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The effect of a tiered body armour system on soldier physical mobility

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Abstract

Current military operations involve complex omnipresent threats, resulting in the need for all soldiers, regardless of occupational speciality, to wear body armour during operational deployment. Body armour is typically comprised of both hard and soft armour and is designed to provide ballistic, fragmentation and stab protection. The weight load and bulk of body armour, which is influenced by the materials used and extent of hard and soft armour coverage of the body, has the potential to affect a soldiers physical mobility on the battlefield. Intuitively it would appear logical that as the external load a soldier carries increases there is an associated decrease in their ability to move on the battlefield. Indeed studies have shown that external load can affect performance of key military tasks and thus compromise mobility when compared to an unloaded state. For example, Holewijn (1992) demonstrated that for every 1kg increase in external load, there was an average performance loss of 1% during tasks including jumping, sprinting, hand grenade throwing and obstacle course completion. The levels of protection proposed as part of the Tiered Body Armour System (Tiered BAS) have not been systematically evaluated and it is therefore unknown whether the weight increments of each level have a significant impact on soldier mobility. This study has quantified performance effects of the Tiered BAS and therefore examined the trade-off between passive protection (body armour coverage and ballistic rating) and active protection (soldier mobility). The results of this study can be reliably employed in conjunction with other important factors (e.g. thermal load) to inform Tiered BAS procurement decisions for the Australian Army. Secondly, results may be used to develop a commander's guide to BAS selection (used in conjunction with threat profile information) on operations. The aim of this study was to assess the impact of different levels of body armour protection (Tiered BAS) on soldiers' mobility. Specifically; Quantify baseline soldier mobility in a military clean skin (MCS) condition. Assess, measure and compare mobility under an Individual Combat Load Carriage Equipment (ICLCE) chest webbing system (control condition) and four levels of Tiered BAS. Underpin findings by correlative investigation with basic physiological and or anthropometric characteristics. Provide summary recommendations of the effects of weight load on soldiers' mobility.

Keywords

physical, armour, mobility, tiered, effect, body, system, soldier

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THE EFFECT OF A TIERED BODY ARMOUR SYSTEM ON SOLDIER PHYSICAL MOBILITY

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EXECUTIVE SUMMARY

Current military operations involve complex omnipresent threats, resulting in the need for all soldiers, regardless of occupational speciality, to wear body armour during operational deployment. Body armour is typically comprised of both hard and soft armour and is designed to provide ballistic, fragmentation and stab protection. The weight load and bulk of body armour, which is influenced by the materials used and extent of hard and soft armour coverage of the body, has the potential to affect a soldiers physical mobility on the battlefield.

Intuitively it would appear logical that as the external load a soldier carries increases there is an associated decrease in their ability to move on the battlefield. Indeed studies have shown that external load can affect performance of key military tasks and thus compromise mobility when compared to an unloaded state. For example, Holewijn (1992) demonstrated that for every 1kg increase in external load, there was an average performance loss of 1% during tasks including jumping, sprinting, hand grenade throwing and obstacle course completion.

The levels of protection proposed as part of the Tiered Body Armour System (Tiered BAS) have not been systematically evaluated and it is therefore unknown whether the weight increments of each level have a significant impact on soldier mobility. This study has quantified performance effects of the Tiered BAS and therefore examined the trade-off between passive protection (body armour coverage and ballistic rating) and active protection (soldier mobility). The results of this study can be reliably employed in conjunction with other important factors (e.g. thermal load) to inform Tiered BAS procurement decisions for the Australian Army. Secondly, results may be used to develop a commander's guide to BAS selection (used in conjunction with threat profile information) on operations.

The aim of this study was to assess the impact of different levels of body armour protection (Tiered BAS) on soldiers' mobility. Specifically;

- Quantify baseline soldier mobility in a military clean skin (MCS) condition.
- Assess, measure and compare mobility under an Individual Combat Load Carriage Equipment (ICLCE) chest webbing system (control condition) and four levels of Tiered BAS.
- Underpin findings by correlative investigation with basic physiological and or anthropometric characteristics.
- Provide summary recommendations of the effects of weight load on soldiers' mobility.

The study was conducted at Robertson Barracks, Darwin, NT during the month of April, 2010. Thirty-one (31) active service Infantry soldiers (male) took part in the study. The soldiers were recruited from 2 Platoon, A Company, 7RAR, 1BDE. All subjects were experienced soldiers and therefore familiar with the movement patterns required to complete the assessments.

Five loaded ensembles were assessed for measures of subjects' physical mobility. This included a chest webbing condition with no protection (Tier 0; control) and four torso body armour (Tiered BAS) conditions (Tiers 1-4); In addition, the study measured the subject's baseline mobility capacity with a military clean skin (MCS) condition. The Latin Square

design was employed for the allocation of soldier conditions to ensure there was no ordering effect. The study was designed so that the various loaded conditions (Tiers 0-4) differed only on the basis of passive protection levels (body surface area coverage and ballistic rating) to allow for an assessment of the active protection (soldier mobility) afforded by each condition. The equipment carried and the associated load list for each loaded condition was standardised in accordance with the ICLCE User Requirement Load Carriage Configuration (LCC) 3 Chest Rig. LCC 3 Chest Rig was established as the most appropriate load list as the Tiered BAS have been specifically designed to carry this LCC.

Each subject completed the mobility assessments dressed in DPCU and combat boots. The five loaded conditions (Tiers 0-4) were evaluated using five different mobility assessments, which provided coverage of the key physical mobility challenges faced by the dismounted soldier moving tactically on the battlefield. The mobility assessments were selected in order to satisfy both scientific rigour considerations (i.e. measurability, discrimination, reliability, and battlefield relevance) as well as practical considerations (i.e. protocols, resources, equipment, administration and safety). The mobility assessments were; 1.) Fire and movement simulation; 2.) Obstacle avoidance simulation; 3.) Combat rush simulation; 4.) Vertical jump and 5.) Stand and reach.

There was strong evidence that the Latin square design countered any potential bias of assessment order between the five loaded ensembles. Importantly, this indicated there was no significant evidence of either fatigue or learning (improved skill) that could have contributed to differences between Tiers 0-4. The current investigation showed that reduced soldier mobility was related to increased external load. Across the five mobility assessments, moving between Tier 0 to Tier 4, there was an average performance reduction of **1.5%** for every **1 kg** of external load added. The performance reductions, both relative and absolute were proportional to the external weight load of each Tiered BAS condition. The external weight load effect was manifested in a range of performance outcomes including;

- Slower movement speeds.
- Longer duration to move between points of cover.
- Reduced ability to generate power from a standing position.
- Earlier onset of physical fatigue during repetitive movements.
- Reduced ability to quickly negotiate obstacles.

The greatest relative difference was always Tier 4 compared to Tier 0 (decrease in assessment performance) and this ranged from 4.91% in the total time to complete the obstacle avoidance assessment to 14.29% in the stand and reach assessment. The smallest relative performance difference was a 0.15% performance decrease (Tier 3 versus Tier 2) during the vertical jump assessment. Some interesting observations specific to each assessment included:

Fire and Movement: Total bound time demonstrated a conditional staircase effect from Tier 0 to Tier 4, whereby the greatest relative change was a 7.28% increase in total bound time (indicating a performance decrease) in Tier 4 versus Tier 0. The range in performance difference was also as little as 0.68% in Tier 3 versus Tier 4. There was no evidence to suggest that performance on the fire and movement assessment could be predicted by the aerobic capacity of the subjects.

Obstacle avoidance: There was no significant difference found between Tiers 1-3 with

respect to a single turning capacity (around one obstacle). Equally, Tier 4 was not significantly slower than Tiers 2 and 3 around one obstacle. With respect to multiple turning capacity (five obstacles), the MCS condition was significantly quicker compared to Tiers 0-4. There was a weak relationship between the relative load carriage and the fastest total time.

Combat Rush: There was no significant difference for acceleration (5 m) across Tiers 0-4. Most notably, this finding supports the acceleration measurements taken in the obstacle avoidance assessment. There was no significant difference between Tiers 0-4 with respect to sustained speed (20 m). Interestingly, there was no indicative trend between load increase and performance loss during combat rush. Relative mass carriage only affected Tier 0 and this may be attributed to bulk and fit.

Vertical Jump: Vertical height achieved in Tier 0 was significantly greater than Tiers 2-4. Tiers 1-4 were not different to each other. As displacement was in the vertical plane and against gravity, the effect of relative load seemed like an obvious determinant of performance. However, from the results there was no significant relationship in jump height performance and relative load increase that could also be attributed to condition. Interestingly, as load carriage increased, so did calculated peak power whereby Tier 4 demonstrated (trend) the greatest power development.

Stand and Reach: When subjects were asked to do the same balance assessment in Tier 0-3, there was no difference between conditions. Tier 4 impacted most on balance, although this was not different to Tier 2. In other words when subjects wore Tier 4 and Tier 2, they fell forwards earlier with arms outstretched, as simulating the act of reaching for an object at height.

Performance in each mobility assessment correlated soundly against absolute mass carriage. The strongest relationship was found in the fire and movement assessment between increasing total bound time against increasing load carriage. The linear equations developed in this study that relate weight load to assessment performance can, within reason, further inform the effects of load carriage on the mobility performance outcomes. At this point in time, the linear equations apply for loads ranging from 4.7 kg up to 29.23 kg mass.

The current study has demonstrated that based upon physical mobility assessments, there are three equally stressful groups, clustered around weight load, for the five conditions under evaluation.

- **Group A:** Tier 0 (19.09 kg) and Tier 1 (21.56 kg)
- **Group B:** Tier 2 (25.01 kg) and Tier 3 (25.98 kg)
- **Group C:** Tier 4 (29.23 kg)

Given that physical mobility impediment was found to be equivalent for each of the three groups it is recommended that the ensemble within each grouping that provides the most protection for the dismounted soldier be considered for procurement and use within the Australian Army. For Group A this would be Tier 1, for Group B this would be Tier 3 and for Group C this would be Tier 4. This recommendation with respect to physical mobility must

be considered in conjunction with other important factors (e.g. thermal load) to inform Tiered BAS procurement decisions.

Ultimately, weight-load is the primary mechanism that influences physical mobility and as such there may be other more optimal configurations of hard and soft armour protection than those investigated in the current study. For instance, substituting the ballistic plates used in the Tier 4 condition (6.3 kg) with those used in Tiers 1-3 (3.7 kg) would result in a total weight load of 26.23 kg which is similar to the weight loads of Group B. BAS design and development efforts should focus on hard and soft armour materials that provide the highest level of protection whilst minimising overall weight load.

A point of interest would come from further investigations that examine load carriage against mobility performance with smaller increments, and perhaps across a greater external weight load range. It may be hypothesised that a threshold load may be exist whereby further load increases then have either an increased or decreased effect on soldier mobility.

Most importantly, future work needs to specifically focus on the concept of individual survivability based on the physical mobility data reported in this study. Rather than determining a statistically significant difference between PPE conditions the work needs to be extended to identify the point at which a reduction in physical mobility starts to compromise personal survivability on the battlefield. Development of a survivability index based on exposure time whilst moving tactically will enable meaningful recommendation to be made on the impact of various PPE ensembles. This approach will need to interface both human physiological performance and mathematical modeling.

AUTHORS

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Greg is a physiologist with over 10 years of research experience. His principal research interests are within exercise physiology, with a focus on skeletal muscle and cardiovascular function. He has worked extensively on projects that have investigated human dietary interventions, heart function and skeletal muscle fatigue. His current research centres on both fundamental science and its practical applications. This research has shown clear links between human cellular composition and the body's response to exercise stress. Greg's research training enables him to assess and investigate the underlying limitations of human performance during work and exercise.

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DSTO staff (Dr Dan Billing, Mr Jace Drain, Ms Renee Attwells, Ms Alison Treloar), with support from UOW (Dr Greg Peoples, Mr Aaron Silk) led the process of defining the research concept, study design and methodology. The execution of the investigation was led by DSTO staff (Dr Dan Billing, Mr Jace Drain) with support from UOW (Mr Aaron Silk, Mr Robert Savage, Mr Daniel Lee, Mr Sean Notley, Ms Brooke Collier, Ms Laura Holland). The analysis and interpretation of data was led by UOW (Dr Greg Peoples, Mr Aaron Silk) with DSTO in support (Dr Dan Billing, Mr Jace Drain). The report writing was led by UOW (Dr Greg Peoples, Mr Aaron Silk) with support from DSTO (Dr Dan Billing, Mr Jace Drain) in reviewing and revising the report.

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1. INTRODUCTION

1.1 Background information on the effect of external load carriage on mobility

Current operations involve complex omnipresent threats, resulting in the need for all soldiers, regardless of occupational speciality, to wear body armour during operational deployment. Body armour is typically comprised of both hard and soft armour and is designed to provide ballistic, fragmentation and stab protection. The weight load and bulk of body armour, which is influenced by the materials used and extent of hard and soft armour coverage of the body, has the potential to affect a soldiers physical mobility on the battlefield.

Mobility is a broad and widely used term used to describe 'the act or process of moving or of changing position' (Tulloch, 1990, p992*)*. However, within the military-based literature the term mobility appears to be used with reference to performance of strength, power and endurance tasks, agility, functional movements, various joint specific range of motion tasks and completion of obstacle courses that are thought to reflect requirements on the battlefield.

Since the early 1960s, load carriage/physical mobility research has been of widely variable quality with regards to its design, rigor and reporting (Appendix A provides an overview of relevant literature). It is evident that the methods have varied and altered dramatically, ranging from well defined, Harman (1999) and Polcyn (2000; 2002), to extremely generalised and descriptive, Ricciardi (2006). These variations are also evident within the sample sizes used in the studies, which ranges from 5 to 70 subjects. The studies reviewed used predominately male subjects and sourced them from the general population rather than from a military or athletic background, which potentially impacts upon the quality of the results and utility for military groups. In addition, Pandorf (2002) and Harman (1999) were the only investigators to study solely female subjects. At times, researchers utilised qualitative data collection methods including RPE, perceived task difficulty and personal preference ranking (Adam, 1991; Bowditch, 2005) over quantitative methods, also adding to the variable nature of the studies presented.

Several linear relationships are evident within the load carriage/physical mobility literature. These include performance reduction with external load increase (Martin, 1985; Nelson, 1982), reduced range of motion about a joint with increase clothing bulk (Woods, 1997b) and increased ground reaction forces with additional load (Sell, 2010). Holewijn (1992) demonstrated that for every 1kg increase in external load, there was an average performance loss of 1% during tasks including jumping, sprinting, hand grenade throwing and obstacle course completion. However this decrement in performance was not observed during an agility run test (Demaio, 2009). Angel (2008) revealed that within body armour design it was bulk (material thickness) that was more detrimental to soldier acceptance than stiffness when external load was equal. This study also found that armour cut and carry design did not adversely impact on the results.

Obstacle courses have been used extensively within performance studies. Some are well detailed and documented (Gruber, 1965; Harman, 1999; Harman, 2008; Bowditch, 2009; Danielsson, 2009; Pandorf, 2002) and others contain minimal detail (Bassan, 2004). In general as load increased, time to complete the obstacle course also increased (Harman, 1999 and Hasselquist, 2008). Whilst most studies have reported only total time to complete the obstacle course, others have detailed times for individual course components in order to

further examine the effect of load on soldier mobility. These within obstacle course differences are evident in work completed by Polcyn *et. al.,* (2000) and Harman *et. al.,* (1999) where they identified movements such as "low crawl" and "prone to feet" were hindered due to increased external load to a greater extent than "sprint" and "zig-zag".

Centralised weight in the form of a torso vest performed better than a weighted backpack or extremity load (Gruber, 1965; Hasselquist, 2008) with backpacks also restricting upper limb range of motion (Martin, 1985). Conflicting findings in regards to position of weight carried on the back when sprinting or during the performance of an obstacle course are present. Derrick (1963) suggests there is no significant difference between upper and whole torso load distribution, while Holewijn (1992) found weight on the lower back proved detrimental to obstacle course performance. Interestingly, during this same study conducted by Holewijn (1992) better performance results in vertical jump and sprint times with weight placed lower on the back were reported. An interesting comparison between hard and soft armour by Danielsson (2005) found that the linear relationship between net climbing performance and added external mass proved more apparent with hard armour.

Intuitively it is logical to assume that as the external load that a soldier has to carry increases there would be a negative impact on their ability to move on the battlefield. However this issue is complicated by the threshold load level that is applied, how the load is distributed, the assessment being undertaken and the participant group involved. Although there has been previous research investigating the effect of load on soldier mobility on the battlefield previous studies have not adequately addressed or controlled for these complications, and have typically included small, non-military participant groups. They have also lacked detail in methods such as weight and distribution of external load, have not adequately justified the assessments rationale to mobility on the battlefield and have generally employed assessments with poor levels of test-retest reliability.

1.2 Statement of the problem

Body armour systems are worn by soldiers to provide passive protection from ballistic, fragmentation and stabbing threats on the battlefield. Increased coverage of the body's surface area with this equipment will provide greater personal protection however it may also result in a heavier load carried by the soldier. Studies have shown that external load can affect performance of key military tasks and thus compromise mobility. The extent to which physical mobility is degraded can vary according to differing weight increments. The levels of protection proposed as part of the Tiered Body Armour System (Tiered BAS) have not been systematically evaluated and it is therefore unknown whether the weight increments of each level have a significant impact on mobility. This study will quantify performance effects of the Tiered BAS and therefore examine the trade-off between passive protection (body armour coverage and ballistic rating) and active protection (soldier mobility). The results of this study can be reliably employed in conjunction with other important factors to inform Tiered BAS procurement decisions for the Australian Army. Secondly, results may be used to develop a commander's guide to BAS selection (used in conjunction with threat profile information) on operations.

1.3 Aims of the study

The aim of this study was to assess the impact of different levels of body armour protection (Tiered BAS) on a soldier's mobility. Specifically;

- Quantify baseline soldier mobility measures in a military clean skin (MCS) condition.
- Assess, measure and compare mobility under a control condition (ICLCE chest webbing) and four levels of Tiered BAS.
- Underpin findings by correlative investigation with basic physiological and or anthropometric characteristics.
- Provide summary recommendations of the effects of weight load on soldiers' mobility.

2. METHODS

2.1 Subjects

Thirty-one (31) active service Infantry soldiers (male) took part in the study (Table 2.1). The soldiers were recruited from 2 Platoon, A Company, 7RAR, 1BDE, Robertson Barracks, Darwin, NT. For the purpose of the report the participating soldiers are referred to as subjects from this point forward. Prior to providing written consent to participate in the study all subjects were informed of the requirements, benefits and potential risks associated with participation in the study. Subjects with a pre-existing injury or illness were precluded from participating in the study. All procedures were approved by the Australian Defence Human Research Ethics Committee (ADHREC) (Protocol number: 572-09).

Table 2.1: Baseline characteristics of all subjects who participated in the mobility study.

No.	Age (years)	Height (cm)	Weight (kg)	BMI [a] (kg/m^2)	Body Fat (%)	VO_2max [b] ($ml.kg^{-1}.min^{-1}$)
S1	23	198	112.7	28.7	18.5	48.4
S3	19	183	112.1	33.5	27.9	47.0
S4	20	188	90.2	25.5	16.5	53.0
S5	23	187	106.6	30.5	19.8	46.9
S6	21	182	91.1	27.5	11.7	50.0
S7	23	183	93.7	28.0	10.7	54.5
S9	35	180	76.7	23.7	7.7	55.5
S10	27	178	77.9	24.6	10.1	61.0
S11	21	181	102.1	31.2	26.7	46.7
S13	19	172	71.9	24.3	17.1	51.2
S14	25	176	79.1	25.5	19.8	54.5
S16	28	189	86.8	24.3	9.4	53.5
S17	29	186	91.5	26.4	10.7	51.7
S18	21	175	70.5	23.0	11.8	52.6
S19	29	176	79.5	25.7	18.6	49.2
S20	20	177	87	27.8	13.9	49.2
S21	20	180	79.3	24.5	15.0	49.2
S22	20	180	85.1	26.3	16.3	50.8
S23	20	168	62.6	22.2	12.5	50.0
S24	26	178	64.6	20.4	10.7	50.4
S25	21	178	80.4	25.4	19.7	49.2
S26	19	184	69.8	20.6	9.2	54.5
S27	22	168	72.2	25.6	14.1	50.4
S28	19	168	78.9	28.0	15.6	54.5
S29	21	180	65	20.1	4.6	62.3
S30	26	174	61.2	20.2	11.3	50.9
S31	18	178	81.9	25.8	15.3	57.5
S34	23	182	87.3	26.4	16.6	52.1
S35	22	176	67	21.6	9.9	51.9
S36	22	180	72.1	22.3	6.0	55.5
S37	23	166	63.6	23.1	11.2	54.5
Mean	**23.0**	**179.7**	**84.7**	**26.1**	**16.1**	**51.0**
SD	**4.0**	**7.0**	**13.4**	**3.1**	**6.1**	**3.4**

BMI [a] = Body Mass Index (BMI) ; mass (kg)/ height $(m)^2$, VO_2max [b] = predicted maximal aerobic power ($ml.kg^{-1}.min^{-1}$) from 2.4 km run.

2.2 Environmental conditions and timing

The study was conducted at Robertson Barracks, Darwin, NT during the month of April, 2010. As the assessments were of short duration (< 5 min), environmental conditions were not expected to impact upon the study. However, to ensure subject safety the environmental conditions were monitored using Wet Bulb Globe Index and Army heat injury management tables. All trials commenced in the morning (i.e. ~ 0730) and were completed by midday (i.e. ~ 1200). An overview of the testing schedule is provided in Table 2.2. Where appropriate, testing was conducted in cooled and/or shaded areas to further minimise the impact of environmental conditions. Where assessments were conducted in the open, shaded areas were provided for subjects whilst resting and regular consumption of water was encouraged.

Table 2.2: Mobility testing schedule overview

Pre-Activity Screening		
Mon, 29 March 2010	Study briefing, informed consent	
Wed, 31 March 2010	Baseline subject testing	
Week 1	**Time**	**Assessments; Obstacle avoidance & combat rush**
Mon, 12 April 2010	0730-1200	Familiarisation and Session 1
Tue, 13 April 2010	0730-1000	Session 2
Wed, 14 April 2010	0730-1000	Session 3
Thu, 15 April 2010	0730-1000	Session 4
Fri, 16 April 2010	0730-1200	Session 5
Week 2	**Time**	**Assessments; Vertical jump, fire and movement & stand and reach**
Mon, 19 April 2010	0730-1200	Familiarisation and Session 1
Thu, 22 April 2010	0730-1200	Session 2 and 3
Fri, 23 April 2010	0730-1200	Session 4 and 5

2.3 Experimental design, conditions and analysis

Five loaded ensembles were assessed for measures of subjects' mobility (Appendix B; Figure 6.1-6.5). This included a chest webbing condition with no protection (Tier 0, control condition) and four torso body armour (Tiered BAS) conditions (Tiers 1-4) (Table 2.3). In addition, the study measured the subjects' baseline mobility capacity with a military clean skin (MCS) condition.

This study was based upon a within subjects experimental design with subjects acting as their own controls, and participating in every condition (control and Tier 1-4) of the mobility assessment. Statistical procedures included computations of variance (1 and 2-way ANOVA)[1], within-subject variance[2] and the coefficient of variation[3] for each of the regression coefficients. Throughout this report all data are reported as mean ± standard deviation (SD).

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[1] Variance of the sample = standard deviation squared.
[2] Within-subject variance = standard deviation squared / number of repeated measures on each subject.
[3] Coefficient of variation = standard deviation / sample mean * 100 (%).

Table 2.3: Description of military clean skin and loaded ensembles.

MCS	Military clean skin consisted of disruptive pattern combat uniform (DPCU), combat boots and weapon (replica F88 SA1). Military clean skin was used to quantify baseline soldier mobility.
Tier 0 (T0)	Tier 0 is a webbing system only (Land 125 Individual Combat Load Carriage Ensemble v2) and provides no passive protection (weight 0.9 kg, medium size vest). This condition served as the control condition.
Tier 1 (T1)	Tier 1 is essentially a "battle bra" that was fitted with a hard ballistic plate and small soft armour insert to cover the wearer's chest (weight 3.4 kg).
Tier 2 (T2)	Tier 2 provides ballistic protection to approximately 50% of a soldier's chest and back. The vest is fitted with soft armour inserts and front and back hard ballistic plates (weight 6.8 kg).
Tier 3 (T3)	Tier 3 provides ballistic protection coverage to approximately 90% of a soldier's chest, back and sides. The vest is fitted with soft armour inserts and front and back hard ballistic plates (weight 7.8 kg, medium size vest).
Tier 4 (T4)	Tier 4 is the current in-service Modular Combat Body Armour System (MCBAS) which weighs 11.0 kg, not including limb, neck and groin attachments (Medium size vest).

The study was designed so that the various loaded conditions (Tiers 0-4) differed only on the basis of passive protection levels (body surface area coverage and ballistic rating) (Table 2.4) to allow for an assessment of the active protection (soldier mobility on the battlefield) afforded by each condition. Therefore the equipment carried and the associated load list for each loaded condition was standardised in accordance with the ICLCE User Requirement Load Carriage Configuration (LCC) 3 Chest Rig. LCC 3 Chest Rig was established as the most appropriate load list as the Tiered BAS have been specifically designed to carry this LCC. The load list (Appendix C, page 67) was advised by Army Headquarters.

A representative simulation load was created (Figure 2.1) to represent a soldier's base load (Table 2.4) as it was not possible to obtain the actual items in sufficient quantity. The simulation load was modelled upon the actual size, weight and quantity of the items included in a soldier's base load. The load carrying pouches were directly attached to the ensembles. The attachment sites for the loaded pouches were standardised across Tiers 0-4 to minimise the potential impact of differences in load distribution on performance in the mobility assessments. Importantly the only difference across the loaded conditions was the weight of the vest, which was attributable to the level of passive protection (i.e. hard and soft armour inserts) offered by the different ensembles.

Each subject completed the mobility assessments dressed in DPCU and combat boots. The total external weight load and the associated load list for each condition are detailed in Tables 2.4 and Appendix C (page 67) respectively.

Table 2.4: Total external load carried by subjects for each condition.

	MCS	TIER 0 ICLCE	TIER 1	TIER 2	TIER 3	TIER 4 MCBAS
Base ensemble (kg)	0	0.89	1.56	3.11	4.08	4.73
Ballistic Plates (kg)	0	0	1.8 CIB-24	3.7 CIB-24	3.7 CIB-24	6.3 MCBAS
Helmet (kg)	0	1.5	1.5	1.5	1.5	1.5
Weapon (replica F88 SA1) (kg)	4.7	4.7	4.7	4.7	4.7	4.7
Load list (see Appendix C) (kg)	0	12	12	12	12	12
TOTAL (kg) *	**4.7**	**19.09**	**21.56**	**25.01**	**25.98**	**29.23**

* Weights for Tiers 0-4 are based on a medium sized ensemble

Figure 2.1 Representative image of the dummy load and loaded pouches

2.4 Mobility assessments

The five loaded conditions (T0-T4) were evaluated using five different mobility assessments, which provided coverage of key physical mobility challenges faced by the dismounted soldier moving tactically on the battlefield (Table 2.5). In addition, the study also measured mobility in MCS as an indication of baseline performance capacity. The mobility assessments were selected in order to satisfy both scientific rigour considerations (i.e. measurability, discrimination, reliability, and battlefield relevance) as well as practical considerations (i.e. protocols, resources, equipment, administration and safety).

All subjects were experienced soldiers and therefore familiar with the movement patterns required to complete the assessments. However, a dedicated familiarisation session was conducted prior to testing to minimize the effects of learning. Subjects undertook familiarisation of all assessments in MCS prior to completing the assessments under the loaded conditions. Familiarisation involved a progressive walk / jog through the assessment and concluded with two maximal efforts (in MCS).

Subjects performed a standardised warm up prior to completing each assessment and final instructions were given immediately prior to each attempt.

Table 2.5: Battlefield relevance of mobility assessment tasks

Assessment	Requirement	Physical Capacity	Battlefield Relevance
1. Fire and movement simulation	Repeated sprint from prone firing position	Leg power / muscular endurance	Ability to repeatedly undertake fire and movement activity (basic drill) as part of a section attack.
2. Obstacle avoidance simulation	Timed 40 m obstacle sprint	Agility and leg power	Ability to rapidly move around obstacles and change direction whilst on the move.
3. Combat rush simulation	Timed 30 m sprint	Leg power / speed	Ability to move between buildings or across roads in one sustained bound (particularly relevant to urban environments).
4. Vertical jump	Maximum vertical jump height	Leg power	Ability to hop or jump over obstacles on the battlefield, rush, take-off for bound, climb stairs.
5. Stand and Reach	Maximum reach forward beyond centre of mass	Balance	Predictive of the ability to perform various battlefield tasks requiring the soldier to reach forward and maintain balance (i.e. fire weapon, balance on obstacles/uneven surfaces).
6. Wall clearance simulation *	Timed 1.5 m wall clearance	Upper body strength / leg power	Climb over wall (or similar obstacle) or through window and the subsequent ability to rapidly move to cover upon clearing wall/obstacle.

* Wall clearance was not completed (see page 22 for explanation).

2.4.1.1 - Assessment 1: Fire and Movement Simulation

2.4.1.1.1 Assessment overview

The purpose of this assessment was to measure a number of parameters surrounding exposure time during a simulated section attack. The fire and movement assessment was based upon doctrine and in-field observations of section attacks conducted recently as part of Australian Defence Human Research Ethics Committee (ADHREC) Protocol 491-07 (Physical Employment Standards). Each subject was required to complete 12 bounds of 5 m each incorporating a rise from prone position on a 25 second duty cycle. The simulation is representative of both the physiological demands and movement patterns involved during section attack activities. Subjects completed this assessment six times; once per condition including MCS.

2.4.1.1.2 Assessment set-up and data collection

The fire and movement assessment was performed on a flat non-slip surface free from hazards or debris that may have caused injury or disrupted performance. Prior to testing in the loaded conditions all subjects underwent appropriate familiarisation in MCS which involved a progressive jog through the assessment protocol followed by one complete maximal assessment.

Figure 2.2 shows the overall setup for the fire and movement assessment. All distances were carefully measured and checked using a trundle wheel and measuring tape. All lines and timing gate positions were marked with tape to ensure accurate and consistent positioning of the lines and timing gates each day, and gate replacement in the event of being moved during the testing sessions. Timing gates (Speedlight) were positioned in order to demarcate two 5 m "bound zones", one zone for each direction of travel. The start lines were positioned 1 m from the timing gates which were to be used to initiate the timing of that bound.

Subjects started each bound in a prone firing position with the leading elbow resting on the start line (Figure 2.3). The assessment was controlled by audio cues on a CD. Subjects were instructed to get to their feet as quickly as they could and then sprint as fast as possible through the finish line making sure they did not slow down before the finish gate. Once upright, subjects were required to place both hands on the weapon until after they crossed the finish line (Figure 2.3). Subjects then decelerated, turned around and readopted the prone firing position on the start line waiting for the next audio cue. With safety in mind, subjects were asked to adopt a kneeling position prior to moving into the prone firing position. The duty cycle for one bound was 25 seconds. There were 12 bounds in total therefore the total test time was ~4 minutes and:45 seconds. The assessment was performed as an up and back shuttle (in the same lane) as per Figure 2.2 and 2.3, with two lanes running side by side concurrently. Data from the timing gates were collected in real-time by a tablet computer and analysed at a later date.

All subjects were fitted with heart rate monitors (Polar Team) that were set to record at 5 second intervals. At the completion of the testing session heart rate monitors were collected, the data downloaded to a computer and analysed at a later date. Figure 2.4 is a typical heart rate response elicited by a subject during the fire and movement simulation. The peak heart rate experienced as a result of each bound can be clearly identified.

Heart rate response was analysed via the following method. It was assumed that the maximum heart rate during the assessment would occur during or at the completion of the final bound. Once this maximum heart rate was identified a time of 4 minutes 45 seconds was deducted and this was set as the assessment start point. Once this start and end point was established mean data was calculated and the rate of heart rate rise (slope of the line that joins peak heart rate after first bound and maximal heart rate) could be established. This method is shown in Figure 2.4.

Two video cameras (one camera per lane) were used to capture the subjects' initial movement from the prone firing position to their feet. Video cameras were positioned at alternate ends of the lanes and captured footage from the subjects' right-hand side. This setup resulted in 6 prone-to-feet samples being captured per fire and movement trial. Initially this prone-to-feet time was to be captured using timing gates but due to equipment difficulty this was not possible.

The start of the prone-to-feet movement was defined as the first upwards movement of the subjects' hips. In order to find the point in the footage where this occurred the most accurate method was to trace backwards through the clip as the hips are lowered to the ground and select the point in time where the hips were first off the ground and translating in an upward direction. The completion of the prone-to-feet movement was defined as the foot strike of the first running pace.

2.4.1.1.3 Measurements

The nature of the fire and movement assessment meant that a substantial range of physiological and mobility based parameters could be simultaneously collected. Specifically, the following measurements were directly or indirectly taken.

Bound specific measurements taken from the timing gates
- Fastest bound time
- Total bound time (cumulative total for the 12 bounds)
- Mean bound time
- Fatigue index = (total bound time - ideal total bound time)/ideal total bound time x 100

Prone to feet specific measurements
- Mean time to move from prone to feet
- Representative still frames at 0, 25, 50, 75 and 100% of prone-to-feet time (MCS, T0 and T4).

Cardiovascular measurements
- Maximum heart rate
- Mean heart rate
- Cardiovascular index (mean heart rate time x total test time)
- Rate of heart rate rise (slope of the line between peak heart rate after bound 1 and the maximum heart rate during the assessment).

Figure 2.2 Representative diagram of fire and movement assessment

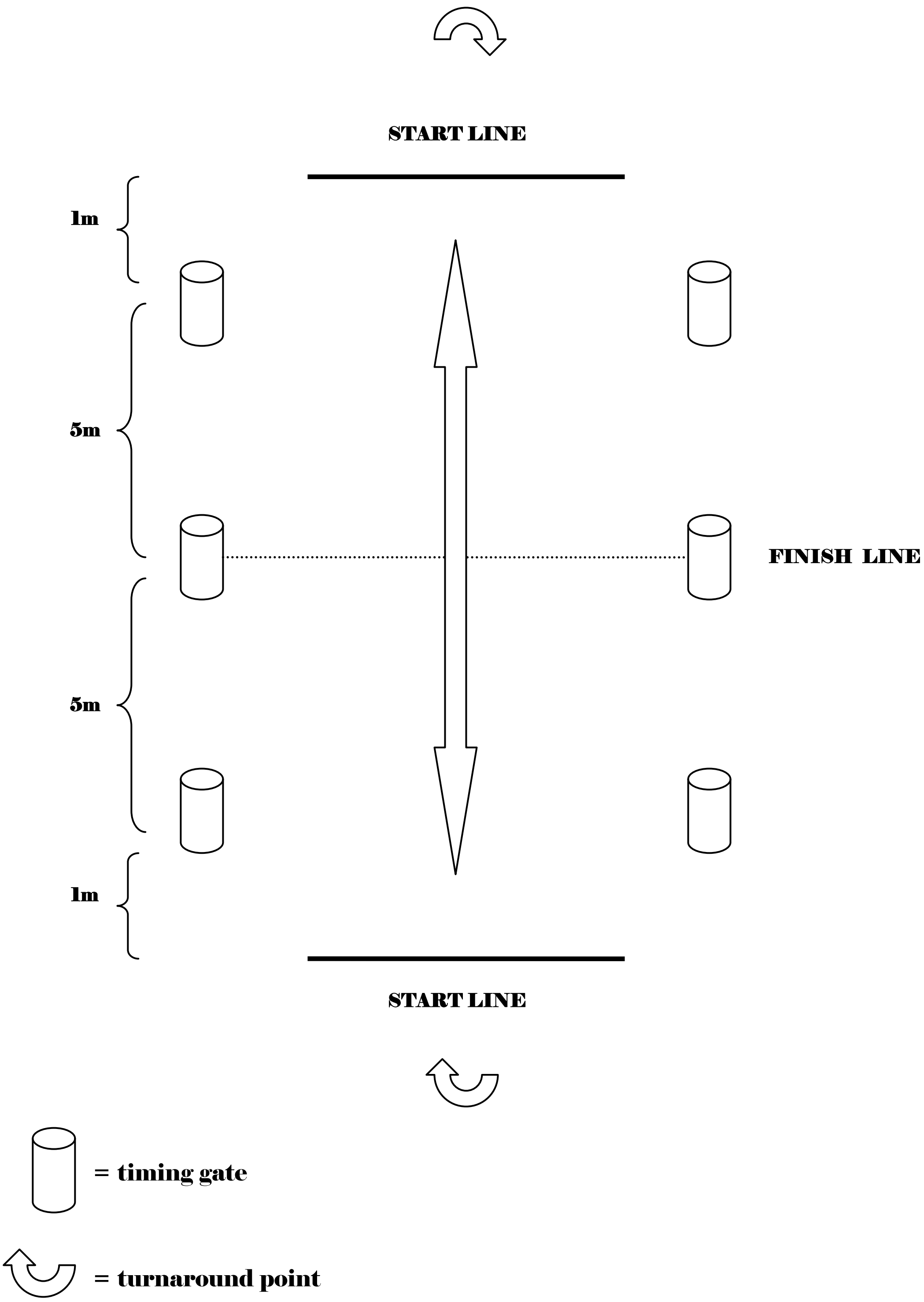
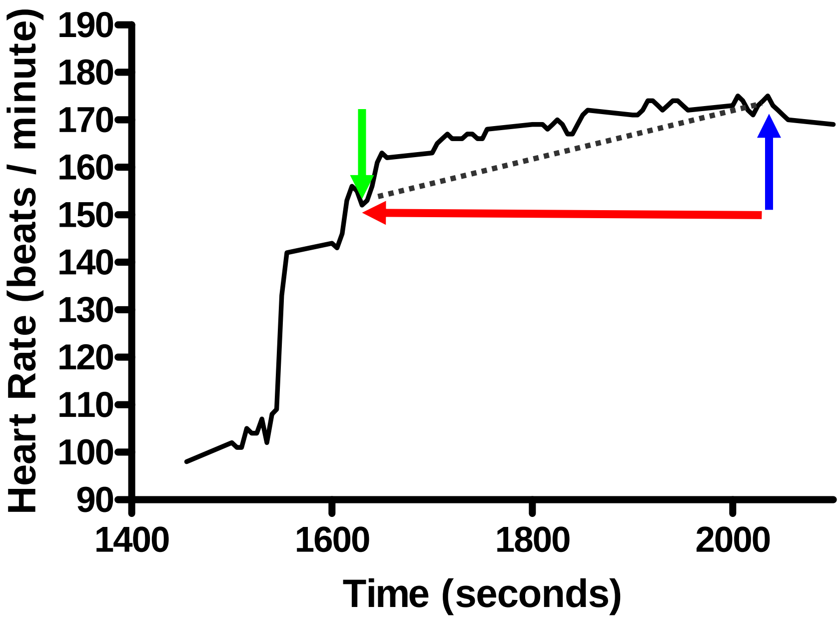


Figure 2.3 Images from the fire and movement assessment

Figure 2.4 Heart rate analysis method - The blue arrow indicates the maximum heart rate achieved by the subject. The red arrow indicates the time period (4 minutes 45 seconds) deducted to establish the start point and calculate mean heart rate. The green arrow indicates the initial rise in heart rate used to create a slope (dotted line) (to maximum heart rate) representing cardiovascular strain.



2.4.1.2 - Assessment 2: Obstacle Avoidance Simulation

2.4.1.2.1 Assessment overview

The purpose of the obstacle avoidance assessment was to measure agility, including speed, acceleration, change of direction and body control. Subjects were required to complete a 40 m running course involving rapid direction changes, simulating the requirement to avoid obstacles on the battlefield. The assessment protocol utilised was originally developed for use in Australian Rules Football and is a valid and reliable assessment of agility capacity. Subjects completed this assessment 12 times; twice per condition including MCS.

2.4.1.2.2 Assessment set-up and data collection

The assessment was completed on a flat, non-slip surface free from hazards or debris that may cause injury or interfere with performance. The obstacle avoidance task required the subjects to negotiate five poles (1.8 m high) (Figure 2.5) over a distance of 40 m (Figure 2.6). The height of the poles ensured that the subjects negotiated each obstacle in a manner consistent with negotiating obstacles (i.e. wall, building, stairwell, doorway) on the battalefield. The position of the start and finish lines, the individual poles and timing gates were measured and marked with permanent marker paint prior to commencement of testing. All distances were measured daily with trundle wheel and checked with measuring tapes. This ensured accurate and consistent positioning of the lines, poles and timing gates each session and pole replacement in the event of one being knocked over by a subject during completion of the assessment.

Timing lights (Speedlight) were set-up at the start and finish lines respectively, 2 m apart. Timing lights were also set-up at the first pole in a line perpendicular to the approach line from the start, and these gates were positioned 2 m from the pole on either side (total distance of 4 m between gates) (Figure 2.6). Data from the timing gates were collected in real-time by a tablet computer and analysed at a later date.

Subjects started from a stationary standing position with the weapon in both hands and front foot touching the start line. When the equipment was ready to collect data the subjects were instructed that they were free to begin, upon which they self-selected when to initiate the obstacle avoidance assessment. Subjects completed the course whilst maintaining both hands on the weapon. The first pole was approached on the subjects left-hand side, the second pole on the right-hand side, the third pole on the left-hand-side, the forth on the right-hand side and the fifth pole on the left-hand side (Figure 2.5). If a pole was touched or a hand was removed from the weapon the assessment was immediately discontinued and the subject repeated the attempt (after appropriate rest). Upon completion of each maximal effort the subject moved to the back of the queue until two successful attempts were completed. This allowed for a minimum of three minutes rest between attempts. This rest period was deemed adequate for recovery between attempts.

2.4.1.2.3 Measurements:

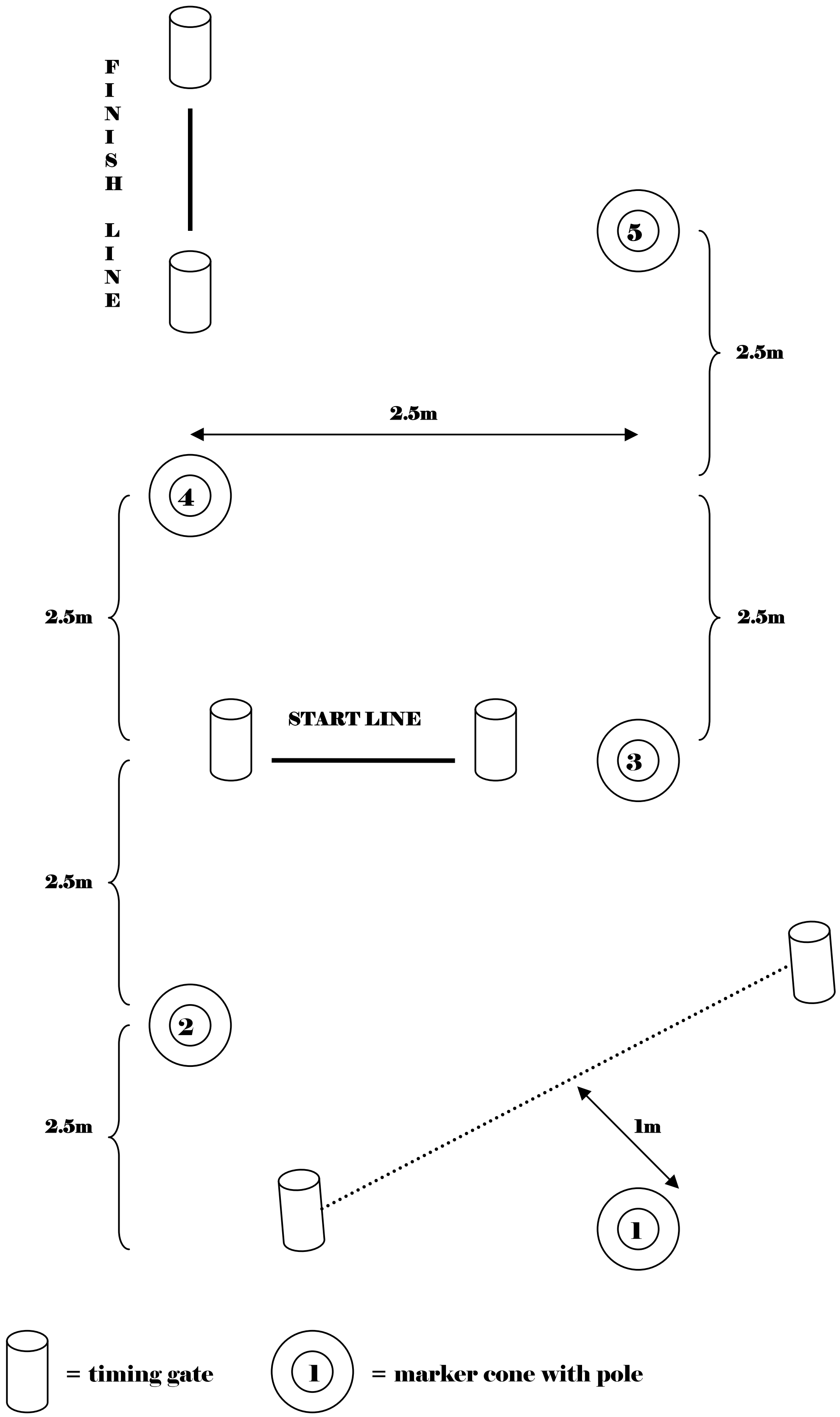
The timing gates allowed for detailed breakdown of split times and total time to complete the obstacle avoidance simulation. Each subject repeated the assessment twice and the fastest time was recorded for data analysis. A number of measurements were specifically collected;

- Time to complete the 40 m agility test
- Time to accelerate through the first timing gate

- Time to negotiate (turn around) the first pole. This 'turn time' commenced when the subject broke the beam for the first set of gates (before negotiating first pole) and ceased when the subject broke the beam for the second time (after negotiating the first pole).

Figure 2.5 Images from obstacle avoidance assessment

2.6 Representative diagram of simulated obstacle avoidance assessment



2.4.1.3 Assessment 3: Combat Rush Simulation

2.4.1.3.1 Assessment Overview

The purpose of the combat rush was to determine time to complete a sprint over 30m (Figure 2.7). Interval splits at 5, 10 and 20 m were measured to further assess the effects of the Tiered BAS on soldier mobility. A timed 30 m sprint from a stationary standing start was implemented to assess speed and leg power. This sprint is representative of the requirement to move at speed in an urban environment and to perform a break contact drill as has been measured recently as part of ADHREC Protocol 491-07 (Physical Employment Standards). Subjects completed this assessment 12 times; twice per condition including MCS.

2.4.1.3.2 Assessment set-up and data collection

The assessment was completed on a flat, non-slip surface free from hazards or debris that could cause injury or interfere with performance. The start and finish line and intermediate splits (5, 10 and 20 m) were marked with permanent marker paint to allow for exact placement of timing gates for each testing session. Cones were placed at 0 and 30 m, with secondary cones positioned to demarcate a safe deceleration zone for the subjects. Timing lights (Speedlight) were set at 0, 5, 10, 20 and 30 m (Figure 2.8). All distances were measured daily with a trundle wheel and re-checked with measuring tapes. Data from the timing gates were collected in real-time by a tablet computer and analysed at a later date.

The subjects started from a standing stationary position with the front foot touching the start line and both hands on the weapon. Subjects were informed when the equipment was ready to collect data after which they self-selected when to commence the combat rush simulation. The subject sprinted as fast as possible through the finish line making sure both hands remained on the weapon and they did not slow down before the finish line. Removal of a hand or dropping the weapon during completion of an attempt was deemed an unsuccessful attempt and was repeated after adequate recovery. The subjects were then instructed to move to the back of the queue after each attempt to allow a minimum three minutes rest between attempts. This rest period was deemed adequate for recovery between attempts.

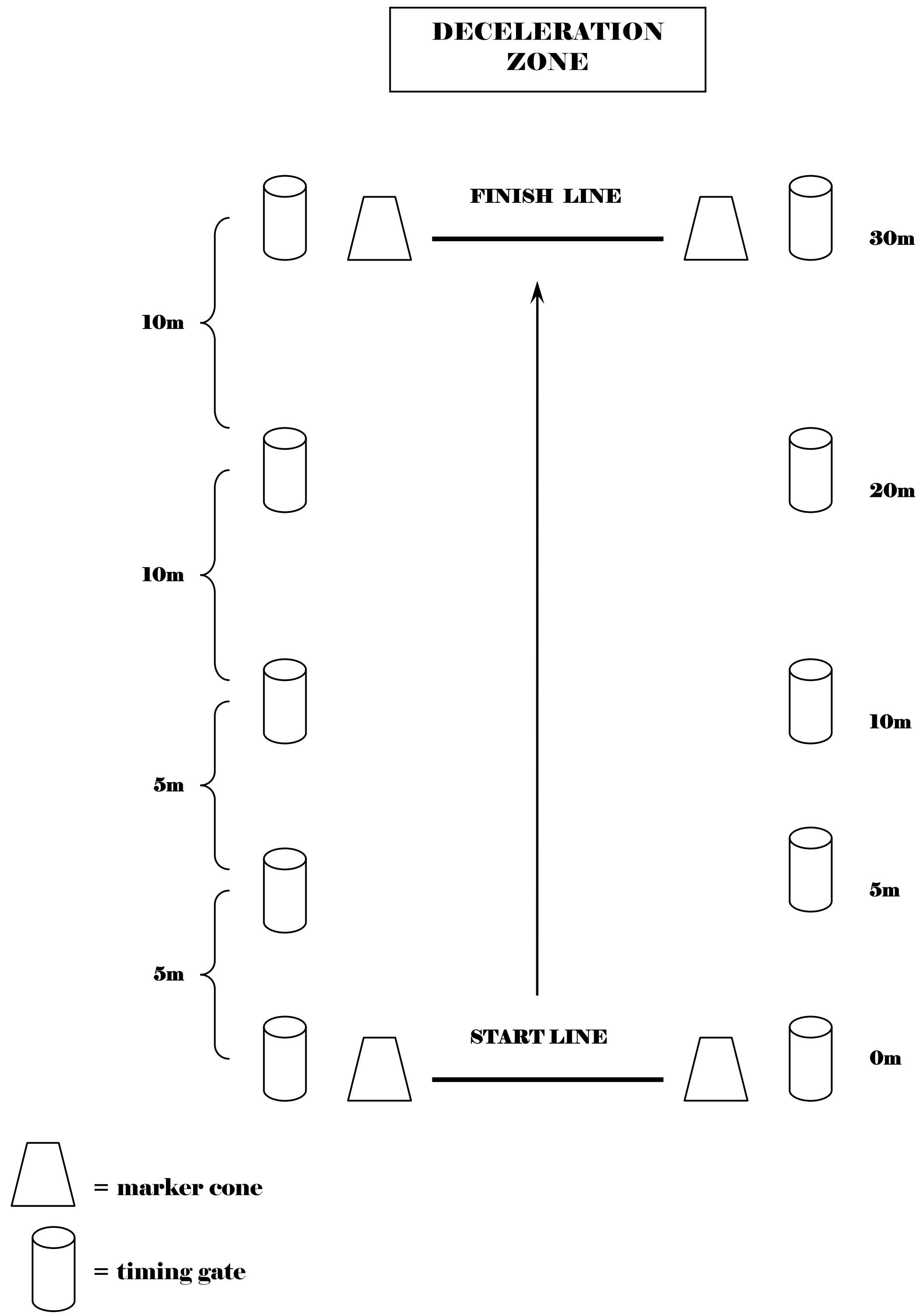
2.4.1.3.3 Measurements

The timing gates allowed for detailed breakdown of split times and total time to complete the combat rush. Each subject repeated the assessment twice and the fastest time was recorded for data analysis. A number of measurements were specifically collected;

- Time to complete 30 m rush
- Time splits at 5, 10, and 20 m

Figure 2.7 Image from combat rush assessment

Figure 2.8 Representative diagram of combat rush simulation layout



2.4.1.4 Assessment 4: Vertical Jump

2.4.1.4.1 Assessment overview

The purpose of the vertical jump assessment was to assess leg power whilst wearing the different body armour ensembles. The subjects were required to perform the jump with both hands on the weapon. The vertical jump was performed with a counter-movement immediately before the upward movement. This assessment has been approved by ADHREC as part of previous research (Protocol 491-07) and provides a safe method of quantifying leg power by measuring jump height. Subjects completed the vertical jump 18 times; three times per condition including MCS.

2.4.1.4.2 Assessment set-up and data collection

The assessment was conducted on a flat surface free from hazards or debris that could cause injury or interfere with performance. The jump mat (Speedlight) and timing gates (Speedlight) were linked to a tablet computer. The data was collected in real-time and analysed at a later date.

Prior to all loaded conditions subjects underwent appropriate familiarisation which included three maximal efforts in MCS. Each subject was instructed to stand with feet shoulder width apart in the middle of a jump mat with weight evenly distributed over both feet (Figure 2.9). The subject held a weapon with both hands in a relaxed position. The subject was then instructed to jump as high as possible with both hands remaining on the weapon. The vertical jump test was performed with a counter-movement immediately before the upward movement (Figure 2.9).

When the equipment was ready to collect data the subjects were instructed that they were free to begin, after which they self-selected when to initiate the vertical jump assessment. The subject landed on the balls of the feet in an upright extended position (i.e. full extension at hips, knees and ankles) (refer to Figure 2.10). Once contact with the ground was made, knees were allowed to bend to soften the impact of landing. The subject had a minimum 2 minutes rest between attempts, to allow adequate recovery.

2.4.1.4.3 Measurements

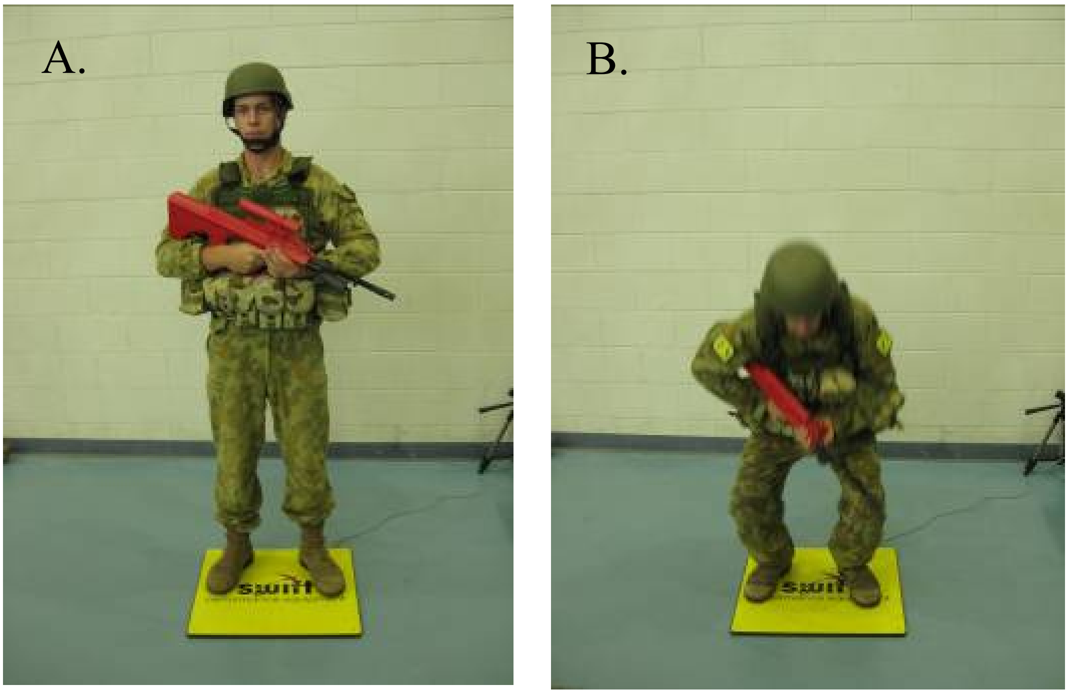
Each subject repeated the assessment three times and the highest jump was recorded for data analysis. A number of measurements were specifically collected;

- Vertical jump height
- Power output

Peak power achieved during the vertical jump was calculated using the following validated equation (Harman *et. al.,* 1990) which has also been has also used in military orientated research (Nindl, *et. al.,* 2007).

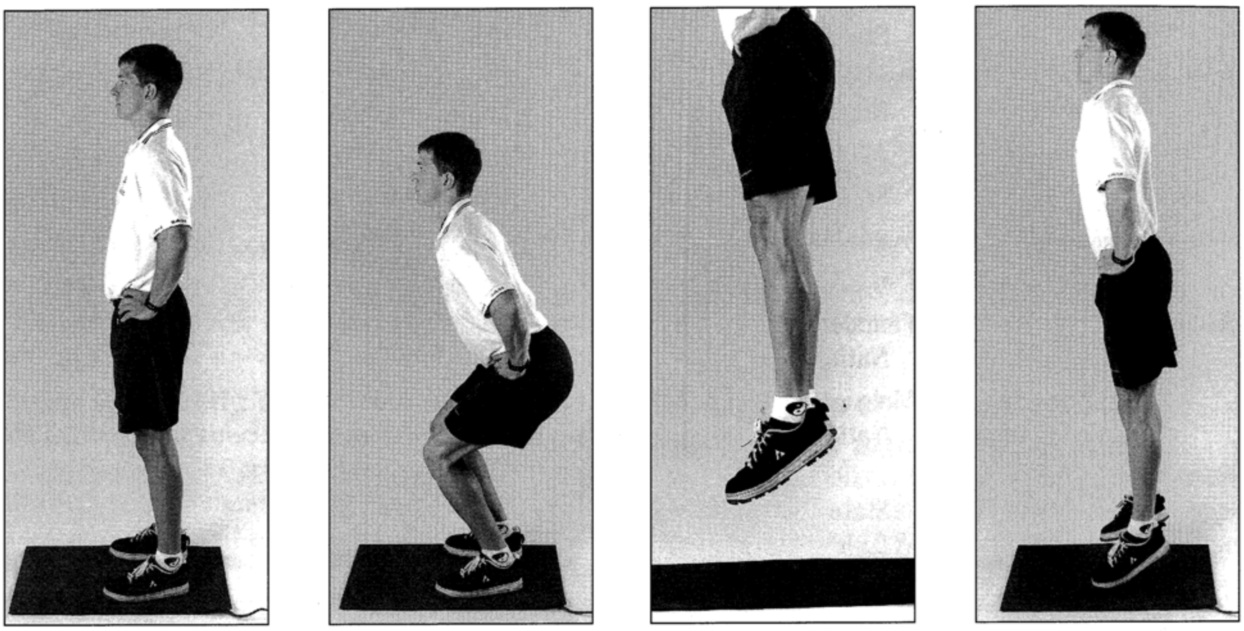
Peak power (W) = {(61 x jump height + (36 x mass)-1822}

Figure 2.9 Images from vertical jump assessment.



A. Subject ready to commence jump. B. Subject performing a counter-movement immediately before the upward movement

Figure 2.10 Representative images of vertical jump performance.



a b c d

2.4.1.5 Assessment 5: Stand and Reach Assessment

2.4.1.5.1 Assessment overview
The purpose of the stand and reach assessment was to measure functional balance in different loaded conditions. This assessment measured the subject's ability to move outside their base of support before loss of balance occurred. This aids in the assessment of the potential impact of different loaded conditions (i.e. body armour ensembles) on the performance of critical military tasks. Subjects completed the stand and reach assessment 18 times; three times per condition including MCS.

2.4.1.5.2 Assessment set-up and data collection
The assessment was conducted on a flat surface and free from hazards or debris that could have potentially caused injury or interfered with performance. A tape measure was attached to the wall at the subject's shoulder height, parallel to the ground. Subjects were instructed to stand with feet shoulder width apart, with the back of their boots aligned to a line marked on the floor. The subject's stood with their dominant side (this may / may not have been the subjects master hand side) touching the wall (i.e. right handed subjects stand with right side of the body against the wall and left handed subjects stand with the left side of the body against the wall). The subject was then instructed to lift both arms to shoulder level (arms 90^{o} to trunk), hands positioned palms facing down (one hand on top of the other) and neutral scapula. This position was marked the 'zero' point, measured from the subjects 3^{rd} finger on the dominant hand. The subjects were then required to reach forward in a horizontal plane beyond their base of support as far as possible without lifting any part of their foot of the ground.

2.4.1.5.3 Measurements
Range of motion was quantified by measuring the distance (cm) of the dominant 3^{rd} finger in a horizontal plane, from the start position to the point at which the subject's heels leave the ground. Bending of the knee joints was not permitted. The subject's median of three attempts for each condition was recorded for data analysis purposes.

2.4.1.6 Assessment 6: Wall Clearance Simulation
A wall clearance simulation (Table 2.5, page 8) was commenced but discontinued due to an unacceptably high level of injury risk and the inability to control for or reduce this risk. The inherent risks associated with the performance of this task included the ground surface conditions (the activity could only be conducted outdoors and on a dirt surface) and the general risk of landing from height with a weight load of up to 29.23 kg. A description of the assessment is provided below for future relevance only.

2.4.1.6.1 Assessment overview
The wall climb asessment was designed to evaluate upper body strength and power. Subjects were required to start from a standing postion, clear a 1.5 m wall (Figure 2.11) then sprint 5 m to clear the area. The average height of the Infantry soldiers in this study was 1.8 m and thus a wall height of 1.5 m puts the top of the wall at approximately chest height. From observations in the field it has been seen that soldiers will find objects to stand on (chairs, other soldiers, etc.) in order to reduce wall height. This is relevant for urban operations (perimeter wall clearance, building entry, etc.) and also for any vehicle mounted missions that require soldiers to ingress/egress from the rear, hatch or turret of the vehicle. The importance lies in minimising the exposure time when clearing the obstacle and then moving to a nearby

point of cover. Eliminating the run up increases the reliance upon the upper body. Whilst leg power may assist in performance of this task, seperation of physical capacities will assist in the identification of factors affecting mobility.

2.4.1.6.2 Assessment set-up and data collection

The assessment was conducted on a flat surface and free from hazards or debris that could have potentially caused injury or interfered with performance. The jump mat was positioned up against the wall on the starting side. Timing gates were set 0.7 m and 5.7 m from the other side of the wall (Figure 2.12). Cones were placed 1 m apart at the finish line (5.7 m from the wall). Timing was initiated when the subject left the start mat. Wall clearance time was recorded when the subject broke the beam of the timing lights on the other side of the wall. Total time and 5 m sprint time was recorded when the subject broke the dual beams at the finishing gate (finishing gate was 5.7 m from the wall and 5.0 m from the first set of timing gates).

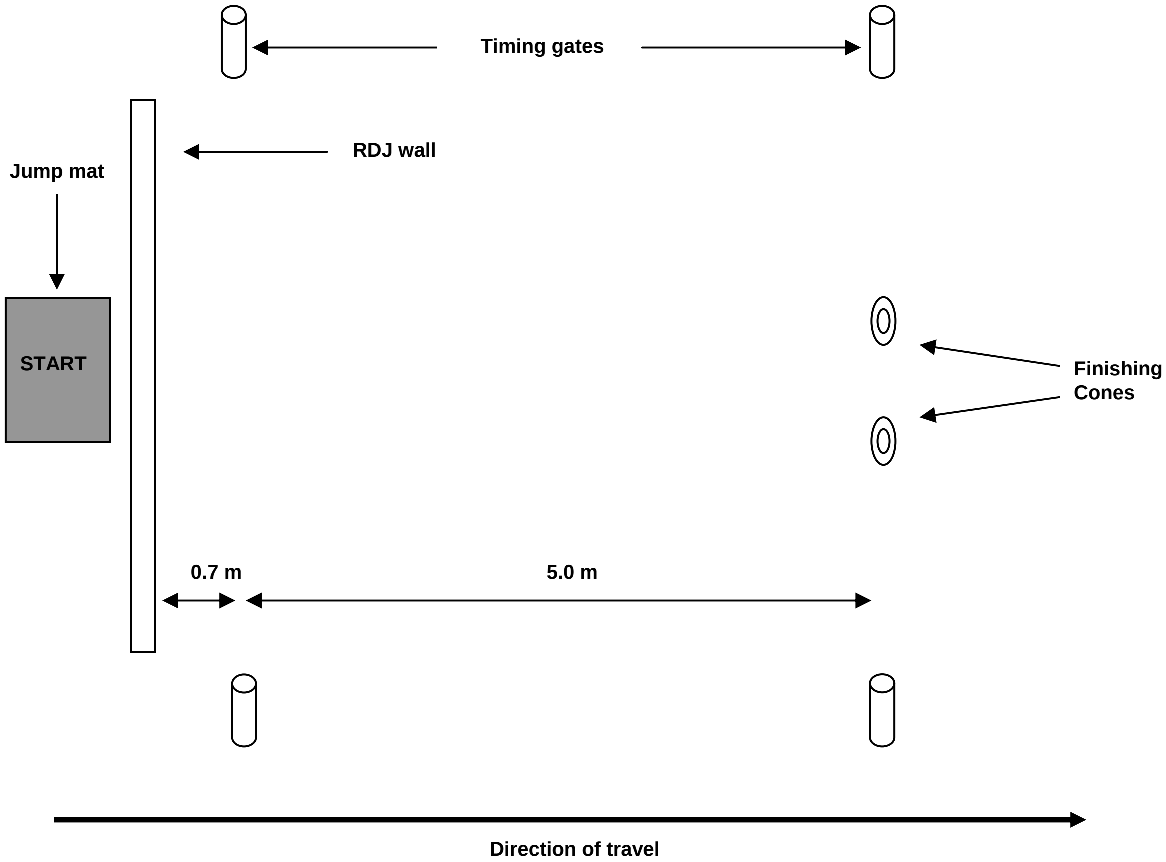
2.4.1.6.3 Measurements

The jump mat and timing gates allowed for three distinct measures of performance to be collected for later analysis. These included;

- Time to clear wall obstacle
- Time to complete 5m sprint
- Total time (wall clearance + 5 m sprint)

Figure 2.11 Representative images of wall clearance performance.

Figure 2.12 Representative diagram of wall clearance simulation layout



3. RESULTS AND DISCUSSION

3.1 Subjects

Thirty-one (31) subjects completed all conditions within one or more of the mobility assessments. Baseline physical characteristics for all subjects are reported in Table 3.1. Mean (± SD) results for the entire subject pool are reported along with the specific assessments (1-5) completed by each subject. Twelve (12) subjects completed all mobility assessments under all conditions. Twenty-two (22) subjects completed three (3) or more mobility assessments under all conditions.

Table 3.1: Subject physical characteristics and completed mobility assessments.

No.	Height (cm)	Weight (kg)	BMI (kg/m^2)	Body Fat (%)	VO_2max [a] ($ml.kg^{-1}.min^{-1}$)	Assessments Completed *
S1	198	112.7	28.7	18.5	48.4	1, 2, 3, 4, 5
S3	183	112.1	33.5	27.9	47.0	1, 2, 3, 4, 5
S4	188	90.2	25.5	16.5	53.0	1, 2, 3, 4, 5
S5	187	106.6	30.5	19.8	46.9	1, 2, 3, 4, 5
S6	182	91.1	27.5	11.7	50.0	1, 2, 3, 4, 5
S7	183	93.7	28.0	10.7	54.5	3
S9	180	76.7	23.7	7.7	55.5	1, 2, 3, 4, 5
S10	178	77.9	24.6	10.1	61.0	2, 3
S11	181	102.1	31.2	26.7	46.7	2, 3, 4, 5
S13	172	71.9	24.3	17.1	51.2	1, 2, 3, 4, 5
S14	176	79.1	25.5	19.8	54.5	2, 3
S16	189	86.8	24.3	9.4	53.5	2, 3, 4, 5
S17	186	91.5	26.4	10.7	51.7	2, 3
S18	175	70.5	23.0	11.8	52.6	2, 3, 4, 5
S19	176	79.5	25.7	18.6	49.2	1, 2, 3, 4, 5
S20	177	87.0	27.8	13.9	49.2	1, 2, 3, 4, 5
S21	180	79.3	24.5	15.0	49.2	2, 3
S22	180	85.1	26.3	16.3	50.8	2, 3, 4, 5
S23	168	62.6	22.2	12.5	50.0	1, 2, 3, 4, 5
S24	178	64.6	20.4	10.7	50.4	2, 3
S25	178	80.4	25.4	19.7	49.2	1, 2, 3, 4, 5
S26	184	69.8	20.6	9.2	54.5	2, 3, 4, 5
S27	168	72.2	25.6	14.1	50.4	2, 3
S28	168	78.9	28.0	15.6	54.5	1, 2, 3, 4
S29	180	65.0	20.1	4.6	62.3	1, 2, 3, 4, 5
S30	174	61.2	20.2	11.3	50.9	2, 3
S31	178	81.9	25.8	15.3	57.5	2, 3
S34	182	87.3	26.4	16.6	52.1	1, 4, 5
S35	176	67.0	21.6	9.9	51.9	1, 4, 5
S36	180	72.1	22.3	6.0	55.5	1, 4, 5
S37	166	63.6	23.1	11.2	54.5	1, 4, 5
Mean ± SD	**179.7 ± 7.0**	**84.7 ± 13.4**	**26.1 ± 3.1**	**16.1 ± 6.1**	**51.0 ± 3.4**	

BMI = Body Mass index; mass (kg) / height $(m)^2$. VO_2max^a = predicted maximal aerobic power ($ml.kg^{-1}.min^{-1}$) from 2.4 km run. * Tests: 1 = Fire and Movement; 2 = Obstacle avoidance; 3 = Combat rush; 4 = Vertical jump; 5 = Stand and reach.

Subject characteristics for each individual mobility assessment are summarised in Table 3.2. There were no differences (*P>0.05*) in subject physical characteristics between the mobility assessments thus allowing between (inter) assessment comparisons.

Table 3.2: Summary baseline subject characteristics for each mobility assessment.

Assessment *	N	Height (cm)	Weight (kg)	BMI (kg/m^2)	Body Fat (%)	VO_2max [a] ($ml.kg^{-1}.min^{-1}$)
1	17	178 ± 8	82.6 ± 16.1	25.6 ± 3.5	14.5 ± 5.8	51.7 ± 3.8
2	25	179 ± 7	82.9 ± 14	25.6 ± 3.2	15.0 ± 5.7	51.8 ± 4.0
3	27	179 ± 7	82.6 ± 14.1	25.5 ± 3.3	14.6 ± 5.4	52.0 ± 3.9
4	22	180 ± 7	81.5 ± 15.6	25.3 ± 3.5	13.9 ± 5.4	52.0 ± 3.6
5	21	180 ± 7	82.8 ± 15.5	25.4 ± 3.5	14.5 ± 6.1	51.5 ± 3.7

Data are mean ± standard deviation,* Assessment; 1 = Fire and Movement; 2 = Obstacle avoidance; 3 = Combat rush; 4 = Vertical jump; 5 = Stand and reach. BMI = mass (kg) / height $(m)^2$, VO_2max^a = predicted maximal aerobic power ($ml.kg^{-1}.min^{-1}$) from 2.4 km run.

3.2 Effect of order independent of condition

The application of a Latin square design was a very important aspect of the methodological design for this study. This design allowed for a within subject control whereby no condition is advantaged or disadvantaged more than any other condition. In saying this, it is always appropriate that the data is cross checked to confirm this theory.

Table 3.3 shows the total bound time and mean bound time (n=13) against the testing session order, independent of condition. There were no differences ($P>0.05$) between total bound times or mean bound times between the testing sessions. Despite the fire and movement assessment being performed repeatedly over the five testing sessions (three days of testing) there were no differences in performance across these sessions (independent of condition). The ranking from fastest to slowest total time and mean bound time suggest there was no systematic learning or fatigue effects influencing performance across the five testing sessions.

Table 3.3: Total time and mean bound times across the testing sessions.

Ranking (fastest to slowest)	Testing Session No.	Total Time (sec)	Testing Session No.	Mean Bound Time (sec)
1	5	14.61 ± 0.80	3	1.22 ± 0.10
2	1	14.74 ± 1.06	5	1.22 ± 0.07
3	3	14.75 ± 1.24	1	1.23 ± 0.08
4	4	14.90 ± 0.91	4	1.24 ± 0.07
5	2	15.03 ± 0.87	2	1.25 ± 0.06

Data are mean ± SD, n = 17, Assessment order: 1 = data collection 1; 2 = data collection 2; 3 = data collection 3; 4 = data collection 4; 5 = data collection 5.

Table 3.4 shows the mean bound time for each individual bound 1-12. There were no significant differences found between any mean bound times. Interestingly, there was some evidence of pacing (possibly subconscious), whereby the 'maximal effort' is distributed across all twelve bounds. In other words, bounds 1 and 2 were the fastest, yet bounds 3 and 4 were in 10th and 12th place. Evidence of such maximal pacing is supported in the sporting literature. A review (Tucker., 2009) of the pacing strategies adopted by world-record breakers during the 1-mile run revealed that the slowest laps in 90% of world-record performances were either the second (34%) or the third (56%) laps. In 76% of races the final lap was either the fastest (38%) or the second fastest (38%) lap. In addition, this pacing is also supported on a physiological basis (St. Clair-Gibson, 2006). The results for the fire and movement bound times (independent of condition) suggest the subjects adopted a pacing strategy similar to these world-class athletes.

Table 3.4: Bound times independent of condition for bounds 1-12.

Place (fastest to slowest)	Bound number	Mean Time (sec)
1	1	1.18 ± 0.08
2	2	1.19 ± 0.09
3	7	1.20 ± 0.11
4	12	1.20 ± 0.13
5	6	1.20 ± 0.11
6	10	1.21 ± 0.10
7	5	1.21 ± 0.11
8	8	1.21 ± 0.11
9	9	1.21 ± 0.12
10	4	1.22 ± 0.13
11	11	1.22 ± 0.13
12	3	1.23 ± 0.16

Data are mean ± SD, n = 17.

All other mobility assessments demonstrated a similar response with respect to order of assessment. Tables 3.5-3.8 demonstrate that there were no significant differences across assessment sessions. In addition, obstacle avoidance, combat rush and standing reach did not demonstrate any trends that would indicate either a learning or a fatigue effect over time.

Despite no significant differences, vertical jump did show a clear trend (*P=0.09*) for progressive improvement from assessment 1 through to assessments 4 and 5.

These results of mobility performance, independent of condition, add weight to any findings that demonstrate significant differences for the conditions under evaluation in this study. It also confirms the scientific rigor of the Latin square design employed in this investigation in order to reduce the potential bias across the various conditions.

Table 3.5: Ranking table for obstacle avoidance assessment (fastest total time) with regards to order of session (independent of condition). Data are mean ± SD, n = 25.

Ranking (fastest to slowest)	Testing Session No.	Total Time (sec)
1	1	10.35 ± 0.43
2	5	10.40 ± 0.33
3	4	10.46 ± 0.46
4	3	10.46 ± 0.35
5	2	10.65 ± 0.57

Table 3.6: Ranking table for combat rush assessment (fastest total time) with regards to order of session (independent of condition). Data are mean ± SD, n = 27.

Ranking (fastest to slowest)	Testing Session No.	Total Time (sec)
1	2	5.51 ± 0.65
2	4	5.58 ± 0.35
3	3	5.64 ± 0.0.36
4	1	5.65 ± 0.0.74
5	5	5.82 ± 0.34

Table 3.7: Ranking table for vertical jump assessment (height) with regards to order of session (independent of condition). Data are mean ± SD, n = 22.

Ranking (lowest to highest)	Testing Session No.	Vertical height (m)
1	1	0.248 ± 0.040
2	2	0.252 ± 0.032
3	3	0.258 ± 0.045
4	5	0.264 ± 0.045
5	4	0.269 ± 0.046

Table 3.8: Ranking table for stand and reach assessment (displacement) with regards to order of session (independent of condition). Data are mean ± SD, n = 21.

Ranking (closer to furthest)	Testing Session No.	Reach (cm)
1	3	31.6 ± 5.4
2	4	32.6 ± 5.5
3	5	32.8 ± 5.0
4	1	33.2 ± 4.6
5	2	33.6 ± 6.0

3.3 Fire and movement simulation

3.3.1 Effect of condition on bound time

Seventeen (17) subjects completed all conditions (MCS & T0-T4) of the fire and movement assessment. Figure 3.1 shows each mean bound time (1-12) for all conditions. As expected, MCS was significantly different to all Tiers. T0 was not significantly faster than either T1 or T2, and T2 and T3 were in turn not significantly faster than T4. This staircase effect of each Tier not being significantly different from the next was also evident when expressed as the overall mean bound time (Figure 3.2).

The ideal bound time (fastest time recorded during the 12 bounds) (Figure 3.3) continued to display the same staircase effect. Once more MCS was significantly faster than T0-T4. However, the ideal (fastest) bound time for T0 was only significantly different to T4.

Total bound time (sum of bounds 1-12), represents the total exposure time when performing repeated high intensity bouts. The time is directly related to the soldiers' ability to cover 12 x 5 m distance (60 m). A difference in total bound time simply indicates a difference in time spent upright and running but does not include any transition from prone to standing. Once again, soldiers wearing MCS were able to cover the 60 m significantly quicker than all Tiers (Figure 3.4). Total bound time between Tiers continued to display a staircase effect. That is, T0 was significantly different to T2, T3, and T4. No difference was found between T1, T2 and T3. Most notably T4, despite the weight difference of 4.22 kg and 3.25 kg was not different to T2 and T3, respectively.

It was evident that subjects were unable to complete every bound as quickly as their fastest or ideal bound time. The fatigue index was calculated as loss of performance over 12 bounds relative to the ideal (fastest) bound time if it was maintained over 12 bounds. There was a large degree of variation and no significant fatigue effect (Figure 3.5).

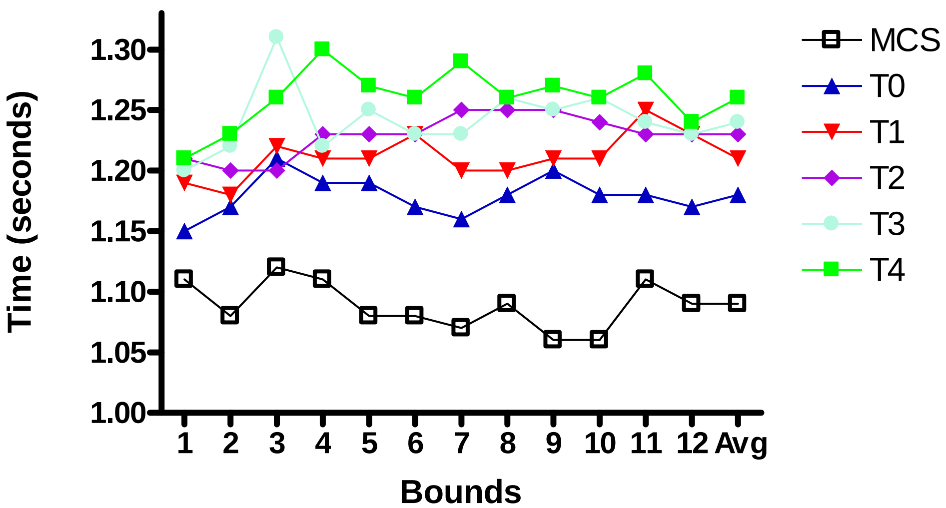


Figure 3.1: Bound times (bounds 1-12) and mean bound time for military clean skin (MCS) and Tier 0 - Tier 4. Data are means (with no error bars showing to add clarity).

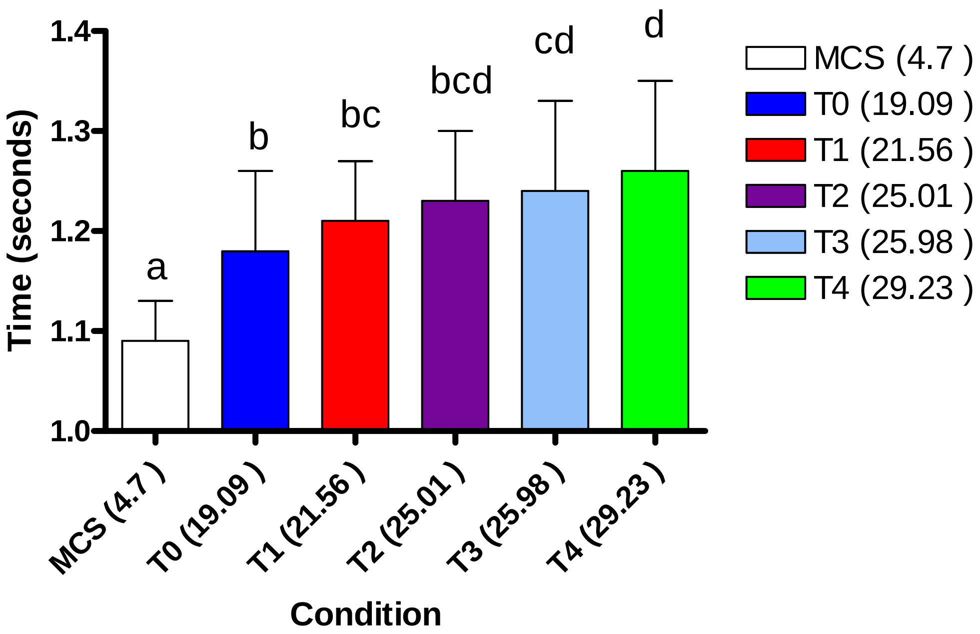


Figure 3.2: Mean bound time for military clean skin (MCS) and Tier 0 - Tier 4. Conditions not sharing common letter are significantly different (P<0.05). Data are means with standard deviations (error bars).

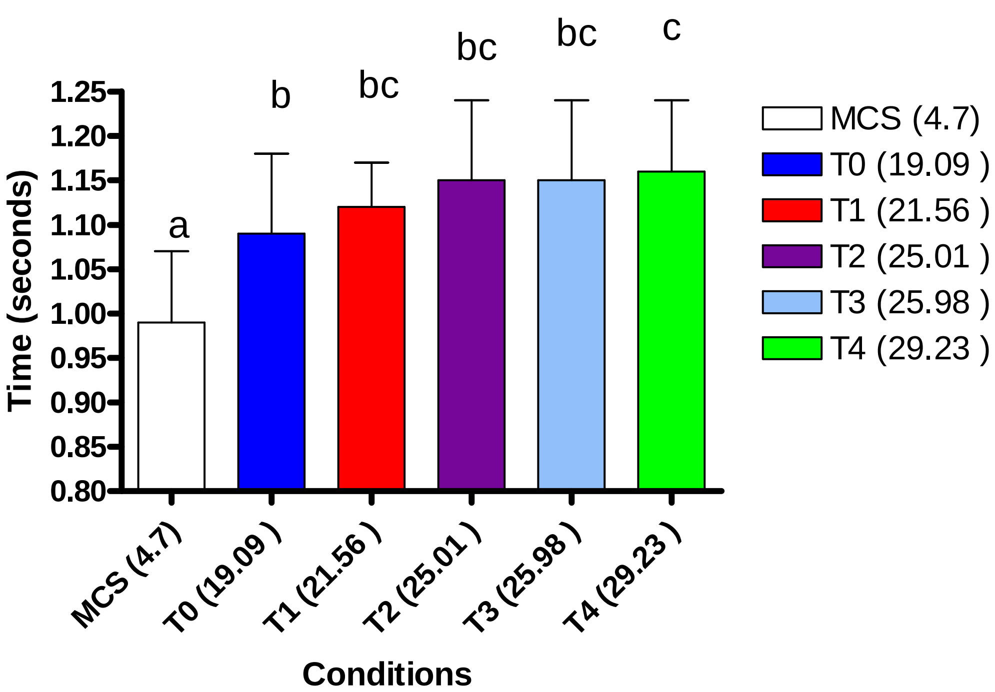


Figure 3.3: Ideal bound time for military clean skin (MCS) and Tier 0 - Tier 4. Weight carried for each condition is displayed in brackets (kg). Conditions not sharing common letter are significantly different ($P<0.05$). Data are means with standard deviations (error bars).

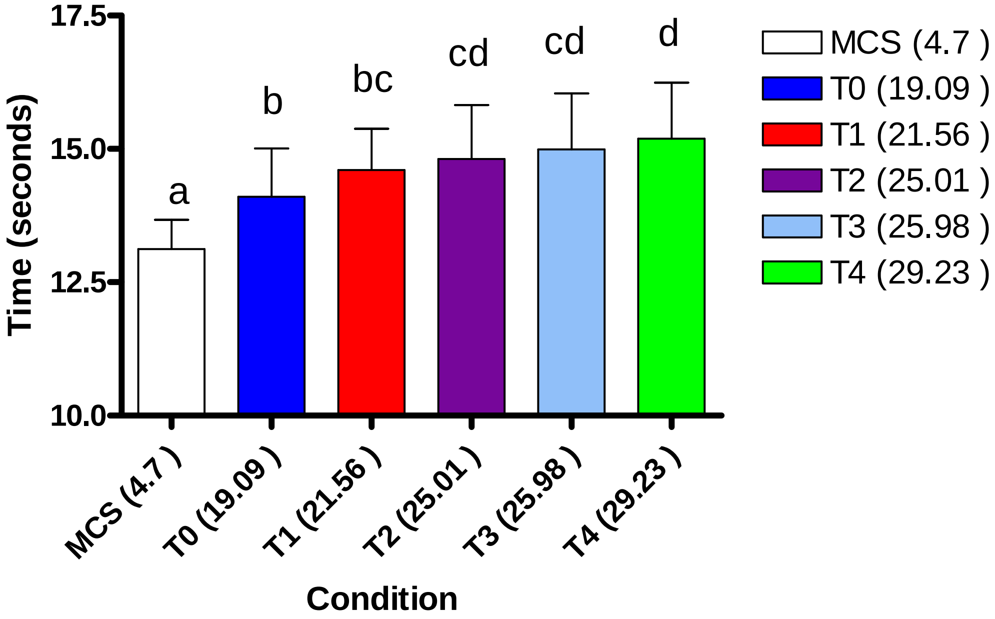


Figure 3.4: Total bound time (sum of bounds 1-12) for military clean skin (MCS) and Tier 0 - Tier 4. Weight carried for each condition is displayed in brackets (kg). Conditions not sharing common letter are significantly different (*P<0.05*). Data are means with standard deviations (error bars).

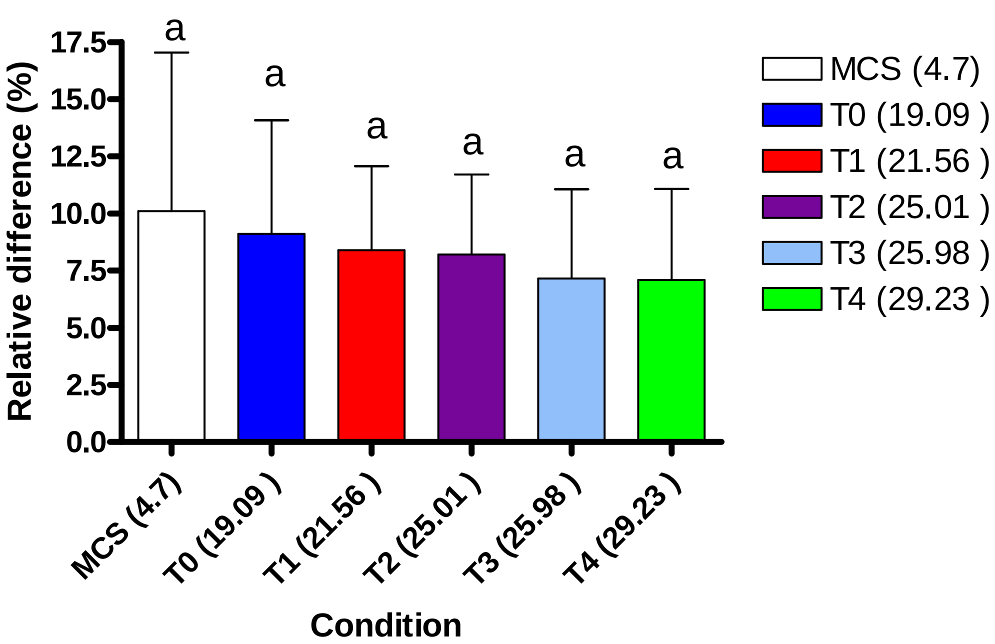


Figure 3.5: Fatigue Index for military clean skin (MCS) and Tier 0 - Tier 4. Conditions not sharing common letter are significantly different (*P<0.05*). Data are means with standard deviations (error bars).

Figure 3.6 shows the relationship between relative mass carriage and total bound time. That is, knowing exactly the subject's weight and the absolute load carriage, a relative mass was calculated and correlated to total performance over 12 bounds. Of particular note was the large range of relative mass carriage across the conditions and the subjects. This can be explained by the large variation in the body mass throughout the pool of subjects (112.7 kg - 62.6 kg).

There was no relationship between relative mass carriage and total bound time independent of condition (r=-0.11; $P=0.35$) (Figure 3.6). However, T0 was different for all other conditions. That is, as relative load carriage increased the total bound time also increased and the relationship was significant (r=0.49; $P<0.05$). The explanation may come from the fact the T0 was the ICLCE vest and displayed larger bulk (weight further from the midline) compared to all other Tiers. Bulk has been shown to impact negatively on mobility (Angel, 2008).

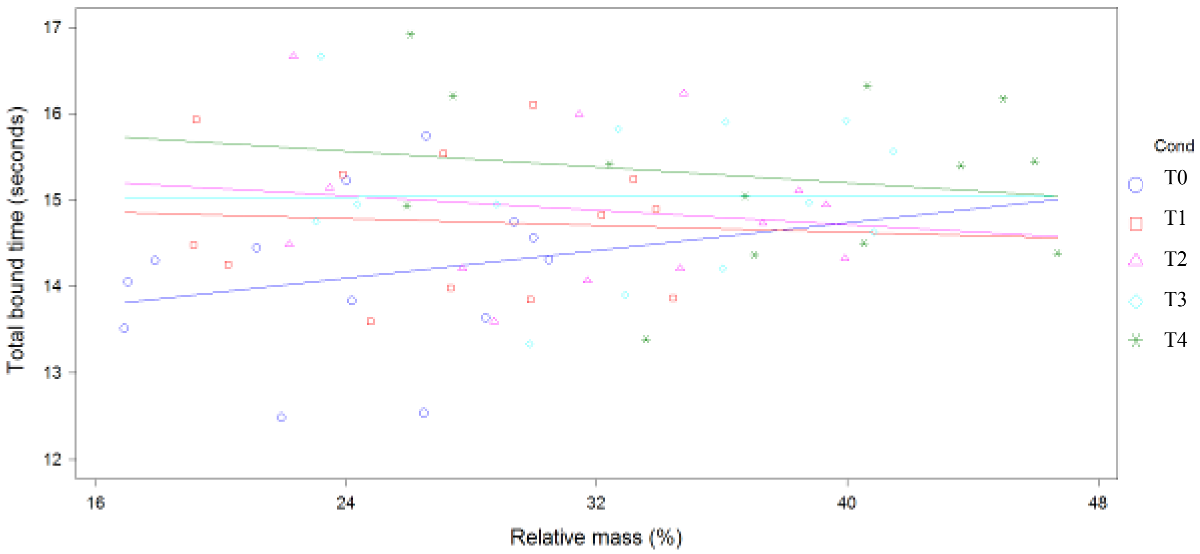


Figure 3.6: Correlation of total bound time versus relative mass (%) (r=-0.11; $P=0.35$ independent of condition) for military clean skin (MCS) and Tier 0 - Tier 4.

Body fat percentage (%) was also matched against total bound time (Figure 3.7). Noting the limitations mentioned previously, when working with indirect anthropometric measures, there was a significant corelation (r=0.43; $P<0.05$). That is, as body fat (%) increased there was a moderated increase in time to complete 12 bounds. However, with a sample size of 17 and only one subject with greater than 20% body fat, further investigation with a broader population is required to confirm these results.

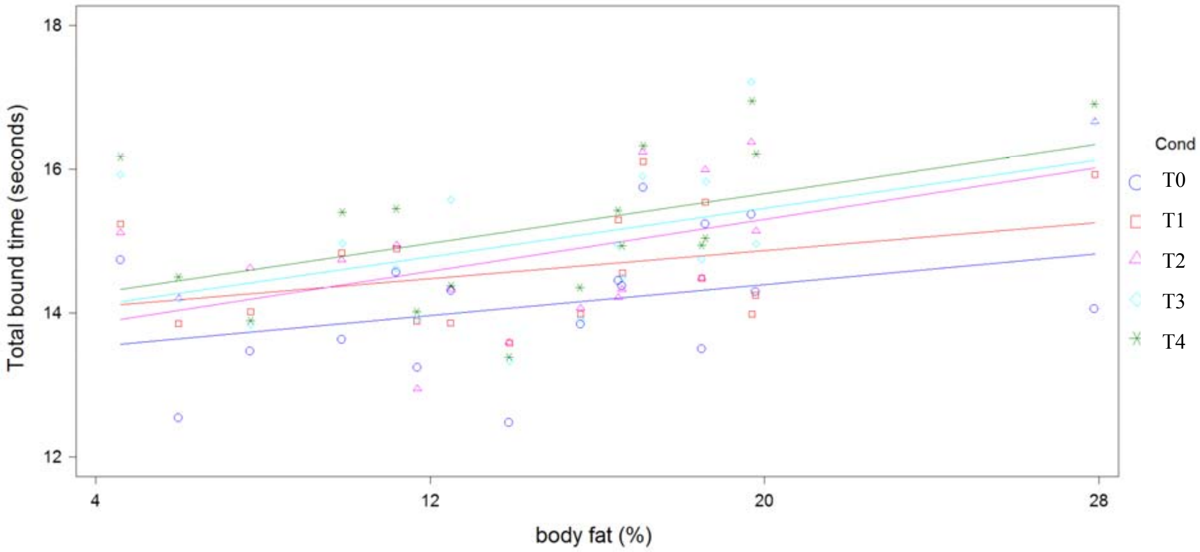


Figure 3.7: Correlation of total bound time versus body fat (%) (r=0.43; *P<0.05*) independent of condition. There were no differences for military clean skin (MCS) and Tier 0 - Tier 4.

3.3.2 Effect of condition on prone to feet movement

The mean time to move from prone to feet is shown in Figure 3.8. It clearly demonstrates that subjects moved significantly quicker from prone to running in MCS. There was no significant difference from T0-T3. However, in T4, there was a significant slowing of absolute time compared to all other conditions.

The prone-to-feet transition of a representative subject was broken down and subjectively examined at 0 (start) 25, 50 and 75 and 100% (finish) of time to complete the movement. Figure 3.9 provides a pictorial illustration at these time points for the MCS, T0 and T4 conditions. Differences in technique are apparent at each stage throughout the series. Of note is the apparent need to have limbs positioned further underneath the worn external mass in order to affect the rise from the prone position (especially apparent in the 25% and 50% comparisons) as weight-load increases. Additionally, a very upright torso is presented at 50% when wearing T4 as compared to MCS and T0. This movement sequence appears to result in a relatively stationary exposure to the enemy force that could prove to be critical on the battlefield. At an identical time point in the series (1.28 s) the subject has completed the prone-to-feet transition in T0 while only being at the 75% stage wearing T4. The relationship between weight load and prone-to-feet transition mechanics requires further investigation.

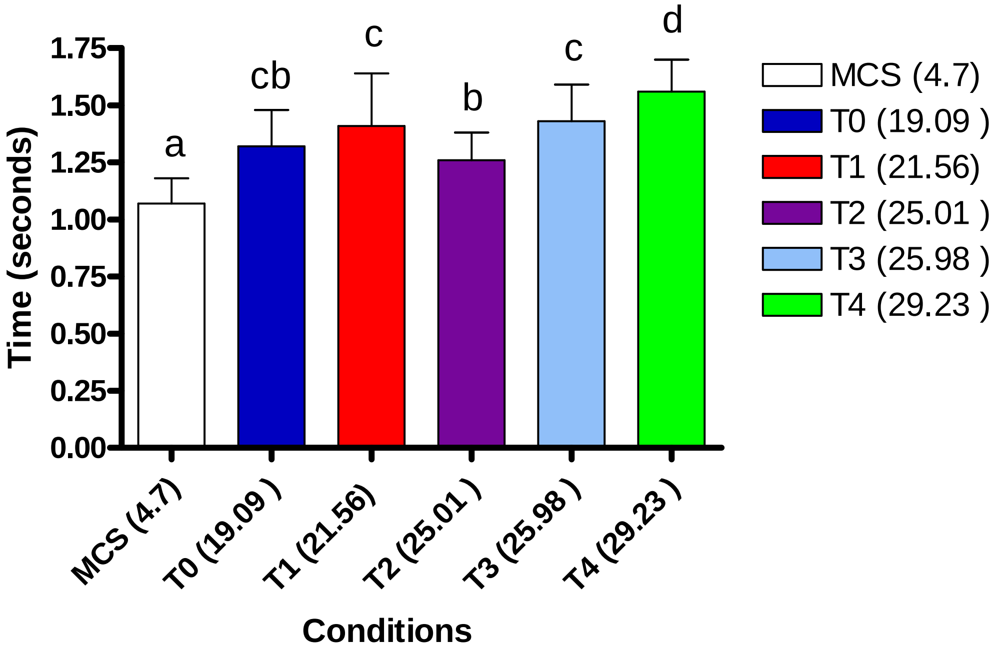


Figure 3.8: Mean prone to feet time for military clean skin (MCS) and Tier 0 - Tier 4. Conditions not sharing common letter are significantly different *($P<0.05$)*. Data are means with standard deviations (error bars).

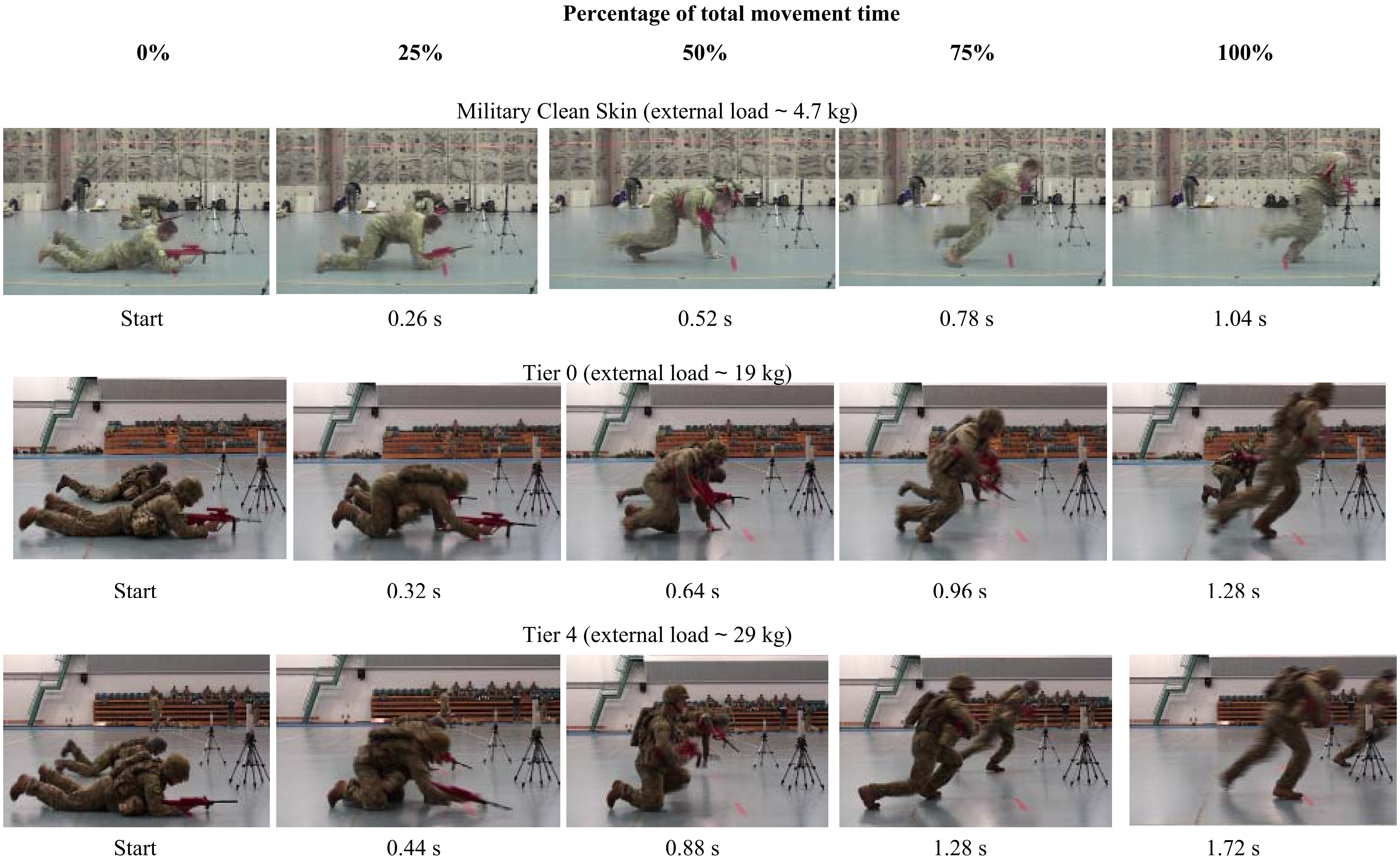


Figure 3.9: Series of pictures illustrating the movement mechanics of a subject wearing MCS, Tier 0 and Tier 4 at different stages of the prone-to-feet transition. Also indicated is the elapsed time at each stage.

3.3.3 The effect of condition on cardiovascular system

Despite the individual bounds (rise from a prone position – sprint 5 m) having a large anaerobic requirement, there was evidence of cardiovascular strain when the bound was repeated 12 times with limited recovery.

Independent of condition, mean heart rate during 4 minute 45 seconds of fire and movement was greater than 150 bpm (Figure 3.10). This represented on average that subjects were working at greater than 70% of maximal heart rate. It is anticipated that the cardiovascular response was a direct attempt by body systems to recover before the next maximal sprint effort.

Maximal heart rate for this assessment was the peak heart rate recorded at the completion of assessment. This heart rate corresponded to bound 12 or just after the completion of the bound. Independent of condition, maximal recorded heart rates were significantly greater than the mean heart rate. This is an indication of the accumulative effect of the repeated anaerobic efforts on the cardiovascular system. In other words, with such a short recovery period afforded between bounds, heart rate never recovered to levels pre-bound 1, and each bound then placed a greater load on the requirement for cardiovascular support. This aerobic demand over repeated sprinting is supported in the literature (Wadley and Rossignol, 1998).

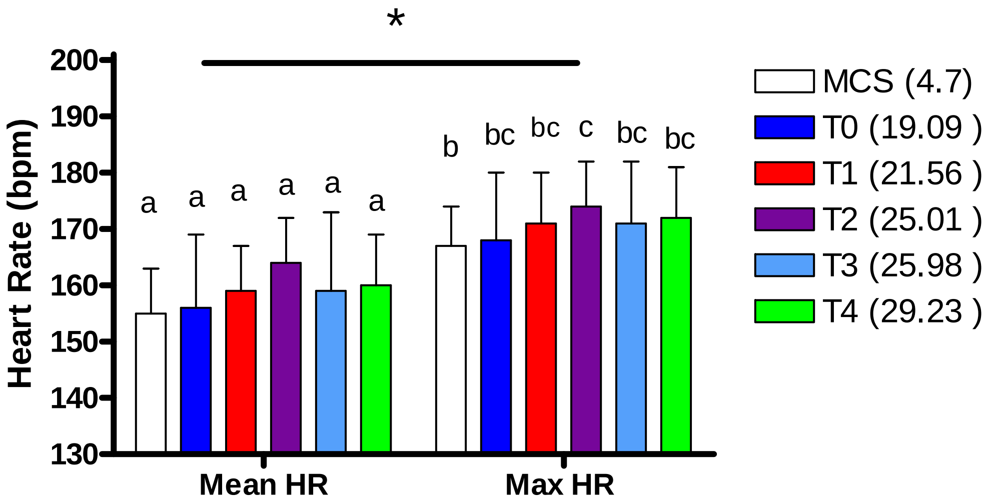


Figure 3.10: Mean and maximal heart rates during fire and movement assessment for military clean skin (MCS) and Tier 0 - Tier 4. Conditions not sharing common letter are significantly different *($P<0.05$)*. * is a significant difference between mean heart rate and maximal heart *($P<0.05$)*. Data are means with standard deviations (error bars).

On the basis that the fire and movement assessment does elicit a large cardiovascular response a number of relationships could prove to be valuable in explaining performance. The first relationship (Figure 3.11) shows that as relative mass carriage increases independent of condition, so too does the maximal elicited heart rate (r=0.27; *$P<0.05$* independent of condition). There was no difference between T0 and T1-4.

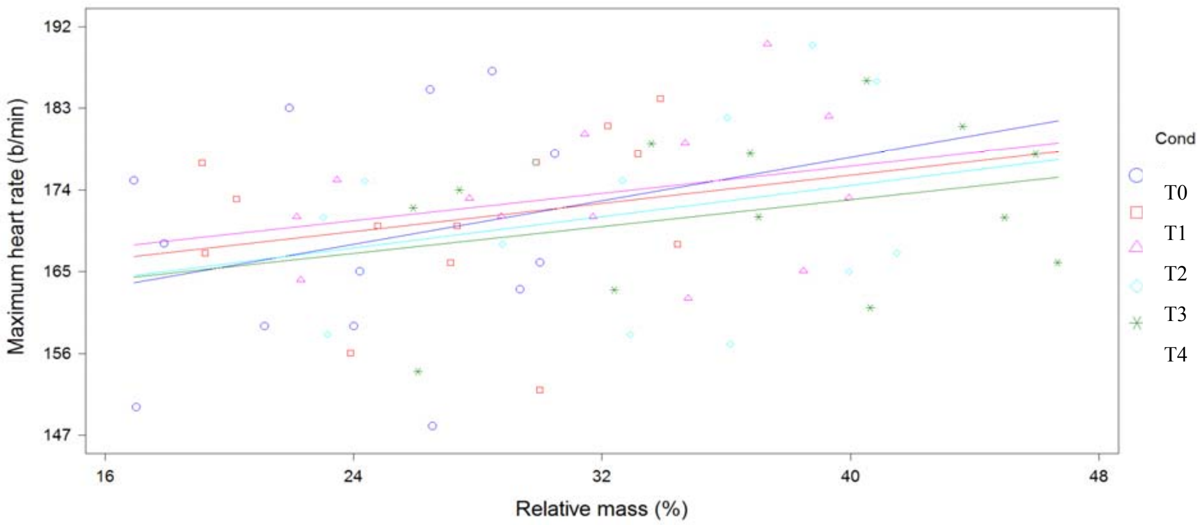


Figure 3.11: Correlation of maximum heart rate (beats/minute) versus body relative mass (%) (r=0.27; *P<0.05* independent of condition) for military clean skin (MCS) and Tier 0 - Tier 4.

The evidence for a large cardiovascular requirement to complete the fire and movement simulation would suggest that there may be a secondary relationship between performance in this assessment and the maximal oxygen consumption of a subject. Once again, caution needs to be adhered to, as the baseline subject characteristics for aerobic capacity is a predicted measure from the 2.4 km timed run. Equally, subject numbers to compete all conditions in the current study do not lend themselves for large predictions. Figure 3.12, shows the relationship between predicted VO_2max and total bound time. There was no significant effect of aerobic capacity on the performance of fire and movement assessment within this group. However, the group did display a rather tight scatter between 46 – 56 $ml.kg^{-1}.min^{-1}$ with only one subject > 60 $ml.kg^{-1}.min^{-1}$.

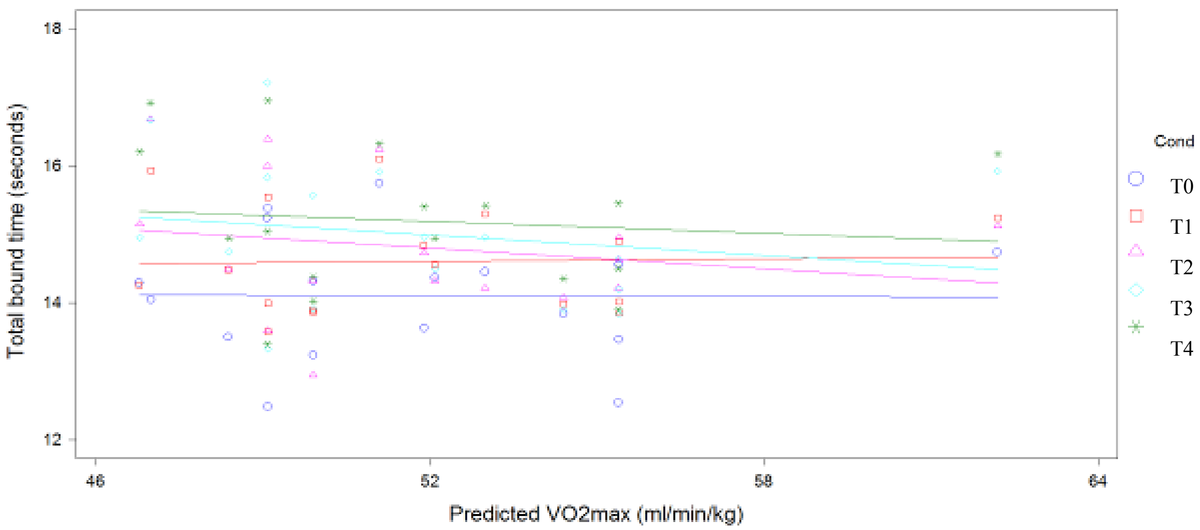


Figure 3.12: Correlation of total bound time (sec) versus predicted VO_2max ($ml.kg^{-1}.min^{-1}$). There was no relationship found independent of condition or for military clean skin (MCS) and Tier 0 - Tier 4.

Evidence in the literature also points to a weak relationship between repeated anaerobic sprinting and maximal oxygen consumption, despite the drive in heart rate (Wadley and Rossignol, 1998). In fact, the only relationship linked to repeated sprint performance and total time was the fastest recorded single sprint time. This indicates that there is still a large determinant placed upon the anaerobic energy systems.

3.4 Obstacle avoidance simulation

Twenty five (25) subjects completed all conditions (MCS & T0– T4) for the obstacle avoidance assessment. Figure 3.13 shows time to the first gate is reported as an indication of raw acceleration and time taken to negotiate the first turning pole as a single measurement of the ability to change direction or overcome inertia.

Acceleration time was only significantly different between MCS and T4. This distance represents raw acceleration using a dominant energy supply of intra-muscular sources, such as adenosine triphosphate (ATP). Within the weight range of Tiers (19.1 kg – 29.2 kg), there was no impact on this ability to accelerate. Most notably, this finding is in support of the acceleration measurements observed in the combat rush assessment (Figure 3.17). Turn time (Figure 3.13) was quickest in the MCS condition. There was no significant difference found between T1-3. Equally T4 was not significantly slower than T2 and T3.

The fastest total time was then the best representative of overall turning ability. Figure 3.13, shows clearly the MCS condition was significantly quicker compared to T0-T4. From that point no Tier was significantly different to the corresponding Tier. However, as weight increased from T0 (19.1 kg) to T4 (29.2 kg) there was evidence for a significantly accumulative slowing of turning ability. If increased absolute weight of 10.1 kg affected the total time, the impact of relative weight was not strong (Figure 3.14). T1-T4 demonstrated a weak relationship between increased relative mass and reduced performance times.

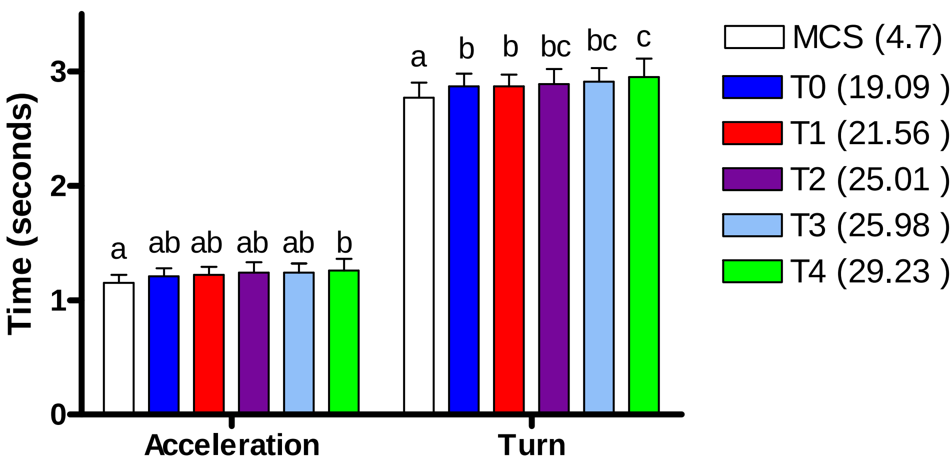


Figure 3.13: Acceleration time (5 m) and turn time for obstacle avoidance for military clean skin (MCS) and Tier 0 - Tier 4. Conditions not sharing common letter are significantly different *(P<0.05)*. Data are means with standard deviations (error bars).

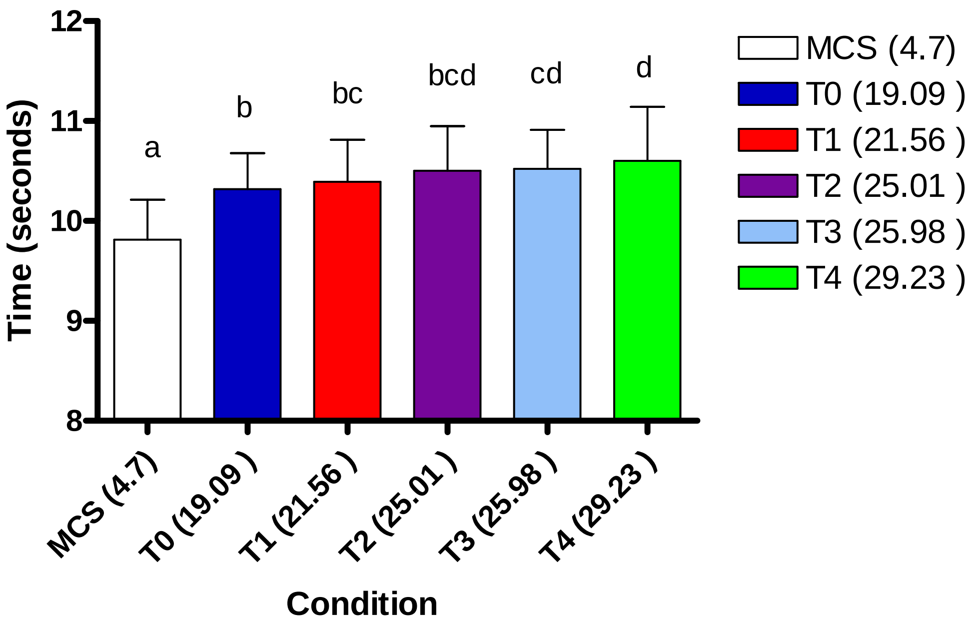


Figure 3.14: Fastest total time for obstacle avoidance for military clean skin (MCS) and Tier 0 - Tier 4. Conditions not sharing common letter are significantly different *(P<0.05)*. Data are means with standard deviations (error bars).

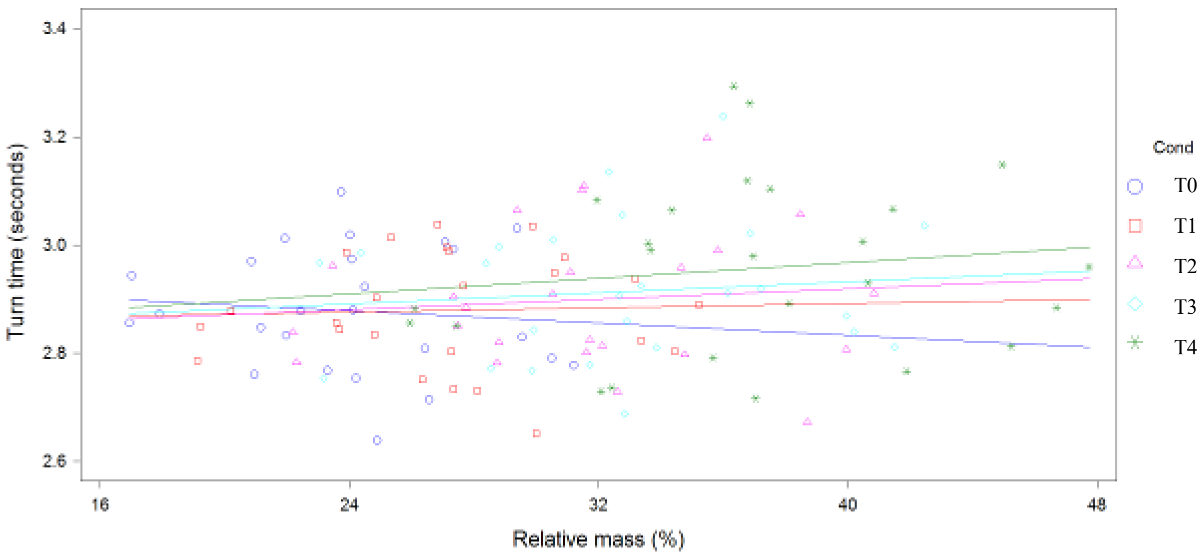


Figure 3.15: Correlation of fastest turn time versus relative mass (%) (r=0.2; *P<0.05*) for military clean skin (MCS) and Tier 0 - Tier 4 during the obstacle avoidance assessment.

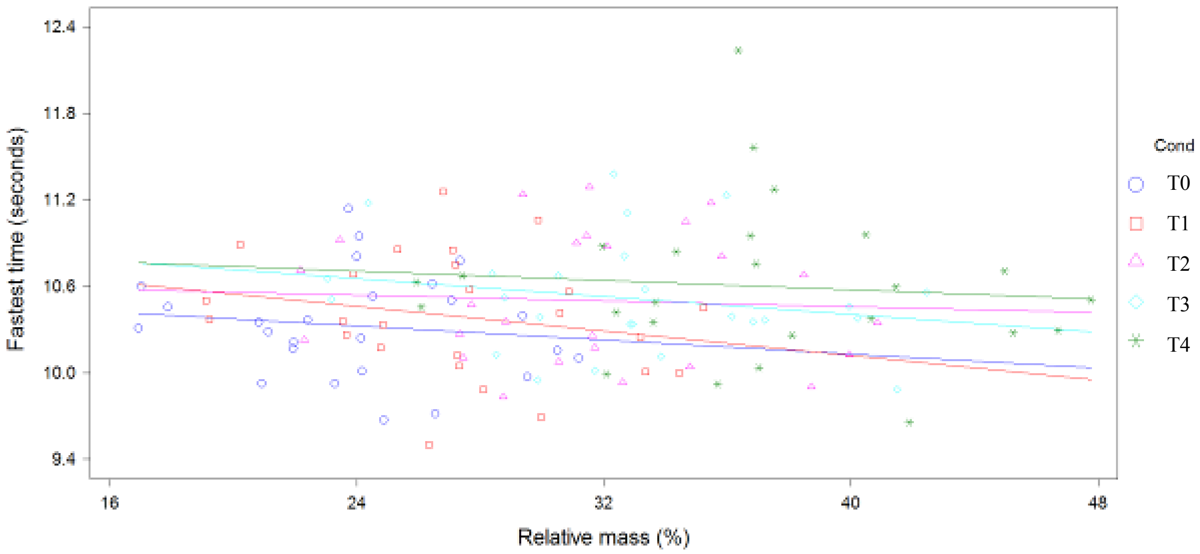


Figure 3.16: Correlation of fastest time versus relative mass (%) (r=0.27; not significant) for military clean skin (MCS) and Tier 0 - Tier 4 during the obstacle avoidance assessment.

3.5 Combat rush simulation

Twenty-seven (27) subjects completed all conditions (MCS & T0-T4) of the combat rush assessment. Figure 3.17 shows the spilt times at 5 m, 10 m and 20 m. There was no significant difference between MCS and any of the T0-T4. This indicates that within the weight range (19.1 kg – 29.2 kg), there was no negative impact on acceleration. Most notably, this finding is in support of acceleration results from the obstacle avoidance assessment.

The next two splits were collected at 10 m and 20 m. At these points pure acceleration turns to maximal speed. It was at this point that MCS was significantly faster at both 10 m and 20 m compared to all T0-T4. However, once more, no significant difference between T0-T4 (Figure 3.17) could be found.

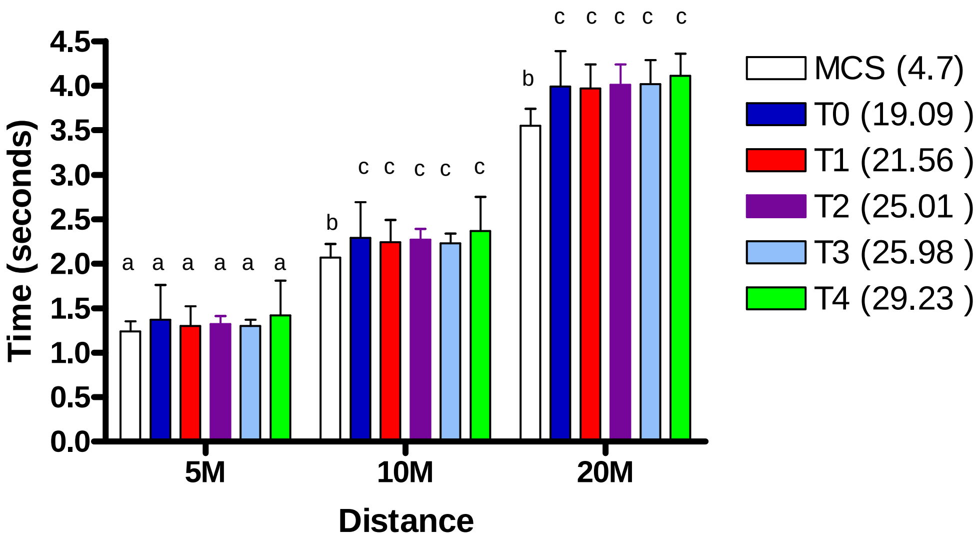


Figure 3.17: Combat rush to 5 m, 10 m and 20 m for military clean skin (MCS) and Tier 0 - Tier 4. Conditions not sharing common letter are significantly different (*P<0.05*). Data are means with standard deviations (error bars).

The fastest time over 30 m is shown in Figure 3.18. At this point maximal speed is shifting to maximal sustained speed. Yet again, MCS was significantly faster than all other Tiers. Within the Tier conditions (0 – 4) there was no particular trend or pattern. Only T1 was significantly slower than T4. This is confirmed by looking at the placement of each Tier from fastest to slowest. T0, the control, demonstrated the second slowest time behind T4.

Figure 3.19 shows the correlation of relative mass carriage versus the fastest total time. There was no significant relationship independent of condition. However, and linked to the observation above of T0 demonstrating the second slowest time, there was a weak (r=0.32) and approaching a significant *(P=0.09)* relationship. In other words, the control condition was most affected by a relative increase in mass and this may be attributed to bulk (Angel, 2008).

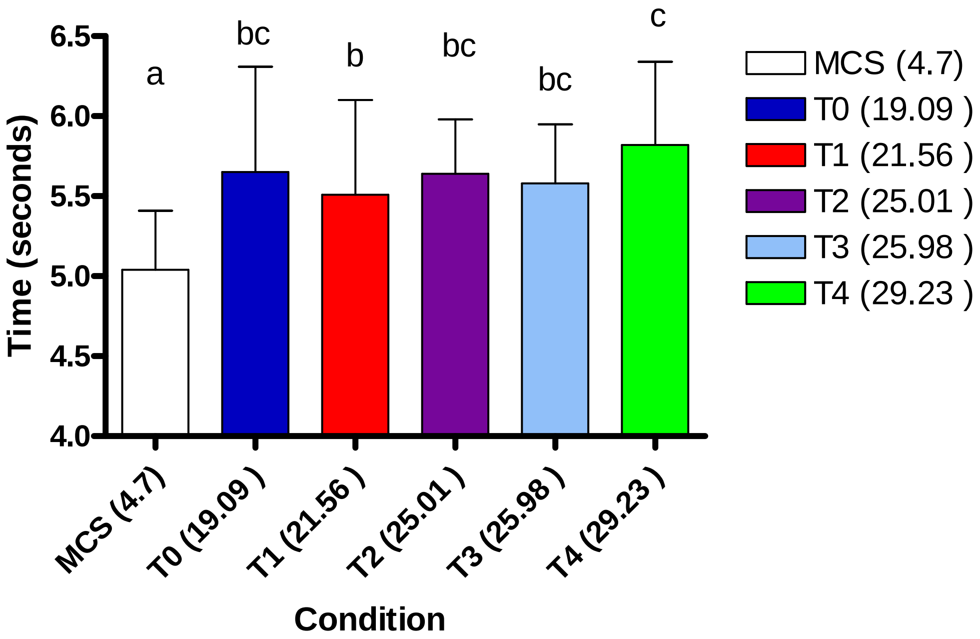


Figure 3.18: Combat rush fastest total time for military clean skin (MCS) and Tier 0 - Tier 4. Conditions not sharing common letter are significantly different *(P<0.05)*. Data are means with standard deviations (error bars).

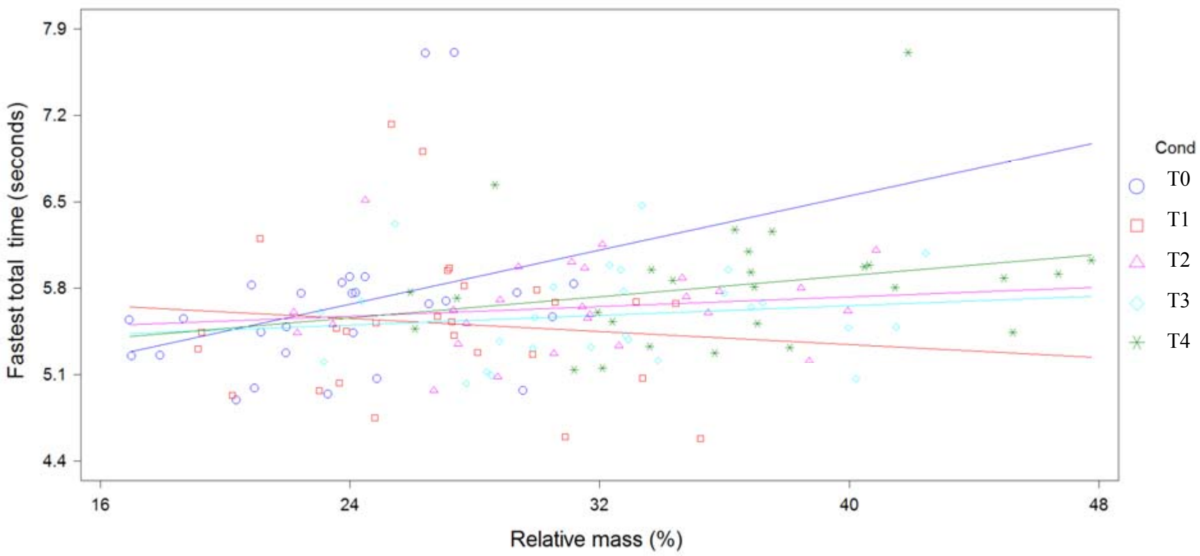


Figure 3.19: Correlation of fastest combat rush time versus relative mass (%) (r=0.2; not significant) for military clean skin (MCS) and Tier 0 - Tier 4.

3.6 Vertical jump

Twenty two (22) subjects completed all conditions (MCS & T0-T4) of the vertical jump assessment. Figure 3.20, shows the absolute vertical jump height for MCS and T0-T4. The height achieved in MCS was significantly greater than all other conditions. Equally the T0 condition was significantly greater than T2-T4. T1-T4 were not different to each other. As displacement was in the vertical plane and against gravity, the effect of relative load seemed like an obvious determinant of performance. However, from the results there was no significant relationship in jump height performance and relative load increase that could also be attributed to condition (Figure 3.21).

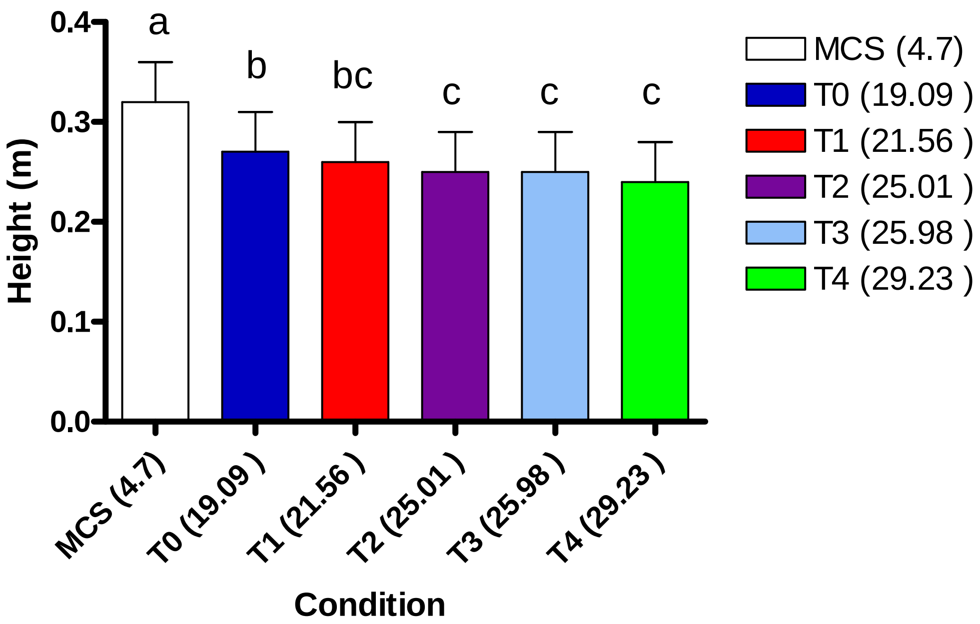


Figure 3.20: Vertical jump (height) for military clean skin (MCS) and Tier 0 - Tier 4. Conditions not sharing common letter are significantly different *($P<0.05$)*. Data are means with standard deviations (error bars).

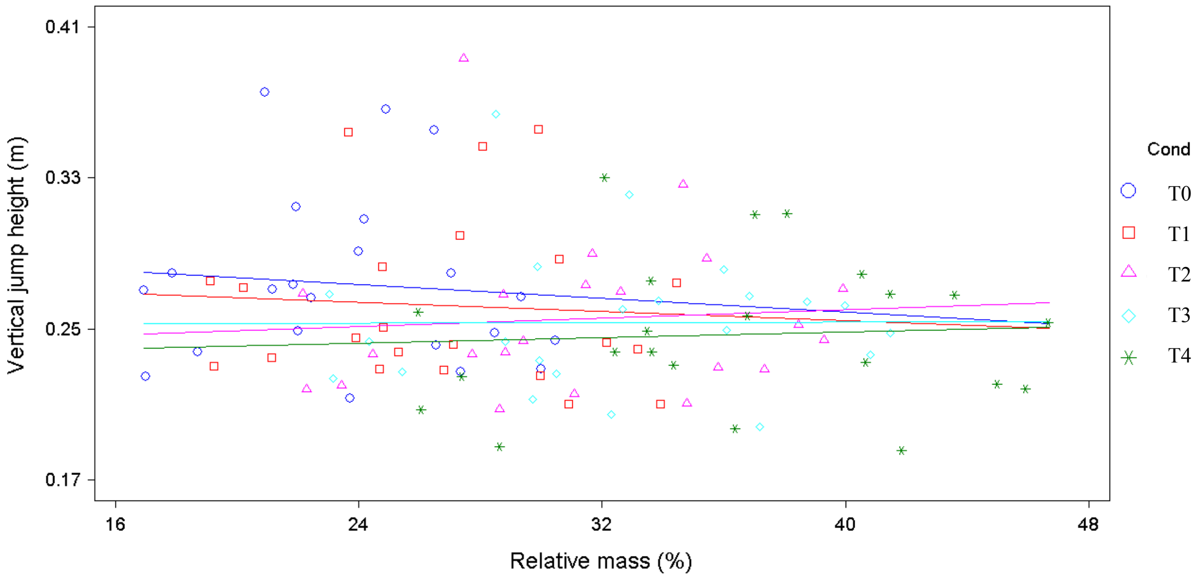


Figure 3.21: Correlation of vertical jump height versus relative mass (%) (r=0.1; not significant) for military clean skin (MCS) and Tier 0 - Tier 4.

The vertical jump assessment is a strong indicator of leg power. A calculation for peak power has been previously validated (Harman *et. al.,* 1990) and used in military orientated research (Nindl, *et. al.,* 2007). The basis of the calculation is derived from the vertical displacement and body mass. The current study has used this equation with regard to total load carriage and so should take some caution from the calculation. With this limitation in mind, Figure 3.22 indicates that peak power achieved in all Tiers were significantly higher than MCS. There was a trend for an increase in peak power from T0 –T4. This outcome can be explained on the basis of minimal difference in absolute vertical jump height and the weak relationship between relative mass and vertical jump performance coupled with a large load carriage (mass) increase from 4.7 kg – 29.2 kg.

Peak power in vertical jump assessment has been documented as a basis of strength attributes, whereby stronger subjects, loaded, also jump higher. In fact, loaded assessment is one recommendation that can be made in an applied environment (Kraska *et. al.,* 2009). Of equal significance, Elorantra (1996) demonstrated that loading variations ranging from 40-110% of body weight did not have significant impact on skeletal muscle recruitment or the movement pattern used.

It is notable to point out that in the current study, despite loading to 29.2 kg, there was no evidence of reduce peak power. That is, future work should now consider further increments in weight >30 kg to firstly discover the turning point in power output and then the decrement in peak power output at very high loads.

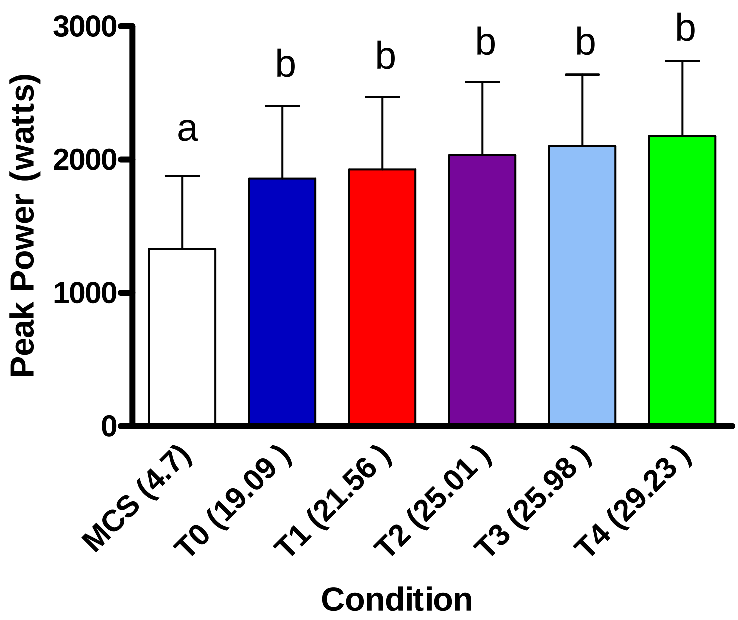


Figure 3.22: Peak power achieved during vertical jump for military clean skin (MCS) and Tier 0 - Tier 4. Conditions not sharing common letter are significantly different *($P<0.05$)*. Data are means with standard deviations (error bars).

3.7 Stand and Reach

Twenty-one (21) subjects completed all conditions (MCS & T0-T4) of the stand and reach assessment. Figure 3.23 shows clearly that when subjects were in MCS they were able to displace their centre of gravity outside their base of support significantly further than all Tiers Furthermore, when subjects were asked to do the same balance assessment in T0 - T3, there was no significant difference between conditions. T4 impacted most on balance, although not different to T2. In other words when subjects wore T4 and T2, they fell forwards sooner with arms outstretched, as simulating the reaching for an object at height.

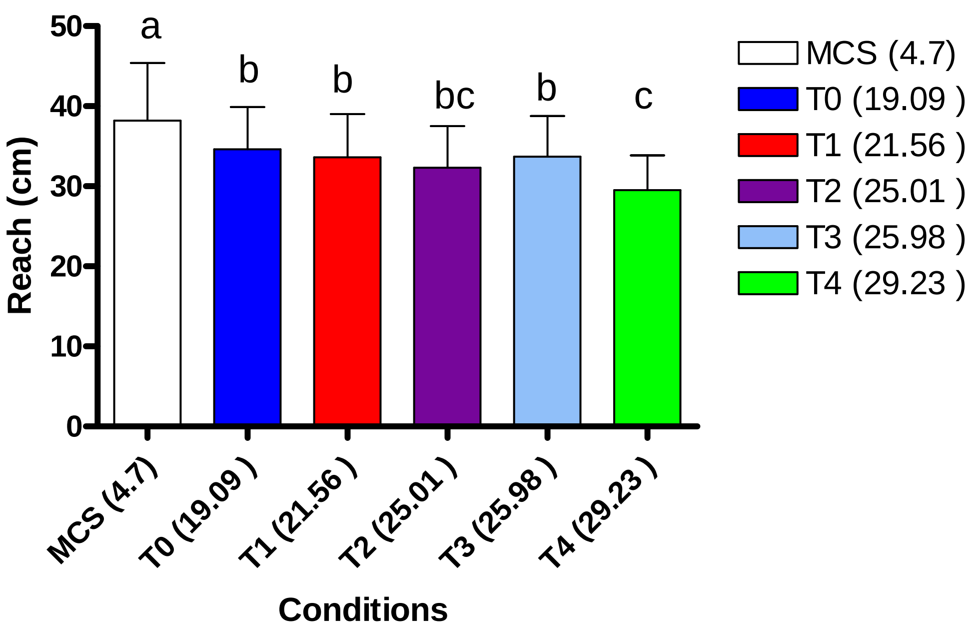


Figure 3.23: Stand and reach for military clean skin (MCS) and Tier 0 - Tier 4. Conditions not sharing common letter are significantly different (P<0.05). Data are means with standard deviations (error bars).

Recently, the Centre for Human and Applied Physiology, University of Wollongong, conducted a number of range of motion tests with NSW Fire Brigade (Taylor *et. al.,* 2010). The stand and reach was one of these assessments and was assessed under control conditions (clean skin) and experimental conditions (full fire fighting load - thermal protection, helmet and breathing apparatus). Table 3.9 indicates a similar absolute and relative reduction in stand and reach capability as seen in the current report between T0 and T4.

Table 3.9: Changes in stand and reach associated with wearing personal protective equipment in the NSW Fire Brigade.

Range of motion	Control	Experimental	Change (%)
Stand and reach (cm)	24.9 (1.2)	20.9 (1.2)	**-25.4**

Note: The change (%) was significantly different ($P < 0.05$).

The stand and reach test provides a first-level assessment of the possible impact of protective equipment upon balance, such that a 25% (in fire fighters) reduction means that individuals are less stable. This can be almost entirely attributed to an elevation in the centre of gravity by the addition of 12.7 kg (helmet and breathing apparatus) above the hips. In the fire fighter study, for stand and reach, was assumed that the added equipment mass above the waist, which represented 16.4% of the average male body mass and 20.5% of the mean mass of the female, had a significantly smaller impact upon the male subjects. This is certainly an area that can be further explored in the current investigation. Figure 3.24 shows the relationship between stand and reach versus relative load. Independent of condition there was a significant

inverse relationship between relative mass carriage and reach displacement (r = -0.37; *P<0.05*). That is, as relative mass carriage increased there was a reduction in the horizontal displacement outside of the subject's base of support (i.e. they fell forward earlier).

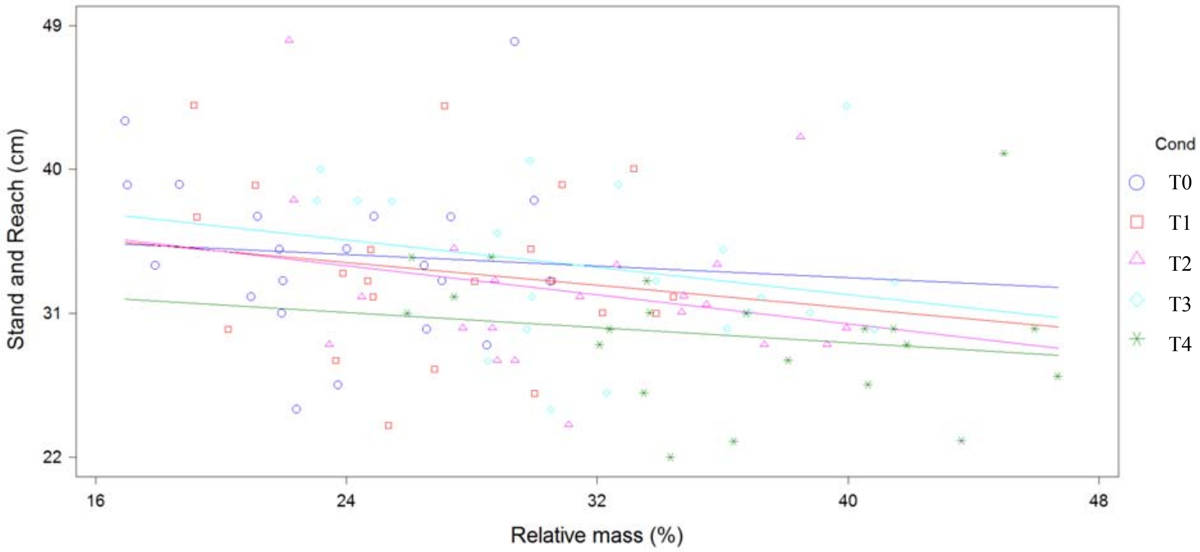


Figure 3.24: Correlation of stand and reach versus relative mass (%) (r= -0.37; *P<0.05*; condition independent) for military clean skin (MCS) and Tier 0 - Tier 4.

3.8 Summary of mobility results

This summary section has been divided into three distinct sections. The first section addresses comparisons of conditions based upon relative and absolute change. The second section considers the correlations between absolute performance change and mass increase and the final section provides a rank sum order table of conditions across all aspects of mobility assessment.

3.8.1 Matrix summary

The primary results for each mobility assessment have been collated into 5 matrix tables. The purpose of the tables are to make a direct comparison of any one Tier to another for a given mobility assessment (Table 3.10, A-E).

The comparisons are made based upon both relative and absolute differences. The relative difference (%) is reported first in each cell with an 'up arrow' indicating a positive relative performance and a 'down arrow' indicating a negative relative performance. The absolute difference for each comparison is then held within (brackets). The tables should be interpreted as 'columns' compared back to 'rows'. A short commentary is provided for each matrix.

Overall, the greatest relative performance difference is reported as a 14.29% performance decrease (T4 versus T0) during the stand and reach assessment. Equally, the smallest relative performance difference is reported as 0.15% performance decrease (T3 versus T2) during the vertical jump assessment. Some interesting observations specific to the assessments can be drawn out as follows, but are not limited to these only. For total bound time a conditional staircase effect from T0-T4 was evident, whereby the greatest relative change was found as a 7.28% increase in total bound time (indicating a performance decrease) in T4 versus T0. The range in performance difference was also as little as 0.68% in T3 versus T4 (Table 3.10, A). Similar staircase effects based on condition are also evident in Tables 3.10, B-E. On the whole, the greatest relative difference was always T4 compared to T0 (relative decrease in assessment performance). This ranged from 4.91% in the total time to complete obstacle avoidance to 14.29% in stand and reach.

Table 3.10: Matrix of relative change (%) and absolute differences (in brackets) for each assessment. Data are presented as T0, T1, T2, T3, T4 against all other Tiers. ↑ indicates a relative performance increase while ↓ indicates a relative decrease in performance. A – total bound time (s), B – fastest time for obstacle avoidance (s), C – fastest time for combat rush (s), D – vertical jump (cm), E – stand and reach (cm).

A

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
Tier 0		↓3.72 (0.05)	↓5.01 (0.71)	↓6.40 (0.89)	↓7.28 (1.09)
Tier 1	↑3.34 (0.50)		↓1.38 (0.21)	↓2.78 (0.39)	↓3.57 (0.59)
Tier 2	↑4.54 (0.51)	↑1.12 (0.21)		↓1.41 (0.18)	↓2.21 (0.38)
Tier 3	↑5.82 (0.59)	↑2.39 (0.39)	↑1.26 (0.18)		↓0.84 (0.20)
Tier 4	↑6.48 (1.09)	↑3.13 (0.59)	↑1.98 (0.39)	↑0.68 (0.20)	

B

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
Tier 0		↓0.61 (0.07)	↓1.79 (0.18)	↓1.84 (0.20)	↓4.91 (0.28)
Tier 1	↑0.56 (0.07)		↓1.20 (0.12)	↓1.24 (0.13)	↓4.31 (0.21)
Tier 2	↑1.69 (0.18)	↑1.11 (0.11)		↓0.10 (0.02)	↓3.14 (0.10)
Tier 3	↑1.74 (0.19)	↑1.17 (0.13)	↑0.01 (0.02)		↓3.05 (0.08)
Tier 4	↑4.58 (0.28)	↑4.01 (0.21)	↑2.87 (0.10)	↑2.85 (0.08)	

C

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
Tier 0		↑0.34 (0.16)	↓2.03 (0.01)	↓1.22 (0.07)	↓5.40 (0.17)
Tier 1	↓1.32 (0.16)		↓2.89 (0.15)	↓2.10 (0.07)	↓6.25 (0.31)
Tier 2	↑1.52 (0.01)	↑2.31 (0.15)		↑0.78 (0.07)	↓3.31 (0.31)
Tier 3	↑0.63 (0.07)	↑1.41 (0.07)	↓0.91 (0.06)		↓4.19 (0.24)
Tier 4	↑4.36 (0.17)	↑5.15 (0.31)	↑2.89 (0.18)	↑3.69 (0.24)	

D

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
Tier 0		↓3.99 (0.01)	↓6.25 (0.02)	↓6.76 (0.02)	↓9.43 (0.03)
Tier 1	↑4.71 (0.01)		↓2.19 (0.01)	↓2.63 (0.01)	↓5.37 (0.02)
Tier 2	↑7.84 (0.02)	↑3.15 (0.01)		↓0.15 (0)	↓2.60 (0.01)
Tier 3	↑8.33 (0.02)	↑3.72 (0.01)	↑0.85 (0)		↓2.42 (0.01)
Tier 4	↑11.23 (0.03)	↑6.58 (0.02)	↑4.01 (0.01)	↑3.17 (0.01)	

E

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
Tier 0		↓2.57 (1.0)	↓6.21 (2.3)	↓2.01 (1.0)	↓14.29 (5.1)
Tier 1	↑3.71 (1.0)		↓2.97 (1.3)	↑1.01 (0.1)	↓11.27 (4.0)
Tier 2	↑7.85 (2.3)	↑4.79 (1.3)		↑5.34 (1.4)	↓7.72 (3.3)
Tier 3	↑3.26 (1.0)	↑0.01 (0.1)	↓3.42 (1.4)		↓12.09 (4.2)
Tier 4	↑17.61 (5.1)	↑14.40 (4.0)	↑10.17 (3.3)	↑14.45 (4.2)	

3.8.2 Correlations of mass carriage and mobility

Each mobility assessment (performance) has been correlated against absolute mass carriage. This analysis provides a relationship outcome (r value) and the potential to predict other absolute mass carriages against mobility performance, within reason. In these instances an equation is provided that describes the performance variable (y axis) in regards to the mass carriage (x-axis). In all mobility assessments (Figure 3.25-3.29) there were significant correlations *(P<0.05)*. The strongest relationship was found in the fire and movement assessment between increasing total bound time against increasing mass carriage (r=0.6). All other results and equations are listed in Figures 3.26-3.29.

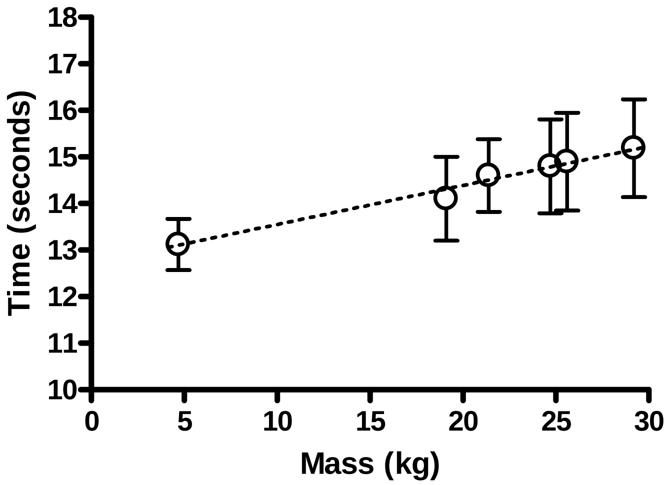


Figure 3.25: Fire and movement - correlation of total bound time (seconds) against absolute mass carriage (kg). r = 0.6 *(P<0.05)*.

Total bound time = 12.6 + (0.086 x mass)

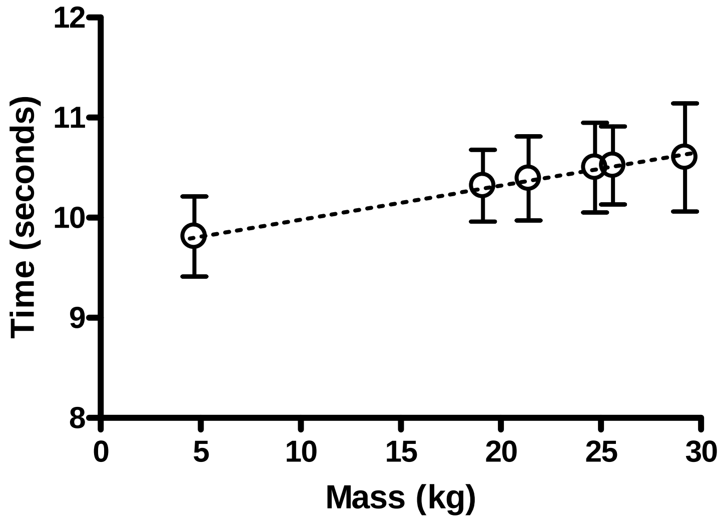


Figure 3.26: Obstacle avoidance - correlation of obstacle avoidance time (seconds) against absolute mass carriage (kg). r = 0.52 *(P<0.05)*.

Fastest time = 9.67 + (0.032 x mass)

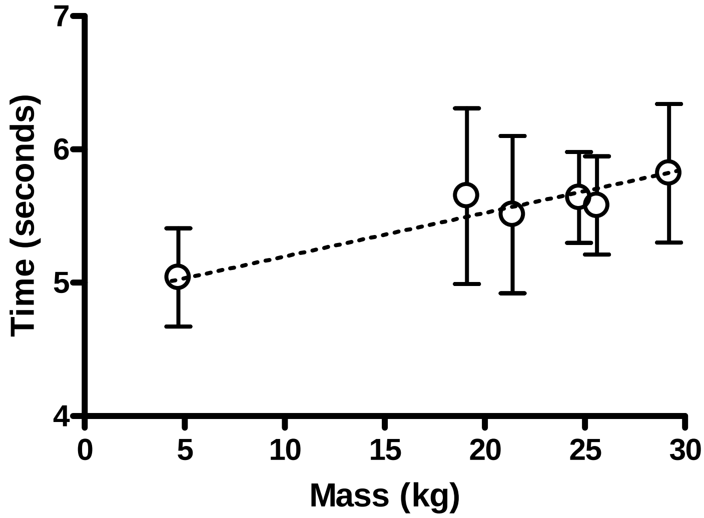


Figure 3.27: Combat rush - correlation of combat rush time (seconds) against absolute mass carriage (kg). r = 0.41 *(P<0.05).*

Fastest time = 4.94 + (0.028 x mass)

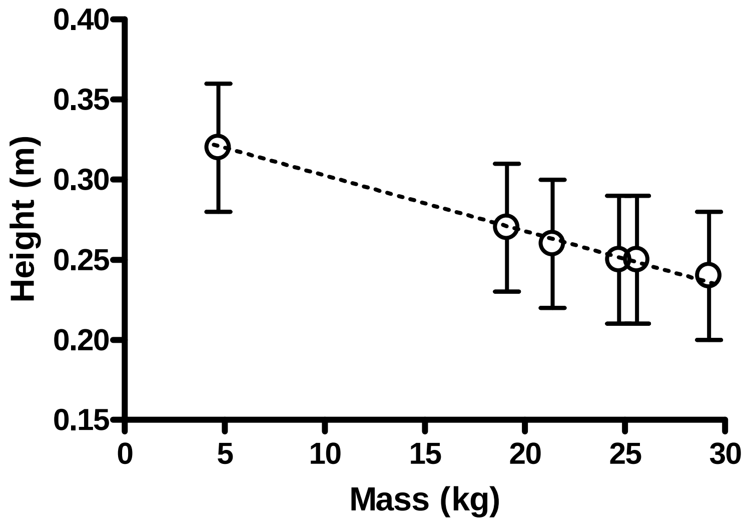


Figure 3.28: Vertical jump - **c**orrelation of vertical jump height (m) against absolute mass carriage (kg). r = -0.55 *(P<0.05).*

Vertical jump height = 0.34 - (0.003 x mass)

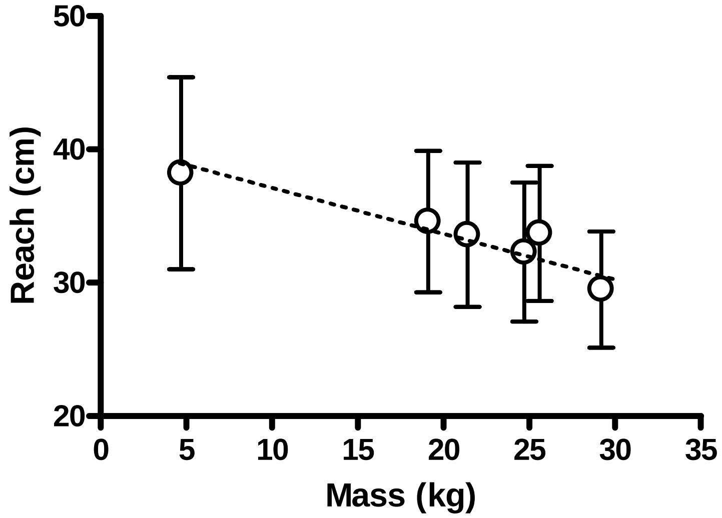


Figure 3.29: Stand and reach - correlation of stand and reach displacement (cm) against absolute mass carriage (kg). r = -0.41 *(P<0.05)*.

Reach = 40.11 - (0.307 x mass)

The linear equations for each relationship are very useful tools for predictive purposes. Their application, within reason, can further inform the effects of load carriage on the mobility performance outcomes. At this point in time, the regression equations are written for loads ranging from 4.1 kg up to 29.1 kg mass. It should be noted that there is a large jump in the current investigation between MCS and T0. At this point in time, a linear relationship has been generated across all loads used in the study. A point of interest would come from further investigations that purposefully pose mass carriage against mobility performance with respect to smaller increments. It may be hypothesised that a threshold load may be achieved whereby further load increases have either decreased or increased effect on performance.

In the current study, an average of **1.5%** performance reduction was measured for every **1 kg** load increase between T0 and T4 (Table 3.11). This compares with previous work by Holewijn (1992) that demonstrated that for every 1kg increase in external load, there was an average performance loss of 1% during tasks including jumping, sprinting, hand grenade throwing and obstacle course completion.

Table 3.11: Summary of relative change (%) in each mobility assessment for every kg of mass increased between T0 (19.1 kg) to T4 (29.2 kg).

Assessment	Measure	Equation	r^2	% change per kg mass increase
Fire and movement	Total time	y=-0.47x-2.55	0.93	-2.12%
Obstacle avoidance	Fastest total time	y=-0.54x+1.2	0.88	-1.85%
Combat rush	Fastest total time	y=-0.63x+176	0.81	-1.58%
Vertical jump	Vertical height	y=-0.75x-2.1	0.99	-1.33%
Stand and reach	Horizontal distance	y=-1.42x+2.7	0.62	-0.7%
Mean				-1.5%

3.8.3 Rank sum order table

The purpose of the rank sum order table is to place T0 - T4 into positional order irrespective of significant difference. That is, the sum provides an indication that either a condition always came first in an assessment, last in an assessment or varied in final order within an assessment. It is important that the sum of the rank order is interpreted with caution. For example, if the rank order of one condition is three times that of another this does not indicated a three fold difference. In fact, there may be no statistical difference between first place and last place. The rank sum table also has included superscripts indicating where statistical significance did or did not exist. Tiers carrying a common superscript are not significantly different from each other for the given mobility assessment.

Table 3.12: Rank sum order for mobility variables across T0 -T4. Tiers with different superscript letters are also significantly different *(P<0.05)* in reference to absolute test results.

Assessment		T0	T1	T2	T3	T4
Fire & Movement	***Total Time***	1^{a}	2^{ab}	3^{bc}	4^{bc}	5^{c}
	Mean Bound Time	1^{a}	2^{ab}	3^{abc}	4^{bc}	5^{c}
	Ideal Bound Time	1^{a}	2^{ab}	4^{ab}	3^{ab}	5^{b}
	Fatigue Index	2^{a}	4^{a}	1^{a}	3^{a}	5^{a}
Agility	***Total Time***	1^{a}	2^{ab}	3^{ab}	4^{ab}	5^{b}
	Acceleration	1^{a}	2^{a}	4^{ab}	3^{ab}	5^{b}
	Turn Time	1^{a}	2^{ab}	3^{bc}	4^{bc}	5^{c}
Combat Rush	***Total Time***	4^{ab}	1^{a}	3^{ab}	2^{ab}	5^{b}
	5m Split	4^{a}	1^{a}	3^{a}	2^{a}	5^{a}
	10m Split	4^{a}	2^{a}	3^{a}	1^{a}	5^{a}
	20m split	2^{a}	1^{a}	3^{a}	4^{a}	5^{a}
Vertical Jump	***Height***	1^{a}	2^{ab}	3^{b}	4^{b}	5^{b}
ROM	***Reach***	1^{b}	3^{b}	4^{bc}	2^{b}	5^{c}
Sum		**24**	**24**	**40**	**40**	**65**

4. CONCLUSIONS

The aim of this study was to assess the impact of different levels of body armour protection (Tiered BAS) on a soldier's mobility. Specifically;

- Quantify baseline soldier mobility in military clean skin (MCS).
- Assess, measure and compare mobility under a control condition (ICLCE chest webbing) and four levels of Tiered BAS.
- Underpin findings by correlative investigation with basic physiological and or anthropometric characteristics.
- Provide summary recommendations of the effects of weight load on soldiers' mobility.

The current study has employed an encompassing range of assessments to address the majority of dismounted soldier physical mobility challenges on the battlefield, namely speed, repeated sprint ability, power, agility and balance. Most recognisable was the very common outcome of all assessments. In other words, on many occasions, there was a clear trend for performance decrement starting from Military Clean Skin slowly progressing to the highest level of protection (Tier 4). This is clearly demonstrated in the rank sum order table (Section 3.8.3 Table 3.12).

Specifically, this investigation has found that reduced physical mobility is primarily dependent on weight load. The performance reduction, both relative and absolute, is proportional to the external load of each Tiered BAS condition. Across the five mobility assessments, moving between Tier 0 (19.1 kg) and Tier 4 (29.2 kg), there was an average performance reduction of **1.5%** for every **1 kg** of external load added. The weight load effect is manifested in a range of performance outcomes including;

- Slower movement speeds
- Longer duration to move between point of cover.
- In some instances, reduced ability to generate power from a standing position. Vertical jump was one assessment where peak power was not significantly affected by the external weight load.
- Earlier onset of physical fatigue during repetitive movements
- Reduced ability to quickly negotiate obstacles on the battle field.

The current study has demonstrated that based upon physical mobility assessments, there are three equally stressful groups, clustered around weight load, for the five conditions under evaluation.

- **Group A:** Tier 0 (19.09 kg) and Tier 1 (21.56 kg)
- **Group B:** Tier 2 (25.01 kg) and Tier 3 (25.98 kg)
- **Group C:** Tier 4 (29.23 kg)

Given that physical mobility impediment was found to be equivalent for each of the three groups it is recommended that the ensemble within each grouping that provides the most protection for the dismounted soldier be considered for procurement and use within the Australian Army. For Group A this would be Tier 1, for Group B this would be Tier 3 and for Group C this would be Tier 4. This recommendation with respect to physical mobility must

be considered in conjunction with other important factors to inform Tiered BAS procurement decisions.

Ultimately, weight-load is the primary mechanism that influences physical mobility and as such there may be other more optimal configurations of hard and soft armour protection than those investigated in the current study. For instance, substituting the ballistic plates used in the Tier 4 condition (6.3 kg) with those used in Tiers 1-3 (3.7 kg) would result in a total weight load of 26.23 kg which is similar to the weight loads of Group B. BAS design and development efforts should focus on hard and soft armour materials that provide the highest level of protection whilst minimising overall weight load.

The work here clearly underpins future studies that can be employed to add baseline knowledge to the focus of soldier mobility and human performance. Future studies should focus on the specific design of armour, load increases and the distribution of this load across the torso and limbs (accounting for weight). Furthermore, functional movements should be identified, defined, analysed and timed, individually to allow specific mobility limitations to be established. Physiological differences within genders are also evident therefore studies should incorporate a wide range of baseline characteristics where possible.

The current investigation made use of active soldiers as subjects. To generate future relevance to military personnel (if the tasks involve a skill component), it would be ideal to continue to use soldiers, rather than the general population with average or varied fitness levels. This will be particularly important in future work that delves more deeply into underpinning reasons and relationships in military orientated tasks.

Most importantly, future work needs to specifically focus on the concept of individual survivability based on the physical mobility data reported in this study. Rather than determining a statistically significant difference between PPE conditions the work needs to be extended to identify the point at which a reduction in physical mobility starts to compromise personal survivability on the battlefield. Development of a survivability index based on exposure time whilst moving tactically will enable meaningful recommendation to be made on the impact of various PPE ensembles. The commencement of this work is highlighted in the current study, whereby the movement patterns of soldiers moving for a prone position to standing was documented and presented in a case study format. This approach will need to interface both human physiological performance and mathematical modeling.

5. REFERENCES AND RECOMMENDED READING

Adams, P.S. and Keyserling, W.M. (1991). *Effects of garment weight on arm movement speed, heart rate and perceived exertion: A Pilot Study.* The University of Michigan, Michigan.

Angel, H.A., Ste-Croix, C., & Morton, A. (2008). *Performance evaluation of soft armour personal protective equipment.* Defence research and Development Canada, Toronto.

Bassan, A.M ., Boynton, A.C., & Ortega, S.A. (2004). *Methodological issues when assessing dismounted soldier mobility performance.* Human Research and Engineering Directorate, US army research Laboratory.

Bowditch, S.C., Boyd, N., De Vrises, A., Dyson, E.H., Gray, L., Gwyther, R., Hepper, A.E., Nevola, R., Shaw, I.D., Stokes, N., Tattersall, S., Toon, W., & Williams, A. (2005). *Improved performance body armour initial examination of rigid insert shape.* Biomedical Sciences (Ministry of Defence), Salisburg.

Danielsson, U. & Berg, U. (2005). *Body Armour. Effects on performance and physical load.* Swedish Defence Research Agancy, Stockholm, Sweden.

DeMaio, M., Onate, J., Swain, D., Ringleb, S., Morrison, S., & Naiak, D. (2009) *Physical performance decrements in military personnel wearing personal protective equipment (PPE).* NATO, Otan.

Derrick, L.G., Hann, H.R., & Malonne, G.H. (1963) *The influence of body armour coverage and weight on the performance of the marine while performing certain simulated combat type tasks.* Scientific and Technical Information, Alexandria, Virginia.

Gruber, A., & Sanders, J.L. (1965). *Development of a methodology of measuring effects of personal clothing and equipment on combat effectiveness of the individual field soldier.* US Army General Equipment Test Activity, Fort Lee, Virginia.

Harman, E., Frykman, P., Pandorf, C., Tharion, W., Mello, R., Obusek, J., & Kirk, J. (1999). *Physiological, biomechanical, and maximal performance comparisons of female soldiers carrying leads using prototype U.S Marine Corps modular light weight load-carrying equipment (MOLLE) with interceptor body armour and U.S Army all-purpose light weight individual carrying equipment (ALICE) with PASGT body armour.* US Army Research Institute of Environmental Medicine, Natick, MA.

Harman, E.A, Rosentein, M.T, Frykman, P.N & Kraemer, W.J (1990) *Estimation of human power output from vertical jump.* Journal of Applied Sports Science Research. 5: 116-120.

Harman, E.A., Gutekunst, D.J., Frykman, P.N., Sharp, M.A., Nindi, B.C., Alemany, J.A., & Mello, R.P. (2008) Prediction of simulated battlefield physical performance from field expedient tests. *Military Medicine,* 173(1), 36-41.

Hasselquist, L., Bensel, C.K., Corner, B., Gregorczyk, K.N., & Schiffman, J.M. (2008). *Biomechanical and physiological cost of body armour.* Natick Soldier research: Development and Engineering Centre, Natick, MA, USA.

Holewijn, M., & Lotens, W.A. (1992). *The influence of backpack design on physical performance.* Ergonomics. 35(2); 149-157.

Martin, P.E., & Nelson, R.C. (1985). *The effect of carried loads on the combative movement performance of men and women.* Military Medicine. 150(7); 357-362.

Nelson, R.C., & Martin, P.E. (1982). *Effects of gender and load on combat movement performance.* The Pennsylvania State University, Pennsylvania.

Nindl, B.C, Barnes, B.R, Alemany, J.A, Frykman, P.N, Shippee, R.L, & Friedl, K.E. (2007) *Physiological consequences of U.S Army Ranger training.* Medicine and Science in sport and Exercise. 39 (8): 1380-1387.

Noakes et al. *Br J Sports Med* 2009;**43**:760-764

Pandorf, C.E., Harman, E.A., Frykman, P.N., Patton, J.F., Mello, R.P., & Nindl, B.C. (2002). Correlates of load carriage and obstacle course performance among women. *Work,* 18, 179-189.

Polcyn, A.F., Bensel, C.K., Harman, E.A., & Obusek, J.P. (2000). *The effects of Load Weight: a summary analysis of maximal performance, physiological and biomechanical results from four studies of load carriage systems.* US Army Natick Soldier Center and US Army Research Institute of Environmental Medicine, Natick, Massachusetts.

Polcyn, A.F., Bensel, C.K., Harman, E.A., Obusek, J.P., Pandorf, C., & Frykman, P. (2002) *Effects of weight carried by soldiers: combined analysis of 4 studies on maximal performance, physiology and biomechanics*. US Army Soldier and Biological Chemical Command Soldier Systems Center, Natick, Massachusetts

Prentice, AM and Jebb, SA. (2001) Beyond body mass index. Obesity Reviews. 2: 141-147.

Ricciardi, R. (2006). *Impact of body armor on physical work performance.* Uniformed Services University of the Health Sciences.

Ricciardi, R., Deuster, P.A., & Talbot, L.A. (2007). Effects of gender and body adiposity on physiological responses to physical work while wearing Body Armour. *Military Medicine,* 172 (7), 743-748.

Ricciardi, R., Deuster, P.A., & Talbot, L.A. (2008). Metabolic demands of body armour on Physical Performance in Simulated Conditions. *Military Medicine,* 173(9), 817-824.

Roberts, W.S., Costa, J., Lau, W.A., Patterson, M.J., & Lee, B. (2005). *Human factors assessment of combat body armour systems for LAND125.* Defence Science and Technology Organisation, Australian Government Department of defence.

Sell, T.C., Chu, Y., Abt, J.P., Nagai, T., DEluzio, J., McGrail, M.A., Rowe, R.S., & Lephart, S.M., (2010), Minimal additional weight of combat equipment alters air assault soldiers landing biomechanics. *Military Medicine,* 175 (1), 1-7.

Tulloch, S. (1990) Oxford Complete Word Finder. London. *p992.*

Taylor, NAS., Lewis, MC., Notley, SR., Peoples, GE., (2010) An evaluation of the physiological burden imposed by the personal protective equipment used by the NSW fire Brigades. Centre for Human and Applied Physiology. Report number HPL-039.

Woods, R.J., Polcyn, A.F., O'Hearn, B.E., Rosenstein, R.A., & Bensel, C.K. (1997b). *Analysis of the effects of body armour and load-carrying equipment on soldiers' movements. Part 2: Armour Vest and Load-Carrying Equipment Assessment.* US Army Natick Soldier Center and US Army Research Institute of Environmental Medicine, Natick, Massachusetts.

Woods, R.J., Polcyn, A.F., O'Hearn, B.E., Rosenstein, R.A., & Bensel, C.K. (1997c). *Analysis of the effects of body armor and load-carrying equipment on soldiers' movements. Part 3: Gait Analysis.* US Army Natick Soldier Center and US Army Research Institute of Environmental Medicine, Natick, Massachusetts.

Wadley, G and Rossignol, P. (1998) The relationship between repeated sprint ability and the anaerobic energy systems. Journal of Science and Medicine in Sport. 1(2): 100-110.

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APPENDICES

Appendix A – Summary of relevant literature

S.Adams, W.M. Keyserling. (1991). Effects of Garment Weight on Arm movement speed, heart rate and perceived exertion: A Pilot Study.	N = 5 (M)	ROM	5 different loads (not specified)	Minimal garment and weight effects found on movement time (increased, p < .15), cranking speed (decreased, p>.05). Garment weight did significantly affect subjective RPE and increased difficulty.
H.A. Angel. (2008) Performance Evaluation of soft armour personal protective equipment.	-ROM -Agility -Obstacle course -speed (all well defined)	-Phase 1- N=20 male -Phase 2- N=11, 10male, 1 female.	Phase 1: - 6 soft armour: B = 34 piles KM2 400 with 1.9kg plates C = 19 piles Spectra shield SA-3118 with 1.9kg plates E = 26 piles KM2 400 with 2.6kg plates G = Baseline (Fragmentation protection vest) with 2.6kg plates N = 2.1kg/m^2 KM2 400, 5.4kg/m^2 Spectra Shield SA-3118 with 1.4kg plates FPV = Baseline with current armour cut with 2.6kg plates. Phase 1a: - 5 soft armour conditions: A = 10 piles KM2 600+ 9 piles with 1.9kg plates. D = 26 piles soft steel with 2.6kg plates. Along with B, G and N conditions. + modular add-on groin, neck, throat and brassard protection for both phases.	- It appears that bulk is a more detrimental factor to soldier than stiffness - By improving the stiffness, weight and bulk of the armour around shoulders/waist, ↑ performance - Different armour cut and carrier design did not impact the results
A.M Bassan, A.C. Boynton, S.A. Ortega. (2004). Methdological issues when assessing dismounted soldier mobility performance.	-Meta analysis-13 studies (between 1973 and 2002)	- Speed -obstacle course	-weighted vests ranging from 15-42lb	- linear relationship between load carried and time to complete obstacle course 0.5kg =additional 3.58sec
S C Bowditch (2005) Improved performance body armour initial examination of rigid insert shape	N = 4-9 (task dependent)	-static/dynamic mobility -obstacle course(well defined) -UL strength (box lift) -LL strength (squats) *NB. All tasks well defined.*	-Hard body armour (plate A, B, C, D) worn over current soft CBA vest and underneath chest webbing A=INIBA plates, B=SAXON plates, C=SAPI plates, D=RUC plate set)	-results based on subjective preference for each task and significant difficulty for each task. -SAPI=restricted breathing. -more subjective complaints (i.e lack of comfort around neck, chest, shoulders) rather than statistical analysis.

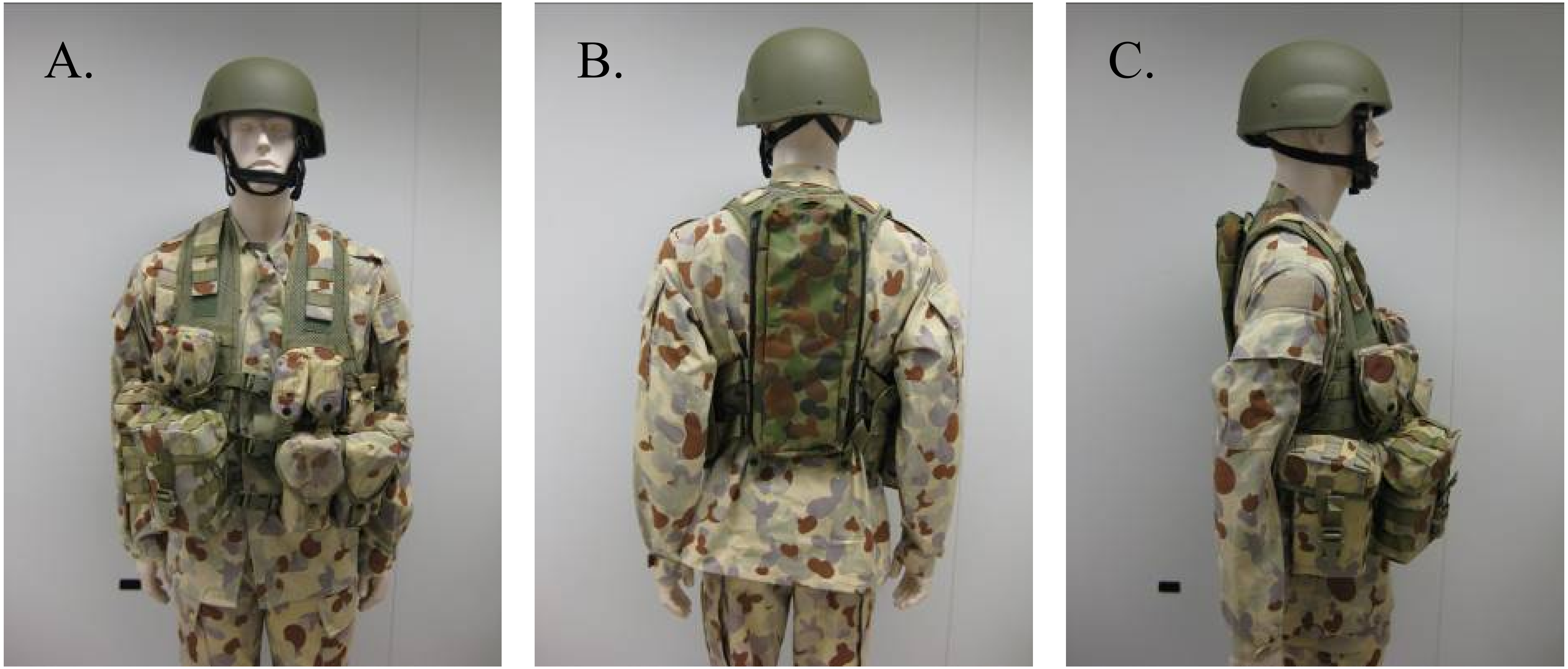
Danielsson. U. (2005)	N = 10	RPI=body motion restriction -obstacle course (well described) -speed.	1=25% relative ↑-combat equipment, no armour) 2=31% relative ↑-combat equipment together with (soft) body armour) 3=39% relative ↑-combat equipment, +armour with front+ back ballistic inserts+ ceramic plates)	-RPI (restriction)↑with body armour -RPI was not higher for hard inserts-Body armour without hard plates did not add to physical load (RPE) -25m dash-time↑with armour and was more apparent #3. - Linear relationship-net climbing+ mass of the equipment; was more apparent with hard inserts vs. Soft armour.
DeMaio. M. (2009) Physical Performance Decrements in Military Personnel Wearing Personal Protective Equipment (PPE)	N=21 (19M;2F)	-Balance -UL power and strength	9.8±0.9kg	-sig results only for postural sway (AP/ML) and COP changes due to fatigue from PPE -non sig results for box lift between PPE and control.
Derrick (1963) The influence of body armour coverage and weight on the performance of the marine while performing certain simulated combat type tasks.	N=35	-speed -ROM -simulated attack -forced march	-3 groups, 2 distributions 16, 14.1, 11.4kg Total torso and upper torso for each weight.	-No significant difference in upper vs. Whole body armour-only in weight of armour
Gruber (1965). Development of a methodology of measuring effects of personal clothing and equipment on combat effectiveness of the individual field soldier.	N=16 M	-speed -Obstacle course (well defined)	*Vest* -4.6, 5, 5.3kg *Backpacks* -4.5, 11.4, 18.2kg	-Backpack vs. Vest?-Backpack= better distribution. -Vest= time was reduced with vest on→speed compromised in sprints and ladder -results based on methodology ideas and suitable weight for further testing
Harman (1999) Physiological, biomechanical, and maximal performance comparisons of female soldiers carrying leads using prototype U.S Marine Corps Modular Light Weight load-carrying equipment (MOLLE) with interceptor body armour and U.S Army All-purpose light weight individual carrying equipment (ALICE) with PASGT body armour.	N=12 F	-Accuracy -Speed -Agility -obstacle course (well defined)	-3loads ALICE *Approach load* (AL) 16.9±1kg *Fighting Load* (FL)28.9±0.8kg *Sustainment Load* (SL) 42.7±0.6kg MOLLE (higher distribution) AL= 17.5±0.5kg FL= 30.9±0.9kg SL= 44.9±0.7kg	-obstacle course results=well defined. -Subjects moved 14%-18% slower with AL than FL and 27%-31% slower with the SL than FL. -Pack removal was 13% sig quicker in MOLLE due to quick release straps -Obstacle course (OC) mean time-AL ↑ than FL. -OC zigzag-↑time MOLLE than ALICE -OC crawl-↑ with AL than FL and ALICE (pack shape?) -MOLLE-↑Centre of Mass=8%↑time OC -↑ weight=↓ upright posture-MOLLE was 2.5%more upright than ALICE -Load COG <ALICE than MOLLE
Harman (2008) Prediction of simulated battlefield physical performance from field expedient tests	N=32 Males	-Strength -Speed -obstacle course (well defined) -simulated casualty rescue.	18kg	-correlations between anthropometry rather than armour weight
Hasselquist (2008). Biomechanical and Physiological cost of body armour	N=11 males	-Speed -Strength -agility	- 14.8kg; 18.45kg;20.40kg (all include vest 8.7kg) -extremities vs. vest	-extremities performed worse than vest -↑ weight=↓ performance in rush, box lift, obstacle course

Holewijn (1992). The influence of backpack design on physical performance.	N=10 males	-mobility/agility -strength -obstacle course (3 diff types)	16kg backpack Distribution=back (low;high)/waist	-distribution of weight: *low on back=detrimental in obstacle course * sprint=best low on back * overall? Waist=1.5-2% ↑ (vertical jump)on waist rather than low/high on back. - -80m dash performance loss occurred when weight was high on back compared to low on back -loss in max performance 1%/kg mass
Martin (1985). The effect of carried loads on the combative movement performance of men and women	N=30 (16M;14F)	-Speed -agility -LL/UL strength -ROM	-Stepped increase UP TO 16kg. (5 loads) -load 4 and 5 distributed evenly in backpack.	-Reduction in performance was linear as load increased -Backpack restricted arm ROM=↑demand on UL mm and ↓in ladder climb times. -Females large ↓ in performance load 3-4. -backpack-restricted UL ROM -↑energy cost when load carried on extremities.
Nelson (1982). Effects of gender and load on combat movement performance.	N=30 (16M;14F)	-speed -power -agility	5 loads (relative to M/F) 1.~9kg; 2.~18kg; 3.~30kg; 4.~37kg; 5.~45kg	-linear performance with ↑in time in speed tests and weight -plateau-load 5 in comparison to load 4 (fatigued??)
Pandorf (2002). Correlates of load carriage and obstacle course performance among women.	N = 12 (F)	Agility, Power, Speed, strength, Obstacle course, timed 3.2km run The obstacle course was comprised of 6 different segments: hurdles, zigzag run, low-crawl, horizontal pipe, wall climb, and straight sprint. No time specified.	3.2km obstacle course. Loads = 14, 27 and 41 kg. Obstacle course4. Loads = 14 and 27kg.	-19% more time to cover distance 27kg load than 14kg in 3.2km walk -44% more time in 3.2km walk with 41kg than 14kg -12-26% longer to hurdle, zigzag and sprin with 27kg than 14kg -clearing 1.37m wall 27% more difficult with 27kg than 14kg -Increased height and reduction in weight=more successful clearance with loads and of 1.37m wall -crawl task- reduction in consistency due to backpack(weight distribution) made it hard to clear and females physically unable to support themselves in constant push up position.
Polcyn (2000) The effects of Load Weight: a summary analysis of maximal performance, physiological and biomechanical results from four studies of load carriage systems	N = 46 (34 M, 12 F)	3.2km transverse course, self paced and externally paced (4.8km/h)	*See below*	30% variance in time to run course is accounted for by the load weight It was found that course completion times and energy expenditure were directly related to the weight carried. Externally paced walking → postural adjustments are found proportional to load increased to maintain stability and force absorption (more increased knee and hip flexion)
Polcyn (2002) Effects of weight carried by soldiers: combined analysis of 4 studies on maximal performance, physiology and biomechanics	N = 46 (34 M, 12 F)	3.2km run/walk, and biomechanics (gait analysis)	*LOADING CONFIGURATION (kgs)* F = Fighting load, A = Approach Load, S = Sustainment load LW1 vs ALICE LW1= 23.45 (F), 35.47 (A), 50.11 (S) ALICE = 14.66 (F), 23.41 (A), 37.54 (S) LWII = 20.42 (F), 32.41 (A), 37.54 (S) MOLLE vs ALICE MOLLE = 13.05 (F), 26.84 (A), 40.16 (S)	An increase in weight carried increased the time spent in double support phase (14% variance) Stride frequency did not change Weight increase = increase energy cost with locomotion (Found Slower speeds with 3.2km run/walk) Increase joint loading with increased weight carried. *Linear relation* with slopes for the maximum joint forces close to 1.0 .

			ALICE 11.82 (F), 24.07 (A), 38.36 (S) MOLLE vs MLS MOLLE = 12.87 (F), 26.84 (A), 40.16 (S) MLS = 12.26 (F), 24.18 (A), 37.65 (S)	Many relationships with biomechanics *(see paper for details)*
Ricciardi (2006) Impact of Body Armor on Physical Work performance	N = 34	Grip Strength, Stair Step Test, Upper body Strength	1. Body Armour approx 11kg 2. Non-BA	No significant difference between grip strength with BA or non-BA - Men (60% ↓) and Womens (63% ↓) upper body strength (sig) - Men and Womens speed/stairs (25% ↓) (Sig)
Ricciardi (2007) Effects of Gender and Body Adiposity on physiological responses to Physical work while wearing Body Armour	N = 34 (17 M, 17 F)	Speed/strength (stairs), Upper body Strength	1. Body Armour approx 11kg 2. Non-BA	Men reduced performance by 66% in pull ups with BA Women reduced performance by 73% with BA Stair stepping performance reduced with BA by 17% and 14%, men and women respectively Percentage of body fat was negatively correlated with physiological work performance. No real gender differences found.
Ricciardi (2008) Metabolic demands of Body Armor on Physical Performance in Simulated Conditions	N = 34	Grip Strength, Upper body Strength, speed	1. Body Armour approx 11kg 2. Non-BA	No significant difference between grip strength with BA or non-BA Physical tasks were significantly affected by BA: under BA, men performed 61% fewer pull-ups and women's hang time was reduced by 63%; stair stepping was reduced by 16% for both men and women
Roberts (2005) Human Factors Assessment of Combat body Armour Systems for LAND125	N = 16	ROM, functional movements, basic drill *(defined)*	7 different BA (weight not specified)	Bulk, weight and fit of all body armour degraded performance to varying degrees (Non Specific)
Sell (2010) Minimal additional weight of Combat Equipment alters air assault soldiers landing biomechanics	N = 70	Stability (2 legged drop landings)	Total weight BA = 15.0 ± 3.7kg	Maximum knee flexion angles, maximum vertical ground reaction forces, and the time from initial contact to these maximum values all increased with the additional weight of equipment. *Linear relationship*
Woods (1997b) Analysis of the effects of body armour and load-carrying equipment on soldiers' movements. Part 2: Armour Vest and Load-Carrying Equipment Assessment	N = 12 (M)	ROM	Base clothing Armour Vest [a)4.0kg; b)3.5kg] and Load-carrying equipment[a)7.8kg; b) 9.1kg]	*Linear relationship* between increase clothing bulk about the joint and reduced ROM. Lighter vest = greater ROM. Load distribution better with 9.1kg load-carrying equipment, ie better ROM than lighter, one due to position of cases.
Woods (1997c) Analysis of the effects of body armor and load-carrying equipment on soldiers' movements. Part 3: Gait Analysis	N = 12 (M)	ROM, Gait analysis	Base clothing Armour Vest (4.0kg) and Load-carrying equipment (7.8kg)	Reduced gait efficiency Linear and angular velocities and accelerations = non significant with load increases

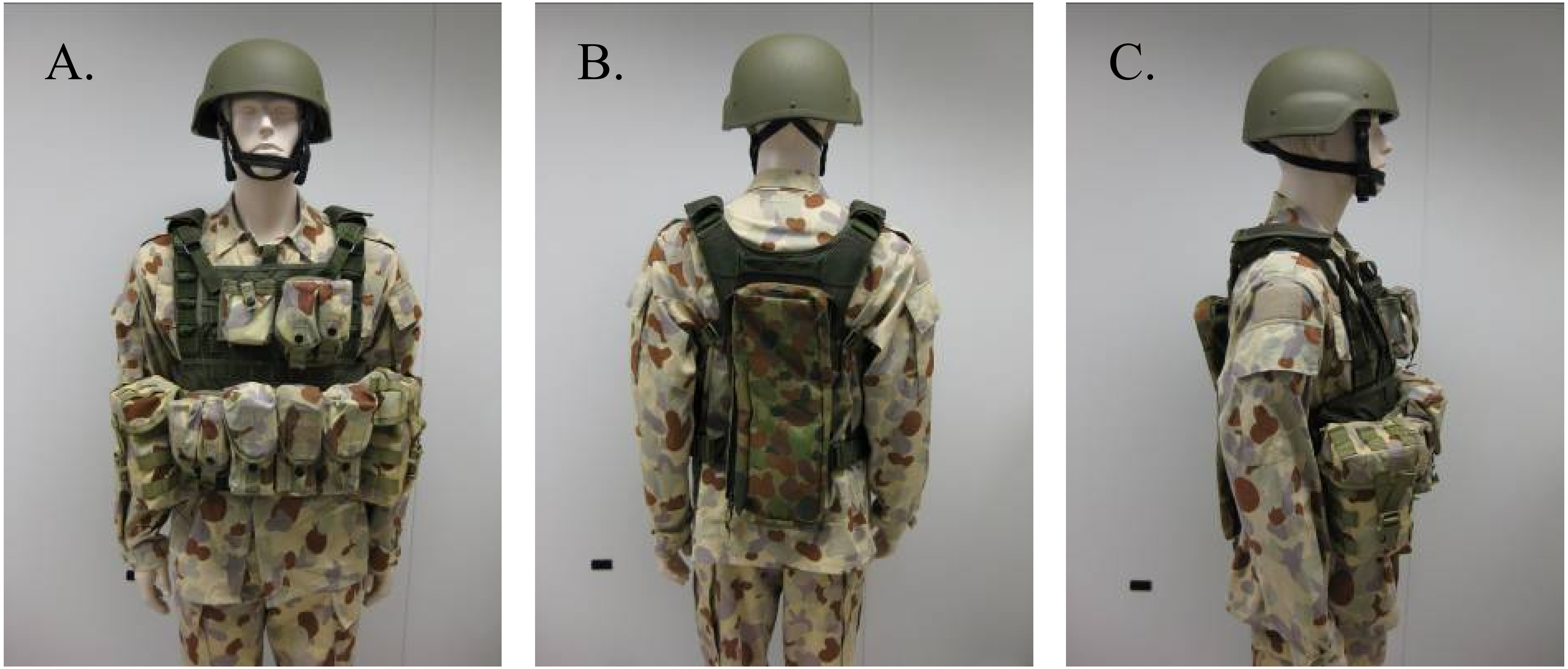
Appendix B – Configurations for experimental conditions

Figure 6.1 Loaded condition 1 – Tier 0 (ICLCE chest webbing - control)



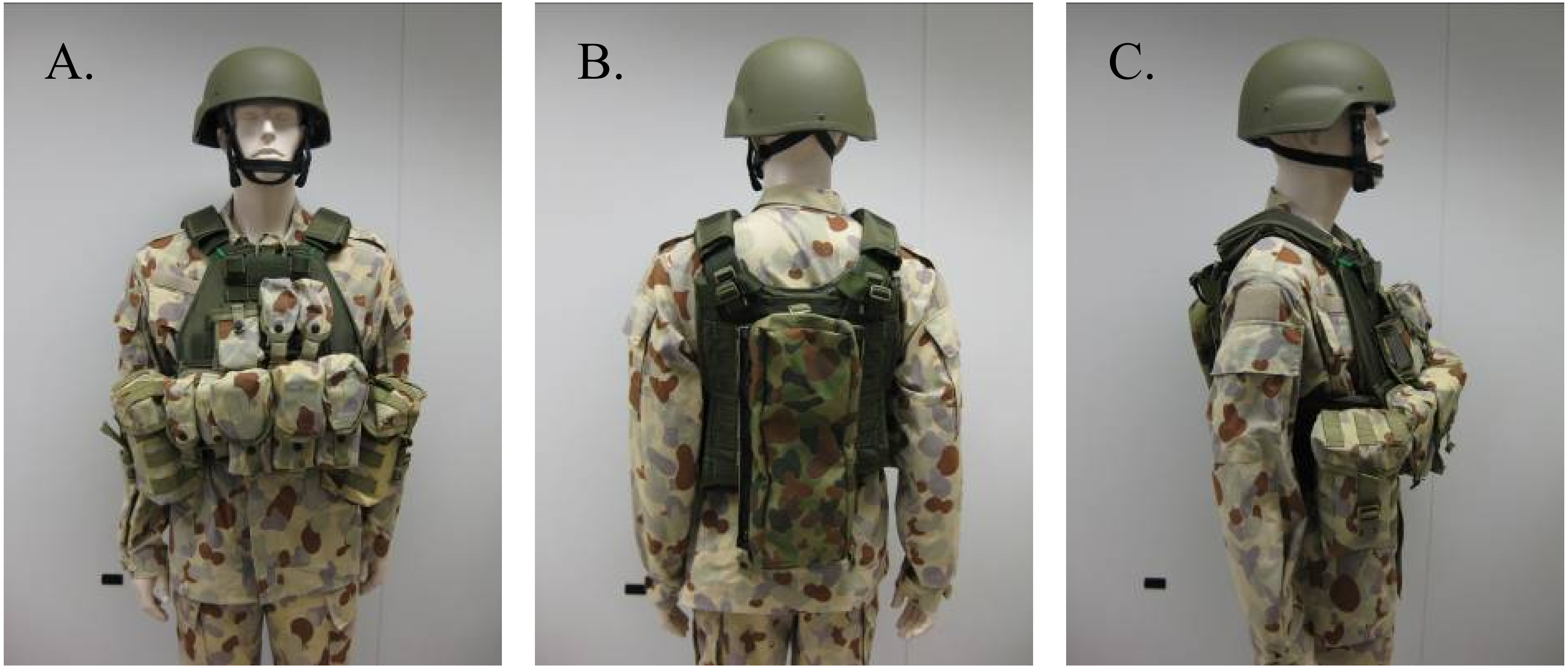
A; front view, B; rear view, C; side view

Figure 6.2 Loaded condition 2 – Tier 1



A; front view, B; rear view, C; side view

Figure 6.3 Loaded condition 3 – Tier 2

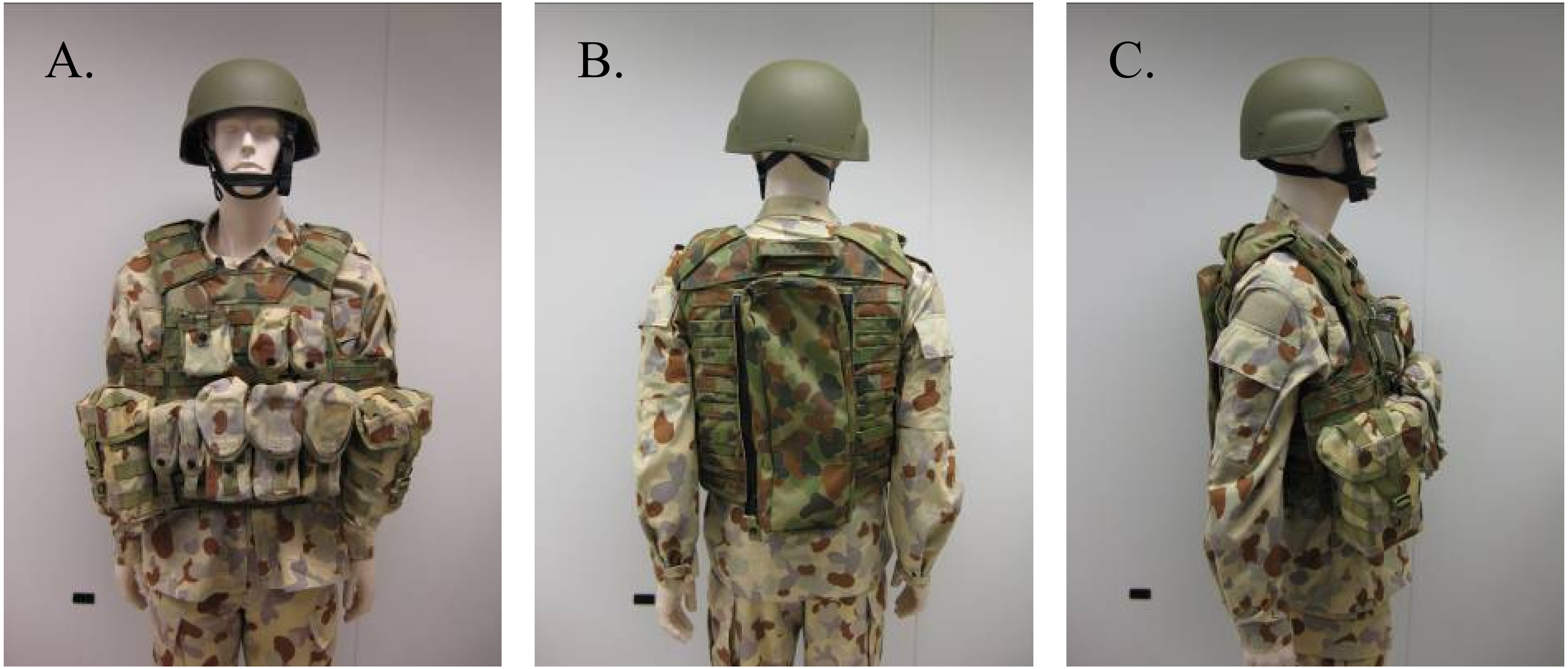


A; front view, B; rear view, C; side view

Figure 6.4 Loaded condition 4 – Tier 3

A; front view, B; rear view, C; side view

Figure 6.5 Loaded condition 5 – Tier 4 (MCBAS)



A; front view, B; rear view, C; side view

Appendix C - Baseline load list for Tiers 0 - 4

ITEM	WEIGHT (kg)	QUANTITY	SUB-TOTAL (kg)	LOCATION
Combat application tournique	0.1	1	0.1	Pouch accessory medium – left (1.7 kg)
Shell dressing	0.1	2	0.2	
Weapon cleaning kit	0.4	1	0.4	
Camouflage cream	0.05	1	0.05	
Compass	0.15	1	0.15	
Binocular/Monocular	0.5	1	0.5	
Gloves, Kevlar protective	0.1	1	0.1	
10m para cord	0.05	1	0.05	
Toggle rope	0.15	1	0.15	
Torch	0.3	1	0.3	Pouch accessory medium – right (1.7 kg)
NVG/NFE/NAD	0.7	1	0.7	
Multi tool	0.3	1	0.3	
Bayonet/combat knife	0.4	1	0.4	
Rifle magazine 30 rounds	0.5	2	1	Ammo pouch 2 x mag (1)
Rifle magazine 30 rounds	0.5	2	1	Ammo pouch 2 x mag (2)
Rifle magazine 30 rounds	0.5	2	1	Ammo pouch 2 x mag (3)
Grenade	0.36	2	0.72	Carrier grenade double (1)
Grenade	0.36	2	0.72	Carrier grenade double (2)
SPR	0.4	1	0.4	Pers role radio pouch
Camelbak bladder	0.16	1	0.16	Camelbak pouch
2L water	2	1	2	
Empty weight of all pouches (n=9)	1.6	1	1.6	
TOTAL (kg)			**12**	