Determining the maximum acceptable length of a Hard Ballistic Plate

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Abstract. Optimising the dimensions of body armour requires consideration of the trade-off between coverage and mobility. However, the acceptable limits of plate length and width against a wearer's anthropometry remain unknown, limiting our ability to properly assess this trade-off. The aim of this work was to study encumbered soldier mobility to determine the maximum acceptable length of a hard plate. Four experimental plate conditions were worn by 45 male Australian infantry soldiers: no plate (Condition A); a reference body armour system (B), the maximum acceptable length plate (C1) and the minimum completely unacceptable length plate (C2). Participants completed four range of motion (ROM) activities and four functional movement tasks comprising rifle handling tasks and wall, window and crawling obstacles. Outcome measures included the ROM measures, obstacle completion time and an interference rating scale. Conditions C1 and C2 were determined by participant interference ratings when assessed with a subset of 27 variable length plates, differing in 10 mm increments. Forty participants met the inclusion criteria. The mean ± SD maximum acceptable plate length (C1) and minimum completely unacceptable plate length (C2) were determined as 29 ± 32 mm and 79 ± 38 mm longer than the wearer's front length respectively. The C2 plate condition resulted in significantly less ROM and longer times on all obstacles than the C1 condition ($p < 0.05$). Similarly, ROM and obstacle performance with C2 was worse than with B for all measures except the wall obstacle. Participants had significantly less ROM and took longer on the crawl obstacle with the C1 plate compared to cleanskin (A). Minimum detectable change values were provided to assess meaningful differences. This study shows how the maximum acceptable length of a plate is related to the wearer's front length and that exceeding the acceptable length limits will result in decrements to soldier mobility and task performance.

1. INTRODUCTION

Hard Ballistic Plates (HBPs) in body armour carriers are a key element of personal protective equipment for the modern soldier. When positioned and sized correctly, body armour provides coverage of important thoracoabdominal organs and structures of the torso. However, this protection is not without cost. HBPs are made from heavy and rigid materials and the use of HBPs may reduce wearers' mobility, ability to rapidly take cover, and their capacity to carry out essential lethality tasks, such as sighting and firing a weapon [1-3]. It is therefore a well-supported position that more protection (coverage) equates to decrements in soldier performance (mobility). Optimising the dimensions of chest-borne HBPs requires consideration of the trade-off between coverage and mobility.

1.1 Coverage requirements

Body armour coverage requirements have been established for Australian soldiers based upon the position of vital thoracoabdominal organs relative to anthropometric landmarks, as identified from supine and standing MRI data [4]. Consequently, coverage requirements state that the positioning of the HBP should protect important thoracoabdominal organs (e.g. heart, liver, spleen, and great vessels) from a front-on, perpendicular threat [4]. The plate should provide as much coverage as possible while remaining acceptable to the user. The likelihood of (perpendicular) coverage provided by HBPs of varying lengths and widths has been defined for a number of important organs [4]. These findings are based on the assumption that the top edge of the HBP is positioned at the sternal notch of the wearer.

1.2 Defining mobility requirements

Body armour is worn by soldiers performing complex and varied physically demanding tasks, often for prolonged periods. The size and shape of body armour has the potential to interfere with the performance of these tasks, and subsequently impact the user tolerance of a body armour system. The user-accepted limits of plate length and width against an infantry soldier's anthropometry remain unknown. The aim of this study is to determine the relationship between user anthropometry and the maximum acceptable length of a HBP, located appropriately at the sternal notch for infantry soldiers. These data may be used to inform the ergonomic acceptability of a new size range of plates and also inform injury models with

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real-life data about the maximum coverage that is likely to be tolerated by soldiers. This study represents a new approach to these issues, combining elements of a regular body armour comparison study with principles used during Fitmapping [5] for protective equipment and clothing.

2. METHODS

2.1 Participant and anthropometric measures

Forty-five Australian infantry soldiers took part in the study. All participants were male with an average age of 24.5 ± 2.9 years and average time in the Army of 3.6 ± 2.6 years. Ethical approval to conduct the study was granted (protocol LD 02-17) in accordance with the DST Group low-risk human research ethics review process. The torso anthropometric measurements of the cohort well reflected the variance within the Australian Army male population [6] (Table 1).

Table 1. Torso anthropometric measures of the male Australian Warfighter Anthropometry Survey (AWAS) and study cohorts. 'Rank' indicates the percentile ranking of the min/max study cohort value within the normalised AWAS cohort.

	AWAS		Study Cohort					
Measures (mm)	**Mean**	**SD**	**Mean**	**SD**	**Min**	**Max**	**Rank of min**	**Rank of max**
Front Length	362	21	367	20	325	419	6th	99th
Chest Circumference	1010	74	1024	82	889	1285	5th	> 99th
Waist Circumference	888	94	880	91	735	1099	5th	99th

The front length is the vertical distance from the sternal notch to the top of the iliac crest. The chest and waist circumference measures are measured at the nipple and navel level respectively.

2.2 Participant assessments

2.2.1 Range of motion tasks

Three formal static ROM assessments were completed: seated torso flexion, lateral torso flexion and seated rotation with flexion. Measures were taken with participants sitting on a 600 mm high box, atop a 400 mm high platform. The base of the box was considered 0 mm and reaches measured below this point described as positive values. A further functional ROM activity was completed in a Bushmaster vehicle seat. Participants performed a seated forward reach; the horizontal distance of the reach was measured from the front of the bushmaster seat base (0 mm). These ROM movements were selected as they were anticipated to be most influenced by a change in plate length. ROM measures were recorded up to three times (average 2.3 measures) and the mean ROM value calculated and used in analysis.

2.2.2 Functional movement tasks

Following ROM tasks, participants completed four dynamic activities; selected for their criticality of function and expected ability to discriminate different plate length. The first three are obstacles from the Load Effects Assessment Program (LEAP): Wall, Window and Low Crawl. These activities were timed. The fourth dynamic task was a simulated marksmanship exercise with the F88 rifle. Participants took prone-, kneeling- and standing aim postures. The rifle exercises were not timed or measured, and were used solely to inform participants' overall interference rating for each system.

2.2.3 Outcome measures

Objective participant outcome measures comprised the measured ROM values and timed obstacle activities. Participants also completed a subjective interference rating assessment (Figure 1) at the conclusion of all ROM and functional movement tasks.

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The length of this plate caused….				
No interference or degradation	**Slight interference: easily worked around**	**Moderate interference; difficult, but able to work around**	**Severe interference, very difficult to work around**	**Extreme interference. Unable to work around; unacceptable**
1	**2**	**3**	**4**	**5**

Figure 1. Interference rating scale, adapted from the scale used by Mitchell et al. (2017) [7]

2.3 Experimental design

The trial was a repeated measures partially-counterbalanced study across four experimental conditions; Cleanskin i.e. no plate (Condition A), a reference body armour system (Condition B) comprising a carrier, training HBP and training soft armour, and a variable-length hard plate and carrier (Condition C). Condition C comprised a maximum acceptable length plate (C1) and completely unacceptable length plate (C2).

Condition B was a fixed-length condition. One size of the reference body armour system was used for all participants. The training soft armour inserts for this system are longer and wider than the HBP, and the plate was held within the bounds of the soft armour, such that a minimum of 20 mm of soft armour bordered the plate in all directions.

Condition C was an adaptive condition determined using surrogate hard ballistic plates of 27 different lengths. The plates were modelled on the 3D shape of the reference front HBP (Condition B). The plates varied in length in 10 mm increments. The width of all plates was held constant (Figure 2). Trial plates were an approximate match in areal density to the training HBP, resulting in the mass of each system scaling with size; a 10 mm length increment corresponded to a mass delta of approximately 65 g. The soft armour inserts were designed to match the dimensions of the trial plates in length and width, were approximately 8 mm thick and had similar stiffness to real soft armour. Carriers were custom-made to house the plates and surrogate soft armour inserts, such that the external carrier length was 10 mm longer than the plate. Carriers were designed to enable maximum adjustability. Comparisons between Conditions B and C are presented in carrier length rather than plate length, in order to account for differences in system design.

Figure 2. a) Top view of plates 1, 10 and 17, **b)** side profile of plates 1, 10 and 17, **c)** carriers for plates 10 and 1, and **d)** soft armour insert for plate 10. N.b. Plates 10 and 17 were 90 mm and 160 mm longer than Plate 1 respectively.

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It was anticipated that the crossover point between ratings 2 and 3 on the interference scale (Figure 1) would represent the maximum acceptable length a wearer would be willing to accept (C1) and that the crossover point between ratings 3 and 4 would represent a completely unacceptable length for the wearer (C2). This assumption was verified by an initial questionnaire asking the participants how much interference they would be prepared to accept (with any body armour). This was completed prior to any participant assessments in the test conditions.

The plate lengths corresponding to interference ratings of 2, 3 and 4 were desired from every participant so that soldiers' subjective experience of wearing the plates could be captured and subsequently compared with the objective measures. Determining the thresholds of interference was the main aim of the study. However, because it was not clear where these points would occur for any individual, an adaptive approach was devised based on the principles of Fitmapping (Figure 3) [5].

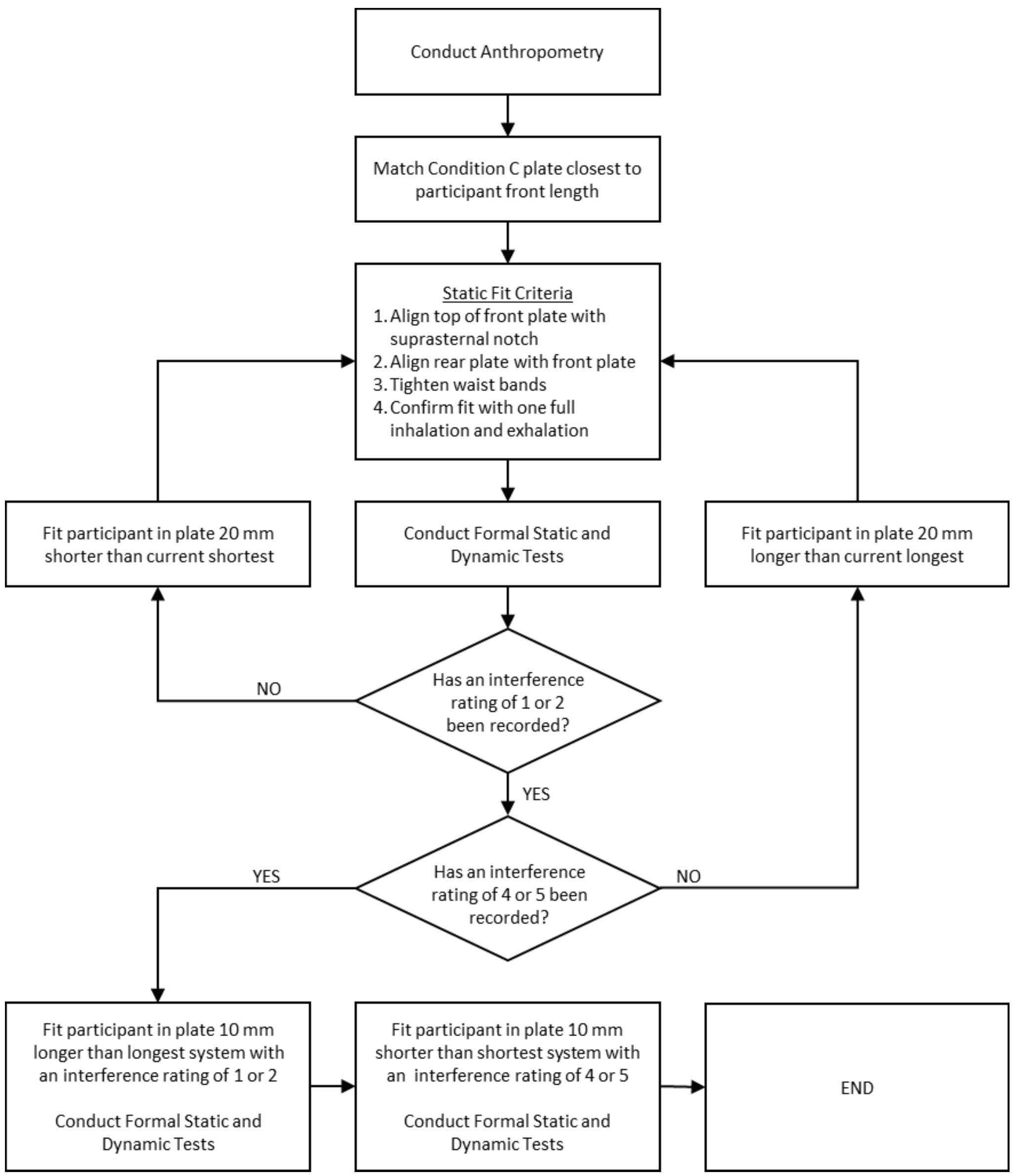

Figure 3. Condition C protocol and decision flow chart

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The first plate length trialled in Condition C was chosen as the length closest to each participant's front length. Subsequently issued plates were either 20 mm longer or shorter, dependent on the subjective interference ratings of each trialled length. Once ratings of 2, 3 and 4 had been established at 20 mm increments, plate lengths at the crossover points from the ratings of 2 to 3, and then 3 to 4, were trialled in 10 mm length increments to increase the resolution at these key junctures. Once this data was collected, the protocol ceased. The decision to initially vary plate lengths in 20 mm rather than 10 mm increments was made to make more effective use of limited participant time and lessen the effects of boredom, fatigue and disengagement that may have affected results during a lengthier trial progressing in 10 mm increments only. The decision to run Condition C as an adaptive condition was deliberate. Although a regular counterbalanced approach is more regularly applied, this may not have yielded the results required to make decisions on maximum acceptable plate length since the conditions must be determined upfront and had to be relatively small in number. As such, resolution may be lost and the actual crossover points not established. It was not expected that trial activities would cause undue fatigue due to their short duration and discrete application, typically a cause of order effects in physical performance trials. Eighteen participants completed a randomised repeat run with a single Condition C plate which they had previously worn. This data was used to test for order effects caused by trial design, and to calculate the minimal detectable change (MDC) for each measure.

2.4 Data analysis

The data were analysed with a one-way repeated-measures Analysis of Variances (ANOVA). The Shapiro-Wilk and Fmax test statistics were used to test the assumptions of normality and homogeneity of variance. Mauchly's test was used to test the assumption of sphericity; Huynh-Feldt Epsilon is reported where violations occurred. Holm-Bonferroni corrections were applied to pairwise comparisons.

The MDC represents the minimum magnitude of change that exceeds measurement error and was calculated from the reliability data of 18 participants based on a 90% confidence interval (i.e. MDC_{90}). This value was calculated for the four ROM and three obstacle measures. The MDC values were used to provide a threshold over which the performance can be considered to have meaningfully changed.

3. RESULTS

3.1 Identifying C1 and C2

Prior to all tasks and test conditions, participants were asked to record their judgement about the amount of interference to their mobility that they would be prepared to accept in order to ensure appropriate coverage and protection. The results supported the initial assumption that the maximum acceptable length occurred at the last rating of 2; the majority of participants (69%) reported that this was the greatest impediment they would be prepared to accept. A further 18% of participants reported a rating of 3 was the greatest acceptable impediment. Therefore, the Condition C plate with the last rating of 2 was identified for all participants as C1. Where there was one deviation in the responses (i.e. a longer plate was rated as lower interference), a conservative approach was adopted whereby the shortest plate rated 2 was taken as the maximum acceptable length (C1). No participants responded in the questionnaire that a rating of 4 would be acceptable; consequently, the completely unacceptable plate length (C2) was classified as the first or only ratings of 4 or 5.

The mean number of variable lengths to achieve ratings of 2, 3 and 4 was 6.96 ± 1.3. This relatively high number supports the assertion that participants had not been cognizant of the progression criteria, or were not minded to engineer their responses to complete the trial with the least number of runs. Checks for consistency of rating response to increases in plate length were perfect for 30 participants (66.7%), deviated on one occasion only for 12 participants (26.7%) and deviated on more than one occasion for 3 participants who were hence removed from any further analysis. A further 2 participants failed to record a rating of 4 or 5, and were also removed from further analysis. Thus, the data of n = 40 participants were included in the subsequent analysis.

The variable-length dataset (Condition C) comprised a total of 276 runs completed by the 40 participants. The Condition C ratings for each plate length were standardised by each individual's front length, i.e. plate length minus front length. As the plate became longer against the participant's front length, the likelihood of obtaining an interference rating of 2 decreased (Figure 4).

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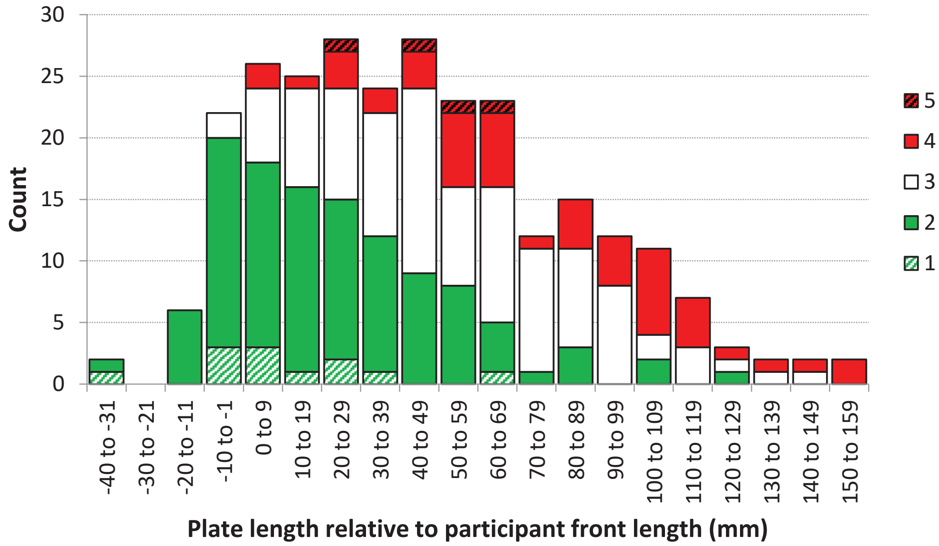

Figure 4. Interference ratings for each standardised plate length for Condition C (plate length minus front length) (total 276 runs)

The maximum acceptable plate length (C1) and minimum completely unacceptable plate length (C2) were determined as 29 ± 32 mm and 79 ± 38 mm longer than the wearer's front length respectively. There was a similar range for C1 and C2 values (142 and 155 mm respectively), indicating large variability and cross-over of the values across the participant sample (Figure 5). Both C1 and C2 datasets satisfied the criteria for normality (Shapiro-Wilk p-values of 0.272 and 0.567 respectively).

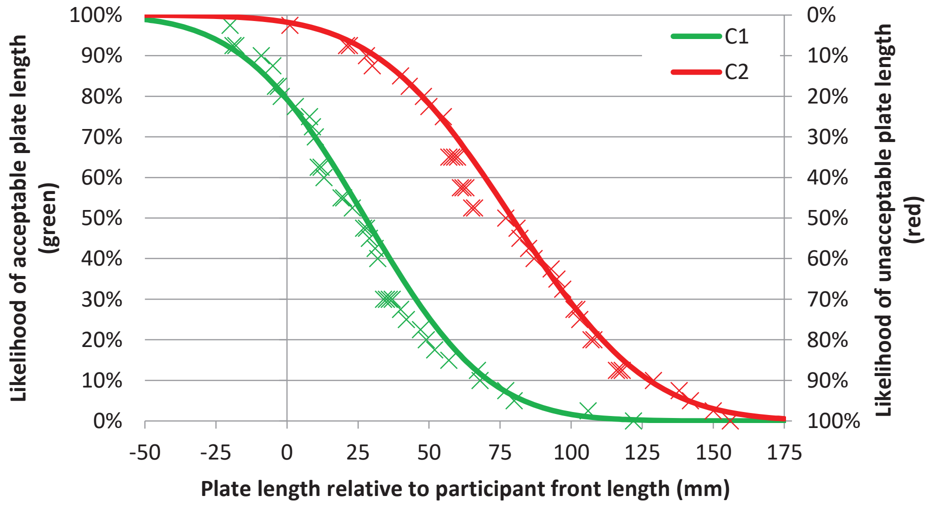

Figure 5. Normalised (line) and raw (cross markers) distribution of C1 and C2 standardised plate length thresholds across trial population (n = 40)

The trial carriers were 10 mm longer than the plates, therefore the maximum acceptable carrier length and minimum completely unacceptable carrier length were determined as 39 ± 32 mm and 89 ± 38 mm longer than the wearer's front length respectively (**Error! Reference source not found.**). By comparison, the fixed-length reference body armour system (B) was 6 ± 21 mm shorter than the wearer's front length.

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Table 2. Relative lengths of reference system B, C1 and C2 carriers for n = 40 participants (carrier length less front length). All values in mm. Negative values indicate front length is longer than the carrier.

	Mean	SD	Min.	Max.	Range
B: Reference body armour system	-6	21	-59	35	94
C1: Acceptable carrier	39	32	-10	132	142
C2: Unacceptable carrier	89	38	11	166	155

3.1.2 Overall interference ratings

No interference ratings were completed for the cleanskin condition (A). For Condition B, the reference body armour system, the overall interference was most commonly rated a 2 (n = 27), with n = 11 participants rating it as 1 (no interference) and n = 2 participants rating it as 3 (moderate interference). By definition, all C1 plates were rated a 2 and all C2 plates were rated a 4.

3.2 Objective measures

3.2.1 Range of motion tasks

The MDC_{90} was calculated for each ROM task (Table 3). The four one-way repeated measures ANOVAs demonstrated significant main effects of body armour length on trunk flexion, lateral flexion, flexion/rotation and seated reach (all $p < 0.001$). Thus, pairwise comparisons were completed for all ROM tasks. Plate condition C2 caused statistically significant and meaningful restriction compared to conditions A, B and C1 for all ROM measures except lateral flexion (which was statistically, but not meaningfully, different). Compared to cleanskin (A), the C1 plate significantly decreased all ROM measures, however only flexion and flexion/rotation measures were meaningfully different. Plate condition C1 resulted in significantly less flexion, flexion/rotation and seated reach compared to B, however none of the measures were meaningfully different.

Table 3. Results of trunk ROM tasks (mean ± SD), all task and MDC_{90} values in mm (n = 40)

	Flexion	Lateral flexion	Flexion/Rotation	Seated reach
MDC_{90}	28.7	63.6	62.0	37.5
A: Cleanskin	69.6 ± 57.1	-105.5 ± 66.6	-110.2 ± 94.7	918.0 ± 83.0
B: Reference	41.4 ± 55.5	-112.0 ± 61.6	-152.4 ± 95.8	907.3 ± 83.9
C1: Acceptable	27.3 ± 60.1	-123.4 ± 67.7	-180.6 ± 100.2	888.7 ± 88.7
C2: Unacceptable	-20.2 ± 73.4	-144.4 ± 55.9	-262.0 ± 97.8	849.1 ± 99.5
Pairwise comparisons (p-values)				
A vs. B	< 0.001*	0.305	< 0.001*	0.078
A vs. C1	< 0.001*†	0.009 *	< 0.001*†	< 0.001*
A vs. C2	< 0.001*†	< 0.001*	< 0.001*†	< 0.001*†
B vs. C1	0.011*	0.069	0.010*	< 0.001*
B vs. C2	< 0.001*†	< 0.001*	< 0.001*†	< 0.001*†
C1 vs. C2	< 0.001*†	< 0.001*	< 0.001*†	< 0.001*†

*statistically significant at the Holm-Bonferroni-corrected alpha level
†difference greater than the MDC_{90}

3.2.2 Functional movement tasks

The MDC_{90} was calculated for each obstacle task (Table 4). The three one-way repeated measures ANOVAs demonstrated significant main effects of body armour length on the time taken to complete the wall, window and crawl obstacles (all $p < 0.001$). Thus, pairwise comparisons were completed for all functional movement tasks. All plate conditions were significantly different for the crawl obstacle. Plate condition C2 resulted in significantly longer time for all obstacles than Conditions A and C1, and for the window and crawl obstacles against Condition B. However, no differences between any conditions were deemed meaningful against the MDC_{90}.

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Table 4. Results of functional movement tasks, task (mean ± SD) and MDC_{90} values in seconds (n = 40)

	Wall	Window	Crawl
MDC_{90}	2.07	1.57	2.77
A: Cleanskin	9.57 ± 1.66	8.52 ± 1.59	10.30 ± 2.56
B: Reference	9.96 ± 2.20	8.84 ± 1.93	11.30 ± 2.37
C1: Acceptable	9.87 ± 2.10	9.07 ± 1.96	12.05 ± 2.55
C2: Unacceptable	10.56 ± 2.39	9.97 ± 2.26	12.99 ± 2.89
Pairwise comparisons (p-values)			
A vs. B	0.107	0.119	0.007*
A vs. C1	0.129	0.026	< 0.001*
A vs. C2	0.001*	< 0.001*	< 0.001*
B vs. C1	0.637	0.245	0.029*
B vs. C2	0.016	< 0.001*	< 0.001*
C1 vs. C2	0.002*	< 0.001*	0.010*

*significant at the Holm-Bonferroni corrected alpha level
†difference greater than the MDC_{90}

3.3 Reliability testing

Eighteen participants conducted a repeat of one of their previously experienced conditions chosen at random. The test-retest correlation was assessed using Pearson's *r*. Most measures had good- to excellent reliability ($r > 0.8$ and $r > 0.9$ respectively) with acceptable reliability ($r > 0.7$) noted for the crawl time. All correlation coefficients were statistically significant with $p \leq 0.001$ for all measures. This data indicates that there were no observable order effects induced by the experimental protocol.

Table 5. Test-retest (mean ± SD) correlations for n = 18 participants

Measure	Test	Retest	Pearson's r	Significance
ROM Flexion (mm)	40.91 ± 41.03	46.54 ± 41.20	0.910	0.000
ROM Lateral flexion (mm)	-108.53 ± 78.38	-94.96 ± 65.25	0.870	0.000
ROM Flexion/Rotation (mm)	-198.35 ± 83.81	-190.51 ± 75.87	0.893	0.000
ROM Seated Reach (mm)	903.33 ± 64.85	908.36 ± 61.02	0.936	0.000
Wall Time (secs)	10.22 ± 2.33	9.93 ± 2.37	0.856	0.000
Window Time (secs)	9.15 ± 1.73	8.96 ± 2.00	0.878	0.000
Crawl Time (secs)	11.99 ± 2.13	12.30 ± 2.40	0.728	0.001

4. DISCUSSION

Measuring body armour length against user front length is a practical method of estimating the likelihood of user acceptability. Condition C1 results suggest that, as a plate extends below the user's front length, the likelihood the plate will be deemed accepted by the user decreases. A plate positioned at a user's sternal notch that is longer than front length will result in the bottom edge of the body armour extending below the top of the pelvis. Military body armour featuring a HBP is heavy and rigid, often worn tightly to the torso to prevent the armour system bouncing or shifting during walking. When extending below the top of the pelvis, the system might act akin to a splint, physically restricting or blocking movement of the torso over the pelvis (i.e. trunk flexion).

Choi et al. [8, 9] evaluated the effects of wearing Improved Outer Tactical Vests (IOTV) in the size above and below that identified by subject matter expert (SME) fit. The IOTV assessed was configured with hard plates at the front, back and sides and soft armour at the front, back yoke and collar. SME fit was based on visual inspection of ballistic plate and soft armour coverage in seating and standing. Standing carrier length was assessed relative to the navel. The average carrier length for SME fit was 76 mm below the navel. It was found increasing armour size beyond SME fit resulted in a movement penalty. User acceptance was not investigated. It is difficult to compare the results of the IOTV study with the current study due to the different anthropometric points of comparison. Additionally, IOTV systems increase in both length and width with each size, scaling primarily with chest circumference.

The current study used short, discrete measures of mobility to provide participants with exposure to movements and actions that would challenge any restrictions to trunk range of movement from body armour length, primarily to inform the subjective rating of interference. The measures themselves were

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not intended to represent the full extent of movements performed by an infantry soldier wearing body armour. As such, although significant differences, including differences exceeding the MDC_{90}, were found between conditions, inferences on the degree to which this may functionally impact a soldier's performance in the conduct of their role are not made. However, the results do indicate that trunk ROM and performance in physical tasks reduced as body armour length increased, and that users may be prepared to accept longer HBP coverage than is currently provided by the reference armour used in the study.

The Condition C plate mass was not held constant. Instead, the mass was scaled to the plate dimensions by approximating the areal density of the Condition B training plate. This resulted in the acceptability of larger plates being negatively influenced by increased mass as well as length. As the ballistic performance of a HBP is a function its material composition, it was assumed that areal density would provide an applicable method of controlling the mass, i.e. any future recommendations for larger plate sizes will also result in heavier plates. Thus, the participant assessments herein, i.e. the interference rating, ROM and functional movement tasks, all consider both the change in geometric dimensions and change in mass associated with varying plate lengths.

The data herein can be used in conjunction with anatomical positioning data [4] to assess the protection and mobility afforded by body armour of various lengths. For example, the 50th percentile Australian Army male front length is 362 mm [6]; if the 50th male was assigned a HBP with length 400 mm, the normal distribution of the data herein would suggest that there is ~40% likelihood they would find the plate length acceptable. Organ mapping data suggests there is ~90% likelihood their inferior liver would be covered and ~80% likelihood their abdominal aorta down to the bifurcation would be covered by a plate of this length. Such assessments are limited to the consideration of perpendicular threats, the assumption that users are wearing their HBPs at the sternal notch and the assumption that the two small samples employed in the respective studies are representative of the wider Australian Army male population. However, these simple comparisons permit the rapid consideration of body armour length against the anthropometry of the target wearer.

This study was designed to investigate a relationship between user anthropometry and the maximum acceptable length of a HBP. Limitations to the applicability of these findings on body armour design include:

- Participants were from a single user group of male-only infantry soldiers. Thus, the results do not consider sex differences in anthropometry, or role-related mobility vs. protection trade-off requirements and preferences.
- The trial carrier was designed for quick and ready adjustment, and did not represent a deployable configuration. Integration with key soldier equipment, specifically load carriage (packs, webbing and pouches) was not attempted.
- Limited use of each system in discrete tasks was not representative of the requirements of an infantry soldier, with extended use in diverse environments, including both mounted and dismounted environments.
- HBP width variation was not included in this trial.
- Bespoke HBP and carrier dimensions will impose significant financial costs. Consolidation of protection and mobility requirements in a realistic range of sizes to suit a given population is not described.

Future research is planned to address these limitations. This study was funded by the Australian Department of Defence, as part of an ongoing effort to improve the fit, form, and function of equipment, to accommodate the diverse body shapes of Australian soldiers.

5. CONCLUSIONS

This study has shown how the maximum acceptable length of a plate is related to the wearer's front length and that exceeding the acceptable length limits will result in observable and objective decrements to soldier mobility and task performance. The subjective interference that users are willing to tolerate has been determined and the distribution of the plate lengths corresponding to these levels of interference provided. The data herein provides researchers with reference values for the evaluation of existing or proposed HBP lengths against male infantry populations of known anthropometry.

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