three trials was gathered for shoulder flexion, shoulder abduction and external shoulder rotation.	Active range of motion for shoulder abduction was significantly reduced in the period immediately post-firing. This finding corresponded to higher pain intensity NPRS ratings in the same post-firing timeframe.

Human Factors Measurement and Description	Relevant Finding
Shoulder isometrics strength. A hand- held dynamometer measured isometric shoulder strength for shoulder abduction, shoulder flexion and shoulder external rotation.	Isometric strength for shoulder flexion in the 48-hour period post-firing increased compared to the immediate post-firing period. Right- and left-handgrip increased across the trials. Higher pain intensity NPRS ratings were observed for shoulder abduction in the period immediately post-firing period compared to pre-firing baseline ratings.
Thermography. Infrared imaging of the anterior region of both shoulders was conducted. Mean scores of ten trials were gathered daily at the following intervals: pre-firing, approximately 90-minutes post-firing and every 24 hours throughout the study.	Temperature of the skin tissue was higher (1.24 ˚C) after firing for the firing shoulder compared to the non-firing shoulder. The differences were resolved by the 24 hours post-firing period and may have been related to skin irritation causing chaffing from the participants' uniform from firing. This position was supported by observations of petechiae and vertical red striae which were observed immediately following firing.
Anthropometry. A stadiometer measured height, and a digital scale was used to measure weight of participants in battle-dress uniform and boots. Other measures were obtained including functional reach, arm length, shoulder-elbow length and shoulder breadth.	Classification of injury. Participants having a height and weight (less than or equal to) 172.72 cm and 79.54 kg, respectively were more likely associated with increased signal intensity at the injury site imaged by the MRI. The probability of correctly classifying injury based on signal intensity changes were 86% (height) and 82% (weight). Sensitivity to correctly predict severe contusion. The severity of the contusions was better predicted by weight and handgrip strength (both 100%) compared to height (67%). Overall, dominant handgrip strength test administered before firing was the single best test for screening participants for predicting muscle contusions via correct classification and sensitivity. This conclusion must be treated with caution given the small sample size.
Body position. Participants tended to rest their cheek against the charging handle while aiming. This position is inconsistent with standard instructions	When firing high recoil energy weapons, the shooter can be struck in the face buy the charging handle and/or rear sight apparatus. Changes to firing techniques better weapon specific may be needed such as accommodating the short length of the weapon and head position.

3.6.2 Recoil Mitigation

A study by Saul and Jaffe (as cited in [15]) reported consistent performance for recoil energies with a range of 11 – 19.3 ft-lbs but increases beyond this level of recoil energy were associated with significant performance decreases. Further, volunteers were more likely to terminate their involvement in a firing task which required 160 rounds per day on three consecutive days using weapons with 25.5 ft-lbs recoil energy.

Recoil reductions enabled by a mitigating device did not increase the probability of hitting a target even though shooters reported a reduced physical impact. Further, the use of the device did not lessen the shooters' reluctance to fire a weapon. A different study (Harper et al. as cited in [15]) reported volunteers fired significantly more shots when a recoil-mitigating device was used compared to when a device was not used for weapons with 34 ft-lb (47.7 versus 7.4 shots, respectively) and 43-ft-lb (38.8 versus 6.73 shots) recoil energies due to shoulder pain. Bruising was observed on participants regardless of whether recoil-mitigating devices were used. Saul and Jaffe (as cited in [15]) reported higher rates of bruising for groups firing weapons with higher recoil (19.3 ft-lbs and 25.5 ft-lbs) compared to lower recoil (11 ft-lbs and 14.9 ft-lbs) even when the protective vest had been donned. In contrast, another study (Ortega, Hickey & Harper as cited in [15]) in which the shooters used a vest for shoulder protection reported positive impacts on aiming and accuracy over 3 consecutive days firing weapons with high recoil energies.

A dynamic analysis was performed as part of the Parametric Recoil Analysis Program to assess recoil mitigating technologies employed on shoulder fired grenade launchers/weapons. [16] The goal of the assessment was to generate a computer model to identify the characteristics of an 'ideal damper' based on known ammunition parameters and weapon configuration. A spring/damper element, referred to as a buffer, is applied to smooth the impulse resulting from firing the weapon. [14] Several critical parameters were identified including weapon weight, recoil impulse, recoil velocity and recoil energy. The generated computer models defined the major components (e.g., mass) and the kinematic joints, represented by the relative connectivity, between these components. Recoil reducing systems from two manufacturers (i.e., Ace shock absorber, Taylor shock absorber) along with the absence of a shock absorber were evaluated to assess the impact on the weapon and the soldier firing it.

Initially, the models were based on the 40 mm M203 grenade launcher system, but subsequent work was performed at the Armaments Research Laboratory (ARL) Weapons Branch at Aberdeen Proving Grounds using a 12-gauge Remington weapon installed in a firing fixture. The fixture incorporated shock absorbers and recoil pads and the motion of the gunner's shoulder was represented by a sliding mass. The results generated from using the computer models were compared to the results gathered from the firing fixture. The mass distributed across the simulated weapon and the connectivity points (represented by spring and damper pairs) that were modelled during the analyses are depicted in Figure 3-5 and described in Table 3-11.

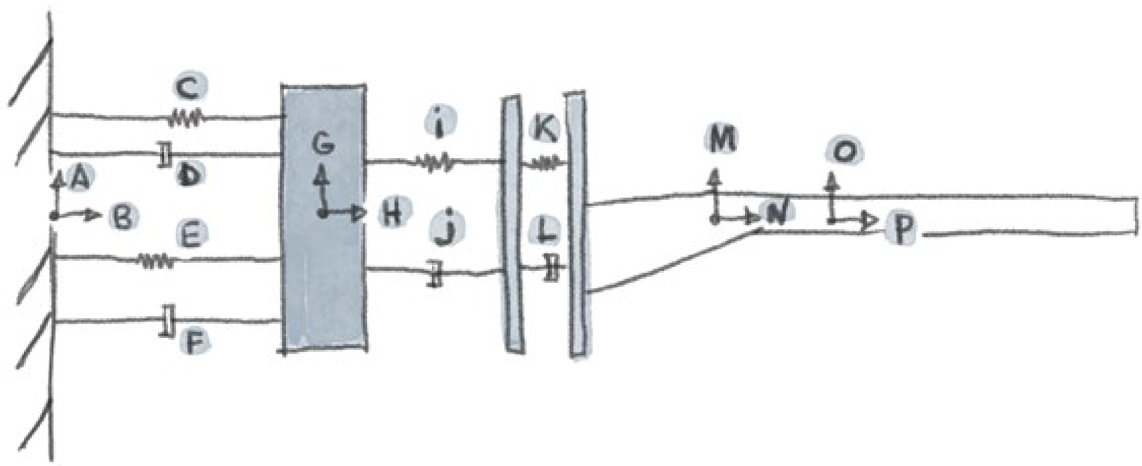

Figure 3-5: Schematic of Simulated Recoil Fixture.

Source: Adapted from Fig 3 from [16].

Table 3-11: Mass and Connectivity associated with Recoil Model

Component	Description
Mass	
Mass 1 B, A	Inertial Reference Frame – all global measurements are determined by this point.
Mass 2 H, G	Mass center of the shoulder (Early ARL test fixture weighed 32 pounds and the later ARL test fixture weighted 11-12 pounds))
Mass 3 N, M	Mass center of the rifle
Mass 4 P, O	Mass center of the projectile
Connectivity	
C, D and E, F	Spring and damper pairs (C, D and E, F) between Mass 1 and Mass 2 represent two springs (Ck_1=E=149 pounds per inch) with operating height and free length equal to 4.4 inches
I, J	Spring and damper pairs between Mass 2 and Mass 3 represents a recoil dissipating device (e.g., shock absorber where I is a constant value and J is a variable with velocity) secondary dissipative device for example a pad with values used for K and L
K, L	Spring and damper pairs between Mass 3 and Mass 4 represents a secondary dissipative device (e.g., a pad with measured values used for K and L)

Three rounds of ammunition were tested including a target mode, a rifled slug load and a heavy magnum load. The pressure-time curves for each round were treated as system drivers. The curves were applied to the projectile for forward motion and in contrast, were applied to the rifle in the rearward direction. The model can be used to study dynamic motion by changing specific parameters such as spring damper rates for future design or redesign.

The comparison between the models revealed a good match with displacement and velocity and, generally for peak accelerations. Further investigation revealed that changing the damping rates related to the shock absorbers when using the Ace shock absorber had a significant impact on motion. Taken together, these findings provide a foundation for further analysis. Three potential limitations were noted by the authors. First, the pressure-time curve associated with the 11-12 pound shoulder mass model was based on the magnum round whereas, the round used at ARL was a Duplex round. Second, some inaccuracies between the simulation data and the test data could have been attributable to errors in the manufacturer's damping data. Third, incorrect code may have been incorporated within the model.

3.6.3 Impulse Noise

Impulse noise is defined by the National Institute for Occupational Safety and Health (NIOSH) as an instantaneous change in sound pressure within a short period. Impulse noise associated with weapon firing, including MANPADS, is extremely hazardous to exposed personnel and exposure in these circumstances (i.e., short-duration, high-intensity noise) is governed by Military Standard 1474. [12] Noise associated with MANPADS and firing limitations were identified as a hazard in Section 3.3.7.

No direct evidence was found in the current documentation set which indicated that firing a weapon could impact negatively on air-filled organs. However, other research has demonstrated that impact noise caused by a blast could potentially cause tissue damage. Air-containing organs or nearby organs stressed by air-containing organs, are affected by blast overpressure leading to a range of effects such as rapid collapse of the tissue and death. These injuries are referred to as 'non-auditory'. Research investigating the impact of blast overpressure on lungs has indicated these organs may not be affected by gross compression. In contrast, local compression has identified a relationship between local compression and negative impacts on lung tissue (i.e., tissue damage and edema). (Yen, 1998 as cited in [12]). The local compression is due to the piston- like motion that occurs in the chest wall which reverberates into the lung tissue creating pressure waves that are much more powerful than those resulting from gross compression. Research has found that wave pressure is directly related to chest wall velocity (Yu et al., 1990 as cited in [12]).

A mathematical model, Pleural Surface Model (PSM) correlates lung injury across a range of blast conditions based on chest wall motion caused by distributed forces and inertia however, the findings are not applicable to local impacts. Consequently, a finite element model (FEM) was generated using both a Finite Element Analysis (FEA) and a thoracic motion model from the automotive industry (Lobdell, 1972 as cited in [12]). The proposed model represents the chest wall response to blast loading for large impactor tests and small projectile and blast loading and provided the foundation for developing a new exposure standard for impulse noise. [12]

Other research was aimed at understanding the impact of impulse noise on the operator as well as personnel located at a distance from the firing site. [13] A study investigated the impact of noise exposure soldiers at located in operator and control positions during military field exercises. In contrast to the operator positions which are located near the weapons, control positions (e.g., artillery observers, paramedics and observation tower observers,) are located away from the firing site. Impulse noise from a range of weapon types was investigated in this study in four physical areas. One of the areas (Area #2) included noise impulse measurements from a shoulder-launched anti-tank rocket-propelled grenade launcher (RPG) gathered from control positions located approximately 45 meters (m), 65 m or 70 m, respectively, from the noise source. Noise parameters were measured and evaluated using commercial devices.

No noise impulse measurements from the crew (i.e., operators) located at the noise source were reported for firing the RPG. Also, the RPG measurements gathered from personnel positioned at control positions were combined with other measurements from two other weapon systems (i.e., BWP-1 gun and PPK MALUTKA) rather than being presented separately. Therefore, the findings are not specific to the shoulder-launched RPG weapon. The finding relevant to impulse noise associated with firing the RPG and other two weapons showed that personnel located in both operator and control positions were exposed to high levels of impulse noise. Personnel located at control positions were recorded greater than 140 and 95 decibels (dB) which exceeded the Polish occupational noise protection standards. [13] A recommendation to implement hearing protection that is equipped with electronic systems that can support verbal communications through improvements to speech sound transmission was provided.

3.6.4 Weight and Length

Weapon design must balance the capability it delivers with its weight and size, particularly for weapons carried by infantry such as MANPADS. Some of the considerations that must be made include, who will carry the weapon, how far and for how long will it be carried, what type of terrain and climate, what tasks must be completed with it. These factors, as they relate to MANPADS, are addressed in Section 3.3.

A study investigated the preferred weight and length of weapons that infantry would carry into combat. [10] Human performance was assessed for mock-up weapons of varying lengths (25 – 43 in) and weights (8 – 24 lbs) carried across three simulated combat conditions (i.e., a 4,000-foot cross-country march, a 3,700-foot road march and an obstacle course comprised of 23 pairs of obstacles). The control condition was comprised of a M72 Light Antitank Weapon (LAW). Qualitative feedback revealed that four sets of bipolar adjectives were useful in describing the soldiers' experiences with the weapons (i.e., ease of carry, comfortable, produces soreness and manageable). The results most relevant to the current literature review showed that soldiers carrying load combinations more than 31 in (i.e., length) and 8 lbs (i.e., weight) were unable to keep pace with the slowest member the squad. Soldiers reported that systems beyond this length and weight were uncomfortable. Compared to the LAW, the eight-pound mock-ups that were 25 and 30 in length were not preferred but were not yet rated as uncomfortable. The eight-pound systems were easy to carry but heavier systems were generally harder to carry. Finally, the data suggest another factor, referred to as reluctance-to-carry factor, may reflect the trade-offs made by soldiers when the weapon transitions beyond 31 inches in length and 10 lbs in weight. These findings provide important considerations that should be made for weapon design. [10]

3.6.5 Heavy Loads

Soldiers manage heavy loads as part of their physical requirements. Several factors have been associated with the impact of load carriage including age, anthropometry, strength, training, body composition, gender, placement and dimensions of load, biomechanical factors, climate, terrain and gradient. [11] These factors are relevant to shoulder-fired MANPADS given their weight while carrying and during launch (see Section 3.3.5) as well as the wide range of environmental conditions in which they are employed (see Section 3.3.6).

A study investigated the impact of increasing load carriage in military load carriage systems (LCS) on soldier's gait and posture for short durations. Four conditions which incremented weight from 8, 16, 40 and 50 kg were included in this study. The final (heaviest) condition included carrying a LAW which weighed 10 kg. A 3D commercial motion analysis system was used to evaluate the sagittal plane of male soldiers. Angles were measured at ankle, knee, femur, trunk and craniovertebral locations and spatiotemporal parameters (i.e., stride length) were gathered during a 5 m self-paced walking task. [11]

Despite the short duration, the results indicated that increased load carriage led to increases in the range of motion for knees and femur. Also, the trunk and the head flexed further forward indicating that these two body regions work together to counterbalance the load. These adaptations require enhanced muscular support and risk the potential for injury. Longer durations would be needed to understand the potential impacts of fatigue and physiological optimization. [11]

3.7 Target Tracking

This section is focused on human factor issues related to target tracking including effects of weapon design on tracking and the effect of human fatigue and anxiety on target tracking. Soldiers are subjected to a range of stressors in a military environment including exercise-induced fatigue and anxiety caused by threats and hostility.

3.7.1 Weapon Design

The literature review identified weapon design features that can impact negatively on aiming of a rifle-launched rocket projectile. [18] These features are identified and described in Table 3-12.

Table 3-12: Weapon Design Features

Features	Description
Weighted front end	Weight added to the front of a lightweight infantry weapon system (i.e., rifle-launched rocket projectile) can increase aiming error.
Recoil	Recoil occurs in the 0.3 sec period between pulling the trigger and prior to the launch of the rocket. If the ignition sequence is initiated by a ball rifle round, then the recoiling can be expected to impact negatively on the gunner's aim. Normal rifle wandering would be expected if the ignition is started by a blank or potentially another recoilless system. During recoil the turbine exhaust causes torque about the spin axis and a lateral displacement of the muzzle. Window-sized targets (4-foot square white panels with 12-in wide by 6-in high black insets) with an approximate range of 200m are not (severely) limited in performance by aiming or cant errors providing the rocket initiation is recoil-free such as firing a blank round.
Orientation	The orientation of the rifle-launched rocket projectile is more cant-sensitive compared to a conventional ballistic system.
Gas/Exhaust	Once the rocket is launched, the exhaust moves downward and towards the backend of the weapon. There may be debris from the motor and the ground that is blown backwards with the potential to cause discomfort for the gunner. In this case, the gunner may anticipate this impact causing an anticipatory flinch which could impact negatively on aiming.
Sighting system	Launching a rocket from rifle requires either a separate sighting system or the launcher needs to be reliably aligned to the rifle-equipped sight.
Gunner position	Launching a rocket from a prone-supported position is associated with aiming errors of approximately 2 milliradians whereas aiming errors associated with an unsupported prone position were .5 milliradians. The study did not include firing from an unsupported standing position which is relevant to MANPADS. [6]

3.7.2 Exercise Induced Fatigue

Shooting while standing is one of the most frequently held firing positions (in addition to a kneeling position) and requires upper body strength and endurance. Exercise intensity has small effects on shooting accuracy when in a prone position. In contrast, shooting accuracy is significantly impacted when shooters are in a standing position. [19] Cognitive and perceptual-motor performance are impacted by exercise-induced fatigue. The relationship between physiological arousal and performance is described by Yerkes and Dodson as an inverted U-shaped function whereby optimal performance is observed at moderate arousal levels. Thus, performance is negatively impacted by arousal levels that are too high or low. Further, the level of mental effort applied to a task can impact performance levels. In this case, optimal performance is observed when arousal levels are low and moderate because mental effort can compensate for decreases in performance whereas, high arousal levels are not effectively influenced by mental effort. The arousal and mental effort required for optimal performance are task specific. [17]

3.7.2.1 *Whole Body Fatigue*

Body fatigue due to whole body endurance tasks (e.g., load carriage while marching, litter carry manoeuvres which combined whole body exercise with lifting tasks that rely upon elbow flexors, combined exposure to altitude and exercise, bicycle ergometry) has been shown to have a negative impact on targeting (i.e., marksmanship). [19]

3.7.2.2 *Localized Upper Extremity Fatigue*

Shoulder-fired weapons must be secured against the shoulder by isometric contractions of the elbow flexors. These contractions reduce the elbow angle allowing the gunner to pull the weapon against their shoulder. Fatiguing of the upper extremity muscles negatively impacts stability leading to reduced shooting accuracy. The effects of induced, localized upper extremity fatigue on shooting accuracy were assessed following the completion of two exercise activities. Participants used a model 7-57A Weaponeer rifle which is commonly used during training and simulates realistic recoil and wore a standard battle dress uniform including a Kevlar helmet. Weapon training was performed prior to the testing period until participants achieved a plateau in shooting accuracy. [19]

Measurements included the number of hits, misses, late fires and shot group size (i.e., the number of shots within a defined area). Reduced shooting accuracy was observed following both types of exercise which fatigued elbow flexion. However, pre-exercise accuracy levels rebounded within five minutes for the number of hits and shot group size and within ten minutes for the number of misses. These findings support earlier research suggesting that shooting accuracy is susceptible to exercise that is performed to the point of fatigue. However, this study also demonstrated that upper extremity fatigue due to lifting, climbing and pulling activities recovered quickly in soldiers who self-reported as physically fit. Thus, fit soldiers require only a very short rest period between firing sessions. [19]

The potential for two contributing factors (i.e., postural sway and heart rate) having a negative impact on shooting accuracy was identified however, additional research is needed to assess the impact of these factors. Similarly, strength and endurance training for upper body flexor muscle groups was recommended as a means of minimizing the negative impacts of localized muscle fatigue on shooting accuracy however, more research is needed to determine how resistance training could have a positive impact performance on combat-related tasks including firing. [19]

3.7.3 Anxiety and Fatigue

Soldiers are confronted with difficult and threatening situations in a military environment that cause anxiety. Experiencing anxiety during task completion is related to decrements in basic cognitive (e.g., memory, math skills), complex cognitive (i.e., decision-making, vigilance) and aiming skills and has been attributed to attentional shifts. In these situations, attention shifts away from information needed to complete a task (i.e., task relevant) and towards irrelevant information (i.e., task irrelevant) which results in decreased solider performance. [17]

Research conducted in other high achievement domains (i.e., policing, sports) demonstrated that attentional changes related to anxiety were associated with decreased perceptual-motor performance such as reduced shooting accuracy. The study findings reported in [17] attributed shooting performance decrements to the anxiety caused by the threat of being hit by simulated fire (i.e., painful coloured soap cartridges). As reported in Section 3.7.1, some aiming errors were attributed to an anticipatory flinch due to the discomfort caused by the blow back of exhaust at the rear of the weapon. [18]

A study manipulating both anxiety and exercise-induced fatigue on performance. Anxiety was associated with decreased shooting performance, particularly in high-anxiety conditions, even with infantry soldiers who had acquired three years of shooting experience. Similarly, high anxiety was associated with reduced performance for basic cognitive (i.e., math) skills although participants still performed with a high level of accuracy (i.e., 79 percent correct answers). More complex cognitive tasks (i.e., decision making) were also impacted negatively by anxiety as soldiers experiencing high anxiety appeared to be more likely to shoot surrendering opponents compared to those experiencing low anxiety however these effects were not statistically reliable possibly due to small sample size since the effect size was demonstrably large. It was recommended that training for shooting behaviours be conducted under anxiety provoking conditions.

In contrast, the impact of exercise-induced fatigue on performance was task-dependent and the authors concluded that elevated arousal could prevent decreases in shooting accuracy. When fatigued, participants tended to decide not to shoot even though they should have. This finding is opposite to the impact of anxiety on shooting where the participants tended to shoot when experiencing high anxiety. As well, cognitive performance (i.e., math) appeared to be negatively impacted when participants were fatigued however, these findings were not statistically significant. Finally, shooting performance was maintained by fatigued participants whereas the rested participants exhibited a significant decrease in accuracy (40 percent) thereby supporting the arousal theory. [17]

3.8 Performance Models

Human performance models can be used to predict and design human operator tasks in complex system. [11] Generally, these models must be based on three criteria including:

- Proposed system and alternatives must describe all critical system tasks;
- The system and the functions must be adequately represented by the computer model (e.g., acceptable accuracy levels needed for predictions vary according to the intent of the model); and
- Estimates of system and sub-system data must be available through data distributions, empirically gathered studies or through estimations.

While several models exist the study team included three performance models in the present literature review due to their relevance to MANPADS. Some of the weapons included in the modelling analyses are no longer in operation.

3.8.1 Optimal Control Model

The computerized Optical Control Model (OCM) of human response was developed to model human tracking error. The OCM generates sample time histories (i.e., trajectories) for error tracking that were compared to field trial data gathered for three anti-tank systems used by the US Army. Two of the anti-tank systems (i.e., the Tube-Launched

Optically Guided System (TOW), depicted in Figure 3-6 and Figure 3-7, respectively, and the shoulder-mounted DRAGON system), depicted in Figure 3-8, are command line-of-sight systems whereas, the third system, (i.e., Improved TOW Vehicle (ITV)) is a rate command system. [20] These weapon systems were mobile but not quickly or easily portable by operators as in the case of the MANPADS.

Figure 3-6: Depiction of a TOW.
Source: Adapted from [21]

Figure 3-7: Depiction of a DRAGON
Source: Adapted from [22]

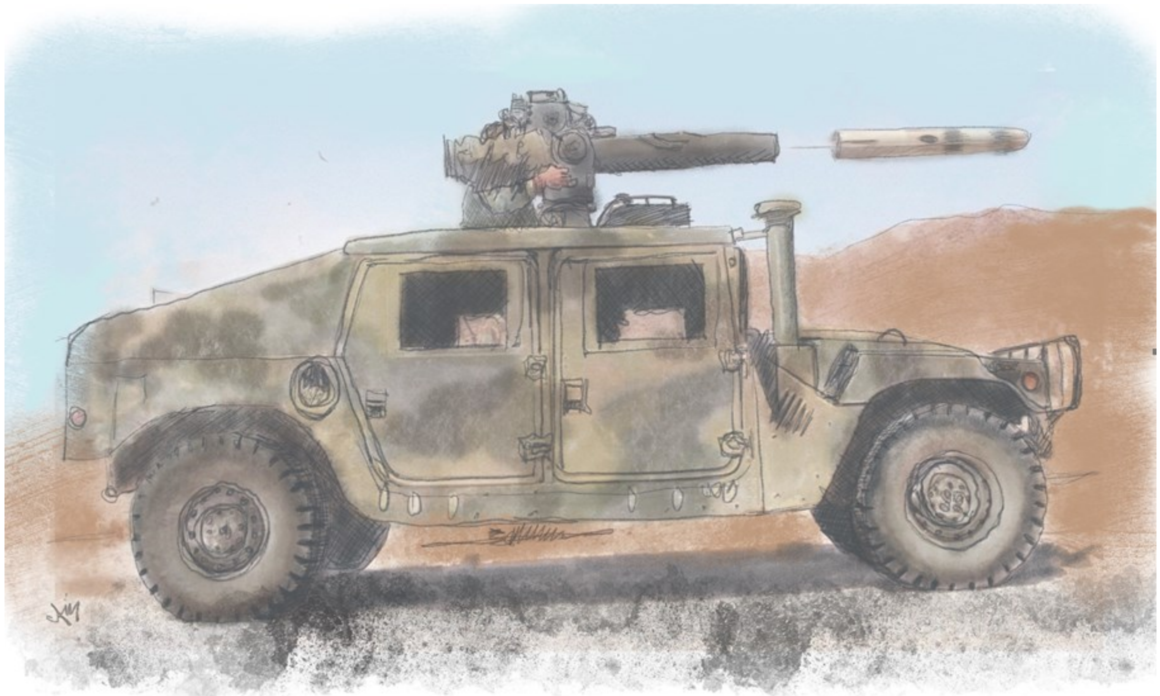

Figure 3-8: Depiction of an ITV

Source: Adapted from [23]

The OCM specifies represents the system-display-manipulator dynamics using three components (and sub-components) to obtain the operator's feedback strategy and generate closed-loop performance results. The three components are briefly described below.

- Task objectives. This component models the operator's strategy, style or technique and could be related to the type of training that is delivered for a particular system. Operators attempt to maintain a small error rate when performing a basic tracking task however, a weighting is used to reflect subjective input on error rate;

- Human operator limitations. This component models the operator's limitations related to the perception of displayed quantities and the execution of intended control motions; and

- Target sub model. This component models the target motion (i.e., velocity, acceleration) and were held constant for the comparison of the three anti-tank systems (i.e., TOW, DRAGON, Improved TOW Vehicle).

The findings indicate that the OCM can be used to accurately model target tracking error using all three anti-tank systems under the conditions listed below.

- Target motion including straight line motion (i.e., crossing targets moving from/to right to left and vice versa) and manoeuvring (i.e., serpentine);
- Targets moving towards the gunner;
- Targets travelling at various speeds;

- Gunner manipulation of the systems; and
- Various gunner postures.

Human factors issues that exist between the operator related to the three mobile anti-tank systems and the target represented in the field trial data are presented in Table 3-13. Refinements to the dynamic inter-axis attentional allocation (i.e., azimuth axis, elevation axis) and the parameter value identification could improve the accuracy of the model.

Table 3-13: Human Factors Issues with Mobile Anti-Tank Systems

Anti-Tank System	Target Represented in Field Trial Data	Physical Interaction
TOW	Crossing target moving at a range of 3km moving towards the gunner following a serpentine path	The launch tube is equipped with a sight that is mounted on a turret. The operator applies torque to point the sight from a crouching or leaning position.
DRAGON	Crossing target moving at 1km with approximately equal runs from right to left and vice versa.	The front of the tube is supported by a stand that acts as a pivot. The rear of the tube is mounted on the operator's shoulder. The operator usually manipulates the DRAGON from a seated position and is required to twist the torso and lean to one side during tracking.
ITV	Crossing target moving towards the gunner at 2km on a 40-degree angle.	The operator manipulates the TOW mount using a spring-loaded handlebar controller from a standing position.

3.8.2 VIPER

The US VIPER is a shoulder-fired infantry weapon system which replaced the US M72A2 light anti-tank weapon (LAW)). A comparison of the weapon features for the VIPER, LAW and the Swedish-built Mini-man (i.e., a shoulder-fired weapon) revealed both similarities and differences related to the shoulder stops (where equipped), trigger mechanism and weapon sight. Previous research which had investigated the VIPER system length, weight, noise, signature, recoil, ruggedness and sights was used as the foundation for the study included in the literature review. [24]

3.8.2.1 *Phase 1: Location of Sight and Trigger Mechanisms for the VIPER*

The first phase of the study employed a mock-up of the VIPER to test the location of the sight and trigger mechanisms. The participants adjusted both the mechanisms in relation to a shoulder stop. The participant group did not represent the full distribution of body sizes (i.e., small and large extreme body sizes) in the US Army. Preliminary testing revealed that the adjustments did not interact with each other and therefore, could be adjusted independently. Two positions were tested including standing and prone. Each position was tested with and without wearing protective body armour to understand the impact of the additional thickness on the locations of the sight and trigger mechanisms (e.g., raises the height of the weapon, shoulder stop is positioned further forward of the shoulder). Measurements concerning the sight are trigger mechanisms were described below.

- Sight mechanism. When adjusting the sight mechanism, it was placed 1-inch forward of the participants' eye and they were looking in a direction that was parallel to the weapon bore such that there was no superelevation. As well, the angular location of the sight was varied in increments that were counterclockwise from the line of fire. The radial height of the peep was adjusted, and measurements were recorded for the preferred height and the range at which the participants could still see through it as well as the distance from the shoulder stop to the participants' eye; and

- Trigger mechanism. The participants moved the trigger mechanism to a preferred location as well as to identify the range of trigger positions that would allow the trigger to be used without difficulty.

The results related to the location of the sight mechanism revealed an impact of the participants' firing position, peep height and wearing protective body armour as indicated below.

- The participants' eye is greater than 2-inches further forward of the shoulder stop in a prone firing position compared to a standing position;
- Wearing protective body armour was associated with the participants' eye being closer to the shoulder stop compared to when the armour was not worn;
- The sight could not be used in the vertical position (zero degrees) by more than half of the participants and one-quarter of the participants had difficulty using the sight in this position especially from a standing position;
- Within the 5- and 30-degree angular limits, the maximum usable height was greater than 6-inches which exceeds the maximum height that is appropriate for the sight; and
- The sight could be used when in the lowest vertical position (i.e., 3.1-inches) and all participants indicated lower heights would be difficult to use.

The results related to the location of the trigger mechanism revealed an impact of wearing protective body armour and participants' firing position as indicated below.

- The trigger mechanism could be operated from almost anywhere on the right of VIPER and forward of the shoulder stop; and
- Wearing protective body armour impacted the angle and shortened the longitudinal distance of the trigger mechanism from the shoulder stop.

3.8.2.2 *Phase 2: Time Requirements for Firing the LAW*

The second phase of the study employed expended LAW weapons to test the time required to prepare the weapon for firing from three positions (i.e., prone, kneeling and standing) and with and without wearing protective body armour. Guided familiarization and practice trials were used to ensure participants understood how to operate the weapon. The weapon was donned in a carry position slung over the participants' shoulder. All participants commenced preparation for firing once the command 'fire' was given. The response time was measured in hundredths of a minute and errors which caused delays in preparing to fire the weapon were recorded.

Despite the pre-trial familiarization and practice sessions, the participants exhibited one mistake or had trouble when preparing the weapon for firing during the initial test conditions. Although these issues were quickly and easily resolved, this finding suggested that the highest level of proficiency was not attained prior to commencing the trial. The following types of errors and difficulties were observed:

- Rear end cap not in fully down position;
- Front end cap not removed;
- Weapon not fully extended; and
- Sling or weapon tube caught on personnel equipment when attempting to remove weapon from shoulder.

The time to prepare the LAW for firing ranged between 0.15 - 0.32 minutes across all trials however, the mean (average) time was observed to be no greater than 13 sec. Based on this finding the expected mean time to prepare the VIPER for firing should also be 13 sec. The use of protective body armour did not have a negative impact on the response times for any of the tested positions.

In summary, the human factors issues that exist between the operator and each of the three shoulder-fired anti-tank systems are presented in Table 3-14 below. The conclusions drawn from the research were as follows:

- There is a great deal of leeway for positioning the trigger mechanism on the VIPER;
- The sight location, including the angular offset and the minimum peep height are more restricted than the trigger mechanism;
- The peep needs to be located well forward of the shoulder stop; and
- A peep with variable range/height increments and a peep with a fixed height can be used.

Table 3-14: Human Factors Issues with Shoulder-Fired Missiles

Shoulder Stop	Trigger Mechanism	Weapon Sight	Eye Position and Eye Relief	Gunner Position
VIPER				
Front - Hinged rigid plastic Rear – Flexible and conforms to shoulder	Location – Offset from vertical due to the larger diameter. Handedness – Equipped for right-handed firing only. Trigger – Right-handed grip and trigger is thumb operated and movement is in-line with the weapon bore.	Type – Equipped with a non-optical sight with a rear peep and a front post. Peep height is adjustable in increments of range/superelevation. The height does not need to vary with temperature because of the type of propellant that is used.	Eye position is relative to the rear peep. Not equipped stadia lines making the eye-position to the rear peep less important. Eye-relief – Varies between firing positions due to the use of the shoulder stop. Eye-relief refers to the distance between the eye to the rear peep.	Operator's head is further forward of their shoulder when firing in the prone position compared to the standing position.
Mini-Man				
Similar to VIPER	Similar to VIPER	Similar to VIPER	No data provided.	No data provided.
LAW				
No shoulder stop	Location – Top of weapon. Handedness – Equipped for left or right handed firing. Trigger – Pressed with fingertips in a direction that is perpendicular to the line of fire. Fingertip placement can interfere with firing and reduce accuracy if trigger is not depressed far enough into the surrounding well.	Location – Top of weapon Rear peep height that varies with temperature is needed.	Eye position relative to the rear peep is important. The range measured via the stadia varies with eye relief.	No data provided.

3.8.3 Sgt York Follow-On Evaluation 1 (FOE I)

In 1985, the Sgt York Follow-On Evaluation I (Sgt York FOE I) was conducted to investigate effective combat use of soldiers and human-machine interfaces related to target acquisition and engagement sequences for weapon systems (see Section 3.3.1) and the use of automation. [25] The evaluation focussed on the Line-of-Sight Forward-Heavy (LOS-FH) element within the forward area air defense systems (FAADS). Four competitive LOS-FH systems with self-contained radars for target location and missiles with a range equal to or greater than 6 km (i.e., ADATS. Liberty, Rapier, Paladin) were evaluated as potential replacements. A 1553 Serial Data Bus to gather objective performance data (i.e., switch actions and button pressing) during Force-on-Force scenario-based trials involving human operators (i.e., squad leaders, gunners) from a Fire Unit. The extensive data gathered from the previously executed Sgt York FOE I evaluation provided the foundation for developing a human performance database for use with computer models and to develop recommendations for improving the effectiveness of human operators and automation within FAADS.

MANPADS (i.e., US Stingers) were included as Blue Force assets however, the data were not gathered from the shoulder-fired systems. For this reason, no data were reported as part of the current literature review, but the following general points may be of interest to future MANPADS research:

- FAADS scenarios are complex and provide several opportunities to investigate operator performance on tasks and the interactions with systems, sub-systems and a wide range of capabilities;
- Higher performance (i.e., quicker times) observed for target selection and classification were not necessarily associated with higher individual training scores achieved by personnel;
- Night trials were fired on at shorter ranges (3.5 – 5.0 km) compared to day trials (0 – 10 km);
- Late day trials were associated with longer mean times to fire (20.1 sec) compared to mid-day trials (14.6 sec) which suggested that operator fatigue may have influenced performance. The pattern was not supported by early morning data (16.5 sec) but should not be ruled out; and
- Range at first sighting by a human operator may be a useful measure but data collection techniques were not available to gather these data at the time of the study.

3.9 Gaps Identified During Literature Review

Gaps identified by the study team during the literature review are presented in Table 3-15 below.

Table 3-15: Gaps Identified During the Literature Review

Topic Areas	Gaps Identified
Concept of Use	• The team’s understanding of the ROE on decision-making and information needed to develop operator SA concerning the overall aerial threat.

Topic Areas	Gaps Identified
Personnel and Roles	• Details concerning the verbal communication pattern between the team members which could be gathered to support gunner training in a simulated environment. • Representation of a full range of human size (i.e., 5^{th}-95^{th} percentile).
System	• Detection rates and accuracy based on visual search patterns (horizontal, vertical). • Influence of sector size on target detection. • Impact of operator fatigue due to eye strain caused by searching at long distance on human performance. • Operator alertness levels on human performance. • Impact of terrain types on human performance. • Team leader's selection of optimal position attacking aerial threats and ensuring adequate protection for the team. • Optimal FOV analyzing gunner preference and accuracy at close/long range, with low light environments and using a night sight. • Representation of a full range of environmental clothing and equipment (i.e., helmets, gloves) to assess feasibility of using MANPADS in cold weather environments. • Use of MANPADS to evolving threats in urban environments.
Automation	• Simulation of vibration and auditory cues and the impact on firing performance.
Training	• Human performance measurements that could be applied to training scenarios. • Interpretation of gunner body movements while tracking the air threat with respect to the target's current position. • Training and firing methods that reduce the risk of physical injury (i.e., shoulder contusions, facial trauma). • Operational procedures to investigate effectiveness of target acquisition and engagement within the battery life of the BCU.
Biomechanical	• Recoil mitigations that may minimize the gunner's flinch leading to potential performance improvements • Optimized weight for the MANPADS and other equipment carried by team members.
Target Tracking	• Impact of long missions performed under stressful conditions and quick movements while load carrying on human performance.
Performance models	• Underlying quantitative datasets that provide the data needed to accurately simulate soldiers' interactions with the MANPADS weapon (e.g., lifting and holding requirements, stability, targeting) and the impact of missions with realistic lengths (e.g., fatigue, anxiety) on the soldiers' performance (e.g., accuracy, response time).

4. EXPERIMENTAL RESEARCH TOPICS

This section presents an overview of the experimental research topics relevant to MANPADS systems that could be investigated using DRDC simulation capabilities. In addition, key guidance that should be considered by study teams when designing research projects is presented.

4.1 Human Centered Design

In theory, military equipment and systems, including MANPADS, are developed in accordance with military standards and industry best practices. Ideally, the definition, design and development are consistent with a user-centered design principles that are represented in Person-Environment-Technology (PET) framework (Figure 4-1) which characterizes the interactions between:

- The *operator* and their characteristics (e.g., anthropometry, biomechanics, physiology, perception, cognition, education, training, attitudes);
- The *environment* and the impact on the users' ability to perform their tasks within it (e.g., operating conditions, hazards, safety); and
- The *tasks* and the required level of performance (e.g., speed, accuracy, frequency, duration, compatibility, complexity).

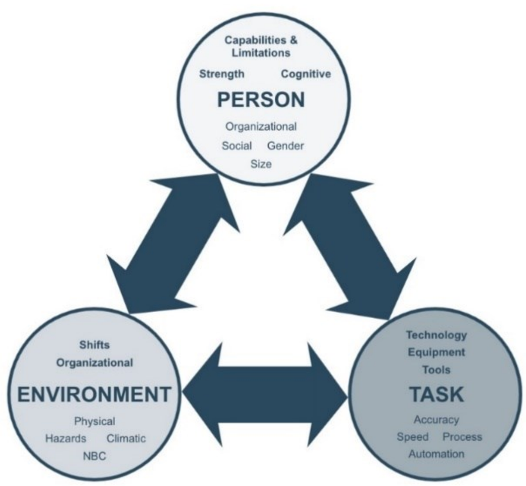

Figure 4-1: Person-Environment-Technology (PET) Framework

Defence-related human factors standards and applicable guidance (i.e., MIL-STD-1472, MIL-STD-46855A) should be used to guide MANPADS development and evaluations according to basic user-centered design principles. Generally, this entails the conduct of a structured analysis, referred to as a Mission Function (Goal) Task Analysis (MFTA).

The output of the MFTA links the system with the human-centric requirements and the measures used to assess the extent to which the system design supports operator roles and facilitates the effective completion of critical tasks and task sequences. The MFTA is comprised of the following interdependent analyses:

- Mission Analysis. A Mission Analysis establishes the boundaries for subsequent analyses understanding the intended use of a system by identifying the scenarios, crew characteristics, anticipated system functions and features, and the operating environments;

- Function (Goal) Analysis. A Function (Goal) Analysis identifies the functions (and hierarchy of functions) that must be satisfied by the system to achieve mission objectives. The Function (Goal) Analysis provides a high-level focus on objectives and desired end states (i.e., why a particular task is conducted), rather than actions (i.e., how a particular task is conducted); and

- Task Analysis. A Task Analysis develops a database of task-related information to generate a baseline for developing requirements. This information is also beneficial to various other activities including system design and specification, user evaluations, system acceptance, and training development.

4.2 Research Design and Analysis Guidance

A standard approach to experimental research design should be employed for research design, methodology, data analysis and interpretation. T&E plans (also referred to as TOP [7]) should ensure appropriate HFE issues are addressed and documented in the evaluation to maintain traceability between the outcomes and any recommendations that are generated as a result. According to the US Army Test and Evaluation Command (as cited in [4]) HFE evaluations should be tailored to intended user group and the operational, environmental and/or training (live or simulated) conditions. [4] In the present case, the T&E would include an audience familiar with MANPADS, the soldiers' clothing and the conditions in which the system is used. The evaluation should involve personnel who have undergone familiarity training and who understand the SOPs associated with using the weapon. SOPs should be finalized to ensure reliability and consistency for data collection. The output of the evaluations should determine the extent to which the design meets the documented requirements and the likelihood of acceptance by the intended audience. [7]

4.3 Research Topics

The study team identified research topics that can be investigated within DRDC's simulated environments and/or with prototyping tools. These topics are identified and briefly described in Table 4-1. The topics require validation to ensure their alignment with the priorities of the DRDC scientific community and to identify the technical requirements that must be met within the simulated environment.

Table 4-1: Research Topics Relevant to MANPADS

Research Topic	Description
Anthropometric analysis	Develop an accurate human performance database that represents a full range of human size (i.e., 5^{th}-95^{th} percentile) in accordance with MIL-STD-1472H.
Environmental clothing and protective equipment	Investigate human performance associated with cold weather clothing and the impact of wearing protective equipment on accuracy and to determine if MANPADS can reasonably be used within cold weather environments.
Operational training procedures associated with TES	Training and practice for operational procedures to ensure target acquisition and engagement can be completed within the battery life of the BCU.
Terrain	Team leader's selection of optimal position attacking aerial threats and ensuring adequate protection for the team.
Mission length	Impact of long missions on human performance that are performed under stressful conditions which required quick movements while load carrying.
Visual search patterns	Investigate optimal search patterns (horizontal, vertical) within small and large sector sizes.

5. CONCLUSIONS AND NEXT STEPS

The current study supported DRDC's investigation of human factors for MANPADS for the RCAF. The open-source literature search was augmented by documentation provided by DRDC. A small body of relevant research was identified for the subsequent literature review. The review addressed the role of human factors related to the MANPADS concept of use, system, training approaches, T&E, automation, biomechanics, target tracking and human performance models.

Based on this review, the study team identified several HFE-related knowledge gaps which, if addressed, would improve DRDC's understanding of human factors within the air defence domain as it relates to MANPADS. Based on these findings, the study team proposed a small set of future research topics that could be addressed within DRDC's simulated environments and/or using prototyped tools. Subsequent investigations would advance DRDC's understanding of weapon employment, operator training and health and safety issues. These research topics require validation to ensure alignment with DRDC's priorities and the feasibility of conducting the research using the available simulation systems and prototyped tools.

5.1 Next Steps

Recommended next steps for advancing DRDC's MANPADS research using simulated environments (as per Section 1.1) or employing prototyping tools include:

1. Conduct data collection interviews with MANPADS operators. Additional data collection is needed to develop a more comprehensive understanding of the team leader and gunner tasks and interactions with each other that provide the foundation for development MOPs and MOEs applicable to a simulated environment;

2. Define the capabilities for the simulated environment. Part task trainers that supply opportunities to acquire or refresh complex skills that are transferrable to an actual operating environment are more valuable to operators that full task trainer that deliver a sub-optimal experience. Once the capabilities of the simulated environment are decided, then effective research design and data collection methods can be developed. SOPs should be finalized and understood prior to commencing data collection efforts to ensure reliability and accuracy of the data;

3. Ensure operator health and safety during training. Significant health and safety issues are associated with firing shoulder-launched weapons. There is a link between ensuring realism during training and effectively transferring knowledge however, the long-term risk of physical injury to personnel must be carefully monitored;

4. Optimize division of practical and simulation training. Some operator tasks can be taught using practical training methods while others should be performed within simulated environments to minimize risk to the operator and systems. The development of complex cognitive skills that can be trained without having to endure the physical impacts of weapon recoil and impulse noise should be considered (e.g., understanding the overall aerial threat, effective identification of aircraft frames). Training approaches should focus on supporting the operators' understanding of how

automation is integrated into the TES and can improve targeting accuracy, decision-making and SA; and

5. Advance human performance data and modelling. Human performance modelling, based on new or existing models and biomechanical data, should be pursued to develop opportunities to minimize the risks posed to personnel. In addition, models should be used to developing enhanced capabilities (e.g., targeting) where a proper dataset exists, and investigating modifications to weapon design to better accommodate human capabilities (i.e., range of human size, sight, alertness, fatigue, carrying) and other equipment (e.g., seasonal clothing, helmets).

ANNEX A. DOCUMENTS INCLUDED IN LITERATURE REVIEW

This Annex presents the list of relevant documents and abstracts included in the literature review.

No.	Title	Abstract/Summary
HFE Issues (N=8)		
1	Use of VR technology and passive haptics for MANPADS training system [2]	Man portable air defense systems (MANPADS) are point-defense weapons that typically form the penultimate layer of defense against aerial threats. Deployed at close ranges to the installation being defended, MANPADS operators get little reaction time to engage attacking aircraft. The situation becomes more complex in a multi-threat scenario such as an airfield under attack. Dealing with such situations requires high proficiency and the capability to make tactical decisions quickly. Live training opportunities allow few operators to fire during live exercises. Simulation training is effective, but customized high-fidelity immersive training facilities are limited. Moreover, low trainee throughput from such high-end facilities is an ongoing obstacle. The main focus of this thesis research is a feasibility study for building a low-cost MANPADS training solution that uses commercial off-the-shelf components. The developed prototype leverages a fully immersive virtual reality system with head-mounted display, game engine, and passive haptics. It provides MANPADS operators with alternative training opportunities in target acquisition, tactical decision making, and situational awareness in a multi-threat scenario, and has the potential of addressing the current training gap. This development experience will provide valuable insights that can be employed to design and create a new generation of low-cost training solutions in other domains as well.
2	Designing VR and AR Systems with Large Scale Adoption in Mind [3]	Large scale adoption of novel solutions is the ultimate goal in many domains, and numerous factors need to be addressed to reach that success. This process is even more challenging when those systems are intended for human operators. Not only the technical performance of the system needs to be of the desired quality, but a range of other characteristics also gets scrutinized as well. The design and development of learning and training solutions will be encumbered by additional factors characteristic of learning and training processes. Current adoption of learning and training solutions is far from the desired state: the extent to which learning, and training solutions became an every-day practice of their intended users is still much lower than the investment made in this domain. Our research suggests that a good part of that blame can be laid on elements of system design that did not match users' needs, skills, and expectations. In this paper, we

		report the results and lessons learned in multiple efforts focused on design and prototyping of a diverse set of training systems that used both immersive and non-immersive virtual reality technologies and a variety of 3D user interface solutions. Approaches discussed and suggested in this paper are equally applicable to the design of systems intended for other human activities in both civilian and military domains.
3	Human factors issues in Land Forces weapon systems evaluations [4]	Human factors issues include the problems of operator performance, reliability, maintainability, availability, safety, and habitability as they relate to the interactions between the human, the machine, and the environment. Within the Canadian Forces (CF) many human factors activities are performed during the field evaluations that are conducted in support of the acquisition of weapon systems 'off the shelf.' This report is based on a review conducted in the early 1990s of some of the 'lessons learned' with regards to human-factors evaluations of 'off the shelf and prototype systems conducted for the CF. From these field evaluations it is concluded that there is a need for increased emphasis on human factors at the requirements and concept development stages of system acquisition. Due to heightened interest in Human Systems Integration issues in procurement, the original review has been revised. Conclusions are drawn and recommendations made with respect to 1) the need to plan for human factors evaluations; 2) common design deficiencies; 3) the limitations of human factors engineering techniques and need for further research, and; 4) the need to address human factors issues in Statements of Requirements (SORs) for new systems and equipment.
4	Maneuver Leader's Guide to Stinger [5]	Stinger missiles provide a key capability for maneuver forces to defend themselves from aerial observation and attack. However, without direct involvement from senior brigade combat team leaders and effective leader training, these missiles will become dead weight at best or a fratricide in waiting at worst. Units must plan effectively to utilize this capability and ensure it ties directly to their scheme of maneuver as opposed to simply task-organizing one Stinger team per company. This guide is designed as a single-entry point for brigade combat team and maneuver battalion commanders and their staffs to effectively train and fight Stinger teams as part of an integrated combined arms team. These planning and employment techniques should prove invaluable to effectively maximize mission effectiveness, allow maneuver forces to retain the initiative, and provide freedom of maneuver from the air.
5	Low Altitude Air Defense (LAAD) Gunner's Handbook [6]	Marine Corps Reference Publication (MCRP) 3-25.10A, Low Altitude Air Defense (LAAD) Gunner's Handbook, complements and expands on the information in Marine Corps Warfighting Publication 3-25.10, Low Altitude Air Defense Handbook, by providing information on tactics, techniques, procedures, and employment of the Stinger weapon system for the low altitude air defense (LAAD) gunners. This MCRP is primarily a reference guide for the LAAD section leader, the LAAD firing team leader, and the LAAD gunner (military occupational specialty 7212).

6	Launcher, Rocket, Individual Weapon [7]	Describes a method of evaluation of rocket launcher operational and functional performance characteristics. Identifies supporting tests, facilities, and equipment required. Provides procedures for preoperational inspection, physical characteristics, safety, personnel training, bore sighting, range, accuracy, antipersonnel/antimateriel capability, durability, reliability, obscuration, security from detection, adverse conditions, portability/transportability, maintainability, human factors, and value analysis. Applicable to individually fired launchers. Not applicable to multiple or vehicular mounted launcher avatems.
7	A Systems Engineering Examination of the Short-Range Antitank Weapon (SRAW) [8]	This paper examines the systems engineering process of the development of a new lightweight weapon system, a Short-Range Anti-tank Weapon (SRAW) for the United States Marine Corps. The systems engineering approach has been applied to this system. The need for such an anti-tank system is established from examining currently fielded antitank systems. The maintenance concept, operational requirements, functional analysis, and requirements allocation are presented with an emphasis on the human interface. The SRAW optical sight requirements are presented to illustrate the flow-down of the systems engineering process to the component subassembly level. The results of a field test verification of the optical sight requirements are presented as one example of the iterative system development process.
8	Grading ManPADS Engagement (U) [9]	To support the analysis of air platform susceptibility to Man-Portable Air Defence System (ManPADS) engagements, DRDC Valcartier has prepared a short letter categorizing various types of ManPADS operators. This categorization helps describe how the expertise of gunner will affect the result of an engagement. When evaluating the impact of the gunner on a successful engagement, utilizing a gunner with a realistic skill set for the simulated scenario is critical. For example, if the test is simulating an attack on a highly defended target against regular military forces, the gunner should be a highly trained individual with extensive experience. Conversely, a test simulating flight over insurgent territory should opt for amateur gunners instead. The gunner should correctly simulate the expected mission environment.
Biomechanical Factors (N=7)		
9	The Effects of Weight and Length on the Portability of Antitank Systems for the Infantryman [10]	A field study was conducted to determine the effect of weight and length of an antitank system on the performance of an infantryman. A portability test course was designed and constructed. The ability of soldiers from the 82d Airborne Division to negotiate the course was measured and the soldiers' ratings of each of the systems they carried were obtained. Functional relationships between weight, length and performance were obtained with an indication of the effects of volume, i.e., multiple carry. The test soldiers were able to discriminate among the loads using the bipolar adjective rating technique, and for what appears to be a reluctance-to-carry factor, tended to rate the loads carried in a manner which parallels the performance findings. The infantryman's performance degrades, and he is reluctant to carry 81mm antitank systems longer than 31 inches (at eight pounds) and heavier than eight pounds when added to his current fighting load.

10	Influence of Carrying Heavy Loads on Soldiers' Posture, Movements and Gait [11]	Military personnel are required to carry heavy loads whilst marching; this load carriage representing a substantial component of training and combat. Studies in the literature mainly concentrate on physiological effects, with few biomechanical studies of military load carriage systems (LCS). This study examines changes in gait and posture caused by increasing load carriage in military LCS. The 4 conditions used during this study were: control (including rifle, boots and helmet carriage, totalling 8 kg), webbing (weighing 8 kg), backpack (24 kg) and a Light Antitank Weapon (LAW, 10 kg), resulting in an incremental increase in load carried from 8, 16, 40 to 50 kg. Twenty male soldiers were evaluated in the sagittal plane using a 3-dimensional CODA™ motion analysis system. Measurements of ankle, knee, femur, trunk and craniovertebral angles and spatiotemporal parameters were made during self-paced walking. Results showed spatiotemporal changes were unrelated to angular changes, perhaps a consequence of military training. Knee and femur ranges of motion (control, 21.1º ±3.0 and 33.9º ±7.1 respectively) increased ($p<0.05$) with load (LAW, 25.5º ±2.3 and 37.8º ±1.5 respectively). The trunk flexed significantly further forward confirming results from previous studies. In addition, the craniovertebral angle decreased ($p<0.001$) indicating a more forward position of the head with load. It is concluded that the head functions in concert with the trunk to counterbalance load. The higher muscular tensions necessary to sustain these changes have been associated with injury, muscle strain and joint problems.
11	Biomechanical Modeling of Injury from Blast Overpressure [12]	The loading of the body by blast overpressure, often generated by explosives or weapon noise, can rapidly collapse the air-containing organs of the body and cause local injury. These effects can range from isolated pathologies, with no observable physiological consequences, to rupture of critical organs and death. Following World War II, animal models were used to study lethality, while in the past two decades the US Army Medical Research and Materiel Command has used animal models to study injury. The lethality data was correlated with pressure-duration characteristics of the free field blast, but these correlations become ambiguous in reverberant environments. Correlations have been proposed based on the motion of the thorax, but without a biomechanical basis, they do not provide insight into injury location or scaling with species and gender. A model of the thoracic injury process has been developed that provides both a biomechanical understanding and a good correlation of experimental observation. This paper reviews the mathematical model, the data supporting the choice of material properties, and the correlation of calculated internal stress with observed injury.
12	Evaluation of Exposure to Impulse Noise at Personnel Occupied	The tests reported in this paper were carried out to evaluate the exposure of soldiers to noise at operator and control positions during military field exercises. The tests were conducted during firing from a T-72 tank, a BWP-1 Infantry Fighting Vehicle, antitank guided missiles, a ZU-23-2K anti-aircraft gun, and a 2S1 GOZDZIK howitzer. The evaluation of noise exposure showed that the limit values of sound pressure level, referred to by both Polish occupational noise protection standards and the Pfander and Dancer hearing

	Areas During Military Field Exercises [13]	damage risk criteria developed for military applications, were repeatedly exceeded at the tested positions. Despite of the use of tank crew headgear, the exposure limit values of sound pressure level were exceeded for the crew members of the T-72 tank, the BWP-1 infantry fighting vehicle, and the 2S1 GOZDZIK howitzer. The results show that exposure of soldiers to noise during military field exercises is a potentially high hearing risk factor.
13	Recoil Considerations for Shoulder-Fired Weapons [14]	This report reviews the physics of recoil impulse and kinetic energy and the means to alter either the magnitude of these dynamic quantities or the temporal distribution of resulting interaction forces by purposeful or serendipitous mechanical filtering. Emphasis is placed on understanding the problem and the experimental approach needed to put recoil/shoulder interactions on a firm scientific basis.
14	Shoulder-fired weapons with high recoil energy: Quantifying injury and shooting performance [15]	Sufficient information is not available to determine health hazards associated with weapon recoil. This study assessed the injury response m US Army Soldiers after firing a shoulder-fired weapon producing recoil energy at the upper limit authorized Additionally, we observed injury rate and potential injury risk factors. 15 infantrymen fired 15 shots using a weapon system producing 59.09 ft-lbs of recoil energy. Markers of injury assessed pre-firing, immediately post-firing, and 24, 48, 72 and 96 hrs post-firing included subjective pain, pain-pressure threshold, bruising, range of motion, strength, a lifting task, and laboratory markers. Thermal imaging and MRI were used to assess skin temperature and edema. Data were analyzed using repeated-measures ANOVA, Pearson correlations, and descriptive statistics. 15 volunteers exhibited bruising at the anterior shoulder, and 11 reported pains with motion post-firing. 14 volunteers (93%) sustained evidence of soft tissue injury on MRI. Three (20%) sustained facial lacerations. Skin tissue temperature increased immediately post-firing and returned to baseline at 24 hr. Dominant handgrip strength had the best predictive value for injury severity on MRI. We conclude that Soldiers are at risk for soft tissue contusions and lacerations at the upper threshold of allowable recoil energy. Injury was characterized by elevated skin temperature, pain with motion, and decreased pain threshold immediately post-firing. Signal intensity changes on MRI were consistent with muscle contusion for up to 96 hrs post-firing.
15	Dynamic Analysis of Shoulder-Fired Weapons [16]	A recoil analysis to assess several recoil mitigating technologies applied to shoulder-fired weapons such as a grenade launcher or shotgun has been conducted. Parameters such as weapon weight, recoil impulse, recoil velocity and recoil energy were identified as critical. A range of values were selected for evaluation. In order to monitor and assess the dynamics occurring during its cyclic motion, a mathematical model for a 12 Gauge weapon has been developed. The model defines each major component and the relative connectivity between them is defined in terms of kinematic joints. A Lagrangian methodology is utilized to formulate the rigid body dynamic equations of motion. Three commercial recoil reducing devices were evaluated in the model to determine their specific effect on recoil motion, both on the weapon and on the soldier firing the

		weapon. A full test program was conducted at the Armaments Research Laboratory (ARL) on a modified 12 Gauge shotgun to measure recoil control for each of the recoil devices. An additional model was formulated for this fixture. Comparisons between model and experimental test results were made. Further tests and evaluation include combinations of recoil devices. Documentation of sample model output is included.
Human Target Tracking (N=3)		
16	The effects of anxiety and exercise-induced fatigue on shooting accuracy and cognitive performance in infantry soldiers. [17]	Operational performance in military settings involves physical and mental skills that are generally investigated separately in lab settings, leading to reduced ecological validity. Therefore, we investigated the effects of anxiety and exercise-induced fatigue, separately and in combination, on cognitive and shooting performance of 22 soldiers in a real-world setting. Findings indicated that soldiers' shooting accuracy and decision-making and mathematical skills decreased significantly under anxiety. Whether exercise-induced fatigue was beneficial or detrimental to task performance depended on the task at hand. The increased arousal levels through exercise prevented shooting accuracy from deteriorating in the decision task. In contrast, cognitive performance suffered from the increased arousal: participants more often failed to shoot when being fired at by an opponent and also math performance seemed to decrease. We conclude that anxiety can deteriorate soldier performance and that exercise-induced fatigue may improve or deteriorate performance in combination with anxiety depending on the nature of the task.
17	Human Factors Evaluation of a Rifle-Launched Rocket Projectile [18]	An experimental investigation was made of the aiming and can’t errors associated with the firing of a rocket round from the muzzle of a rifle. The unusual features of the system were an appreciable weight at the muzzle (5-7 lbs) and an appreciably delay (.3 sec) between ignition and launch. If ignition is accomplished by firing a ball round from the rifle, launch errors of 4-7 mils may be expected. If the ignition is recoilless, errors of 2 mils may be expected. Can’t errors of about 1 .40 appear typical.
18	Upper Body Fatiguing Exercise and Shooting Performance [19]	This study assessed the effect of upper extremity muscle fatigue on shooting performance while in a standing, unsupported firing position. Nine male and three female soldiers fired at targets before and after performing upper extremity exercise to fatigue using both (1) an upper body ergometer and (2) a Military Operations in Urban Terrain obstacle course. Shooting accuracy, assessed by the number of hits, misses, and shot group size, was significantly decreased ($p < 0.05$) immediately following both types of exercise and recovered to pre-exercise values within 5 minutes for all measures except the number of misses, which returned to pre-exercise values by 10 minutes. There was no relationship between fitness measures and shooting performance, although muscle endurance was a factor in the duration of exercise prior to fatigue. We conclude that shooting accuracy recovers rapidly in fit soldiers following fatiguing lifting, climbing, and pulling activity.

Human Performance Models (N=3)		
19	Modeling Human Tracking Error in Several Different Anti-Tank Systems [20]	The Optimal Control Model (OCM) of human response serves as a mechanism for generating sample time histories of human tracking error in different anti-tank systems. The systems under study include TOW (Tube-Launched Optically Guided System), DRAGON (Shoulder Mounted) and ITV (Improved TOW Vehicle). The model-generated trajectories are compared with field-test data across several dimensions including time-domain (temporal) statistics, frequency content and subjective comparisons on individual runs.
20	Location of Sights and Trigger Mechanism and Time to Fire for a New Infantry Shoulder-Fired Antitank Weapon (Viper) [21	The US Army is developing an infantry weapon system named VIPER to replace the M72A2 light antitank weapon (LAW). In a technology program leading to the development of VIPER, the US Army Human Engineering Laboratory (HEL) investigated system length, weight, noise, signature, recoil, ruggedness and sights. The investigation described here was conducted to provide additional data for the VIPER system specification (6) and scope of work for engineering development (5). Specifically, experiments were conducted to (1) determine the location on the weapon of sights and trigger mechanism to provide an effective man-weapon interface, and (2) to quantify time to prepare VIPER for firing based on performance characteristics for the weapon VIPER will replace, the M72A2 LAW.
21	Human Factors Performance Data for Future Forward Area Air Defense Systems (FAADS) [22]	The Fort Hood Field Unit of the US Army Research Institute for the Behavioral and Social Sciences (ARI) conducts research and development to promote the effective combat use of the soldier and to improve soldier-machine interfaces in future system designs. Data are reported here from the Sgt York Follow-On Evaluation I (FOE I), which generated objective performance measures on individual soldier, team, and system performance in the execution of the target engagement sequence. The implications of these data for developing future air defense systems are discussed for such areas as system and subsystem performance, tactical performance, individual and crew performance, personnel factors, and training. The primary objective of this effort was to structure the data into a human performance data base that could be incorporated into computer models of human and system performance in future Forward Area Air Defense Systems (FAADS). Further, the data, the analyses, and the recommendations in this report provide information directly relevant to consideration of the soldier into future FAADS design.

ANNEX B. REFERENCES FOR FUTURE RESEARCH

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This study was conducted for the Defence Research and Development Canada (DRDC) Toronto Research Centre (TRC) under Task 13 of Contract W7719-185397/001/TOR in support of DRDC's modelling and simulation (M&S) capabilities within the Advanced Platforms and Weapons (APW) Strategic Focus Area (SFA). The current study examined human factors issues related to man-portable air defence systems (MANPADS).

An open-source literature search augmented by documentation provided by DRDC was performed to identify relevant publications for a literature review. A data collection framework was developed for compilation and evaluation. A refined documentation (N=21) set was selected based on extent to which the literature was focussed on MANPADS and human issues. The study team reviewed and summarized the documentation. The review addressed the role of human factors related to the MANPADS concept of use, system, training approaches, test and evaluation (T&E), automation, biomechanics, target tracking and human performance models. Several human factors engineering (HFE) knowledge gaps were identified in the domain.

Cette étude a été menée pour le Centre de recherche de Toronto (CRT) de Recherche et développement pour la défense Canada (RDDC) dans le cadre de la tâche 13 du contrat W7719-185397/001/TOR à l'appui des capacités de modélisation et de simulation (M&S) de RDDC au sein du Domaine d'intervention stratégique (SFA) sur les plates-formes et armes avancées (APW). La présente étude a examiné les problèmes de facteurs humains liés aux systèmes portables de défense aérienne (MANPADS).

Une recherche documentaire de sources ouverte au public, complétée par la documentation fournie par RDDC, a été effectuée pour identifier les publications pertinentes pour une revue de la littérature. Un cadre de collecte de données a été élaboré pour la compilation et l'évaluation. Un ensemble de documentation raffinée (N = 21) a été sélectionné en fonction de la mesure dans laquelle la littérature était axée sur les MANPADS et les problèmes humains. L'équipe de l'étude a examiné et résumé la documentation. L'examen a porté sur le rôle des facteurs humains liés au concept d'utilisation des MANPADS, au système, aux approches de formation, aux tests et à l'évaluation (T&E), à l'automatisation, à la biomécanique, au suivi des cibles et aux modèles de performance humaine. Plusieurs lacunes dans les connaissances en ingénierie des facteurs humains (HFE) ont été identifiées dans le domaine.