EVALUATING LOAD CARRIAGE SYSTEM STATIC FIT IN CANADIAN ARMED FORCES SOLDIERS

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Abstract

Load carriage systems (LCSs) are critical to soldier performance and safety; however, their effectiveness is often compromised by poor fit and discomfort during use. Poorly fitting equipment has been associated with reduced mobility, increased discomfort, and elevated risk of musculoskeletal injury, highlighting the need for improved evaluation approaches. While objective methods exist to quantify body–equipment interaction, subjective evaluations remain essential for understanding user experience in applied military settings. This thesis aimed to (1) identify which aspects of perceived fit and comfort most strongly influence overall equipment acceptability, and (2) compare these perceptions across LCS configurations, specifically between the current in-service Clothe the Soldier (CTS) system and the newer Body Armour Carriage System (BACS). Subjective responses were collected from Canadian Armed Forces soldiers across 10 equipped configurations using structured surveys that assessed regional fit, comfort, and overall acceptability. Linear mixed-effects models were used to evaluate differences between configurations and examine predictive relationships between variables. Results demonstrated significant differences across configurations, with BACS systems consistently receiving higher ratings of fit and comfort compared to CTS ($p < 0.05$). Perceived fit and comfort were strongly associated, and both significantly predicted overall acceptability ($p < 0.001$), with comfort emerging as the primary determinant. In contrast, total system weight was not a significant predictor of fit or comfort ($p > 0.05$) and demonstrated a small negative association with overall acceptability. These findings establish a subjective baseline of perceived fit under standardized conditions and highlight the role of comfort in equipment acceptability. Optimizing comfort and body–equipment interaction appears more critical to acceptability than reducing system weight alone. This work provides a foundation for future research integrating subjective and objective approaches to support the development of more effective and acceptable LCSs.

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-Doménica Paulette Solano Ocampo

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Definition of Terms

3D	Three-dimensional
4D	Four-dimensional
CAF	Canadian Armed Forces
DRDC	Defense Research and Development Canada
LCS	Load Carriage System
PPE	Personal Protective Equipment
FPV	Fragmentation Protective Vest
TV	Tactical Vest
FFO	Full Fighting Order
ROM	Range of Motion
MSK	Musculoskeletal
CTS	Clothe the Soldier
BACS	Body Armour Carriage System
ISO	International Organization for Standardization
LMM	Linear Mixed-Effect Model
EMMs	Estimated Marginal Means
CI	Confidence Interval
SE	Standard error
R^2	Coefficient of determination

Chapter 1: Introduction

The safety and operational effectiveness of Canadian Armed Forces (CAF) members are significantly enhanced by appropriate personal protective equipment (PPE). Load Carriage Systems (LCSs), a vital category of PPE, are an integrated assembly of components including tactical vests, rucksacks, small packs, harnesses, and belts, engineered to help soldiers transport their mission-essential items efficiently and safely. However, the effectiveness of a LCSs is fundamentally dependent on how well the system fits the user's body, as ill-fitting LCSs have a significant impact on comfort (Schmidt et al., 2016), mobility (Brisbine et al., 2022; Lenton et al., 2016), operational performance (Choi et al., 2016), and potentially an increased musculoskeletal (MSK) injury risk (Runge et al., 2021). Ill-fitting LCSs is particularly pronounced for female soldiers, an issue that has prompted calls to develop a new evidence-based framework to improve how equipment is designed and evaluated for female soldiers (Armstrong et al., 2025). Historically, LCSs have been designed based on male anthropometry (Coltman et al., 2020), meaning the anthropometric dimensions of female personnel are often not adequately accommodated, leading to greater dissatisfaction and fit-related issues. Notably, a recent survey of CAF members confirmed this discrepancy, finding that female personnel reported significantly reduced fit and acceptability for key equipment items, such as the length of body armour and rucksack, compared to their male counterparts (Brisbine et al., 2022; Coltman, Brisbine, & Steele, 2021; Gruevski et al., 2024).

The concept of "fit" is multifaceted, encompassing static, dynamic, and even cognitive aspects (Stirling et al., 2020). Despite its importance, the assessment of fit remains methodologically challenging. Traditional approaches have relied on anthropometric surveys (Mangan, 2012; McConville & Churchill, 1980) and subjective evaluations (Brisbine et al., 2022).

While subjective assessments provide essential insight into user experience, they do not fully capture the complex three-dimensional interaction between the body and LCSs. In response, modern techniques such as 3D body scanning have improved the objectivity of anthropometric assessment (Rumbo-Rodríguez et al., 2021; Shu et al., 2015); however, standard protocols require minimal, form-fitting clothing to ensure accuracy, limiting their applicability for evaluating bulky equipment such as LCSs. Together, these limitations highlight the need for approaches that better capture how LCSs interact with the body from the user's perspective.

Notably, this is particularly relevant within the CAF, where efforts to improve LCSs have led to the acquisition of a new body armour system, called the Body Armour Carriage System (BACS). This system has been modernized in comparison to the current in-service Clothe the Soldier (CTS) kit, offering a modular design enabling personalization across a wider size range. However, this new kit design has not been adequately evaluated in comparison to the CTS kit, and little is known regarding how the two systems differ, particularly regarding static and subjective equipment fit. Examining these differences provides an opportunity to better understand how equipment configuration influences perceived static fit. This will contribute to our understanding regarding the factors that contribute to optimal fit.

Therefore, this study aims to evaluate perceived fit, comfort, and overall acceptability across both CTS and BACS systems, using subjective surveys completed by CAF soldiers. In this context, perceived fit refers to how well the equipment conforms to the body, while comfort reflects the user's experiential response during wear, and acceptability represents the overall evaluation of the system. By examining how these parameters vary across configurations and relate to one another, this study provides insight into the factors that influence user experience with LCSs.

Chapter 2: Literature Review

2.1 Anthropometrics

Anthropometry is defined as the scientific study of human body measurements and proportions, which is crucial to understanding human body diversity and characteristics (Jones, 2023). Traditionally, anthropometric data have been acquired using traditional methods involving 1D surface measurements, taken with manual tools like calipers and tape measures, an approach valued for its simplicity and low cost (Rumbo-Rodríguez et al., 2021; Shu et al., 2017). To promote accuracy and consistency, anatomical landmarks and chosen measures have been standardized through internationally recognized efforts such as those described in ISO 7250-1 (Coltman, Brisbine, Molloy, et al., 2021; ISO 7250-1:2017, 2017; Shu et al., 2017).

Historically, 1D techniques have dominated product design and ergonomic applications which, while practical, have significant drawbacks. A primary issue is their reliance on skilled personnel for both measurement collection and subsequent fit assessment, a factor that directly contributes to considerable inter- and intra-observer variability (Choi & Zehner, 2009; Rumbo-Rodríguez et al., 2021). In addition, manual measurements are time-consuming, sensitive to postural changes, as well as variations in tape pressure. These techniques are further hindered by difficulties in consistent landmark identification, especially with higher adiposity (Rumbo-Rodríguez et al., 2021). Collectively, these limitations highlight the need for more advanced measurement techniques to enhance objectivity, precision, and consistency when collecting anthropometric measurements for fit assessment, particularly as it relates to PPE.

To overcome traditional 1D anthropometry limitations, modern 3D and 4D body scanning technologies have emerged as transformative tools for capturing human body geometry (Dāboliņa & Lapkovska, 2019; Rumbo-Rodríguez et al., 2021), with reported sub-millimetre measurement accuracy of 0.1-0.6mm (De Rosario et al., 2023). Early 3D scanners provided significant advantages, including rapid, non-invasive data acquisition, and the ability to generate comprehensive digital body models, from which numerous measurements can be extracted post-hoc (Rumbo-Rodríguez et al., 2021; Shu et al., 2017). To effectively utilize this dense scan data, automated algorithms have been developed to identify landmarks and automatically compute various anthropometric parameters (Jun-Ming Lu & Wang, 2010; Parrilla et al., 2020; Shu et al., 2017). While 3D methods correlate with traditional techniques, direct comparisons between the two approaches have revealed challenges in achieving consistent accuracy across all anthropometric measures (Rumbo-Rodríguez et al., 2021; Shu et al., 2017). Such inconsistencies may be attributed to several factors, including operator-dependent variables (Meletani et al., 2024) and deviations from established standards such as ISO 20685-1:2018 (ISO 20685-1:2018, 2018).

In this context, 4D scanning technologies offer advantages for both static and dynamic assessments by capturing full-body geometry over time, which allows for the selection of stable postures and helps mitigate the influence of movement-related artifacts (Parrilla et al., 2020; Rumbo-Rodríguez et al., 2021). Such detailed data provides the anthropometric measurements, which, with further analysis, allow the quantification of cross-sections to determine the gap between the body and the equipment (Choi & Zehner, 2009; Stirling et al., 2020). High-fidelity anthropometric data is fundamental to evidence-based PPE design and sizing, where accurate static fit is critical for user safety and operational effectiveness. Indeed, beyond equipment design, anthropometrics combined with body composition variables, specifically fat and lean mass, are associated with performance outcomes, largely through their influence on load carriage capacity, movement efficiency, and fatigue resistance. These factors underpin success in elite Special Forces selection and proficiency in simulated direct-fire engagements, including sprint and marksmanship performance under combat loads (Farina et al., 2022; Stein et al., 2023).

2.2 PPE

Personal Protective Equipment (PPE) refers to specialized clothing and equipment designed to enable users to perform tasks safely and protect them from environmental influences (Dāboliņa & Lapkovska, 2019). In military contexts, PPE, particularly LCSs and body armour, is critical for the safety and effectiveness of personnel such as those in the CAF. Body armour, primarily functions to offer passive protection to a soldier's vital thoracoabdominal organs against ballistics, fragmentation (i.e., shrapnel), and stab threats (Coltman, Brisbine, & Steele, 2021) while simultaneously needing to allow for comfort and mobility (Choi et al., 2016). In parallel, LCSs enable personnel to transport mission-essential equipment, often involving substantial loads. These loads typically range from 20–30 kg and can reach up to 61 kg in infantry contexts (Knapik et al., 2004), which can exceed the soldiers body weight, representing a significant burden that exposes them to an increased risk of MSK injury (Coll et al., 2025).

Design practices for military equipment present significant challenges to achieving optimal fit across users. Historically, the design of gear such as body armour relied predominantly on anthropometric data exclusively from male populations. This male-centric approach has resulted in unisex sizing systems, producing significant fit discrepancies for female soldiers, compromising comfort, mobility, and safety (Brisbine et al., 2022; Coltman, Brisbine, Molloy, et al., 2021; Gruevski et al., 2024). This limitation has prompted formal calls for a new evidence-based framework to guide the research and development of clothing and individual equipment specifically adapted for female soldiers (Armstrong et al., 2025). Furthermore, equipment design is evolving beyond traditional flat plates. Solutions now include curved plates and armour optimized for female-specific geometries derived from 3D scans (Abtew et al., 2018; Coltman et al., 2022b) and flexible ballistic materials like 3D woven fabrics that enable body armour to conform to the body (Mica & Suh, 2023; Schwartz, 2019). These novel systems are aimed at improving the integration between the soldier and their PPE.

In summary, modern LCSs must be designed to optimize both user protection and comfort. Poorly fitting systems have been associated with discomfort, altered movement patterns, and reduced task performance (Andersen et al., 2016; Choi et al., 2016; Coltman et al., 2020). From a survivability perspective, poor fit can be dangerous: undersized armour may leave vital organs insufficiently covered and restrict movement, while oversized armour can shift on the body, creating gaps in protection and compromising or restricting mobility, thereby increasing exposure to external threats (Choi et al., 2019; Coltman et al., 2022a; Laing & Jaffrey, 2019). These challenges highlight the importance of accurately characterizing fit from the user's perspective. In this context, subjective evaluations of fit, comfort, and overall acceptability provide insights into how equipment is experienced during use and how design features influence user perception.

2.2.1 CTS and BACS

The CAF is currently transitioning from the in-service CTS system to BACS. This transition represents a fundamental shift in how ballistic protection and load carriage are integrated, with important implications for fit, comfort, and overall user experience. The in-service CTS system is based on a layered design, where ballistic protection and load carriage are handled by separate components. Specifically, the Fragmentation Protective Vest (FPV) houses the ballistic plates, while a distinct Tactical Vest (TV) is worn over the FPV to carry mission-essential equipment such as ammunition and supplies. Although functional, this approach has been associated with limitations in integration and adaptability, and the system itself was originally designed over two decades ago for peacekeeping operations, later proving less suitable for modern combat environments such as those encountered in Afghanistan (L. Bossi et al., 2020; L. Bossi & Tack, 2001).

In contrast, the BACS system adopts an integrated and modular design, combining load carriage directly with ballistic protection. Equipment is attached using the Modular Lightweight Load-carrying Equipment (MOLLE) system, allowing pouches and mission-specific components to be secured directly onto the plate carrier and associated elements (Lafiandra & Harman, 2004). This integration eliminates the need for a separate load-bearing vest and enables a more streamlined interaction between the system and the body. A defining feature of BACS is its high degree of modularity and configurability. The system includes over 250 components and supports multiple load carriage configurations (e.g., chest rig, belt kit, or plate carrier setups), introducing scalable protection, where soft armour coverage can be adjusted depending on operational requirements, environmental conditions, and threat levels.

The transition to BACS is particularly relevant for light infantry personnel, who operate in dismounted contexts and are required to carry substantial loads over extended distances. In this setting, equipment design must balance competing demands related to protection, mobility, and MSK health, often referred to as the soldier "survivability trade-space" (Mavor et al., 2022). As such, understanding how these two systems differ in terms of perceived fit, comfort, and acceptability is critical for evaluating whether the new system effectively addresses the limitations of its predecessor.

2.3 Fit

The concept of "fit" has been incorporated into the core definition of ergonomics. According to Grandjean (1988), an ergonomic system is an environment that "fits" human capability and needs. In the context of the present document, fit refers to the relationship between a soldier and their LCS. Importantly, fit extends beyond mere physical sensation; fit also entails psychological dimensions, such as situational appropriateness and personal preferences (Ross, 2005).

A more technical framework from Stirling et al. (2020) further breaks down the concept, categorizing fit into three key dimensions. Static fit refers to the physical alignment between the user's anthropometry and the system; dynamic fit describes the interaction between the user and the system during movement; and cognitive fit considers the system's influence on the user's perception–cognition–action decision process. While all three dimensions contribute to overall user experience, the present study focuses specifically on static fit as the foundational component of body–equipment interaction. As the initial point of contact between the body and the system, static fit plays a critical role in shaping user perception, influencing comfort and ultimately contributing to overall equipment acceptability.

2.3.1 Static Fit

Static fit is defined as the alignment between the soldier's anthropometry and their equipment when the user is in a standardized posture. International standards, notably ISO 7250-1, stipulate definitions for anthropometric landmarks, measuring conditions, and standardized posture (ISO 7250-1:2017, 2017). On the other hand, for 3D scanning applications, ISO 20685 specifically addresses 3D scanning methodologies for internationally compatible anthropometric databases. Within this context, the A-Pose is a widely adopted standard because its specific arm and leg positioning (feet shoulder-width apart and arms held away from the body at a 45-degree angle with palms facing inward and fingers straight) minimizes self-occlusion, allowing for a more complete surface capture (ISO 20685-1:2018, 2018; Meletani et al., 2024).

Beyond standardized posture, the comprehensive evaluation of static fit relies on the examination and integration of both subjective assessments and objective measures. Subjective assessments capture the soldier's perception of fit, such as perceptions of tightness or looseness. In contrast, objective measures quantify the physical relationship between the body and the equipment, for which 3D scanning is a particularly powerful tool, enabling the precise analysis of the space between the body and equipment through the analysis of cross-sections extracted from the scans (Wang et al., 2006). Despite their complementary nature, these approaches are applied independently, and a standardized framework integrating both perspectives remains lacking.

Within objective approaches, key quantifiable metrics have been established in equipment design. According to the literature, five primary characteristics traditionally determine a good equipment fit: Ease, Line, Grain, Set, and Balance. While all five contribute to overall fit, Ease and Line are the most important (Erwin & Kinchen, 1964). Ease refers to the space between the equipment and the body (Fig. 2.1) at specific locations (Choi & Zehner, 2009). It reflects how tightly or loosely the system interfaces with the user and is influenced by factors such as equipment design, activity demands, and individual preference.

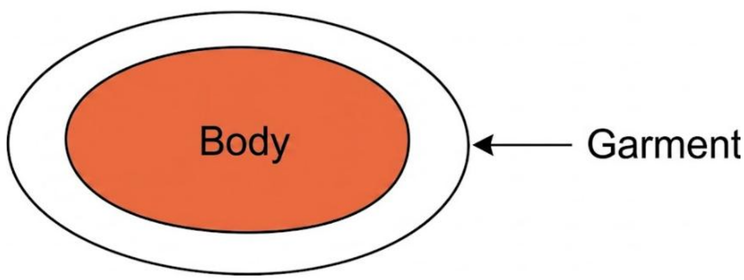


Figure 2.1. *Theoretical Cross-Section at Clothed Waist*. From (Choi & Zehner, 2009).

Line, in contrast, includes all basic silhouette seam lines, circumference seam lines, and design lines. Generally, for a good fit, the shoulder seam should be at or near the shoulder's top, and elements like the shoulder seam, armhole, underarm seam, and side seams of skirts or slacks should appear continuous. Line describes the alignment of the equipment relative to anatomical landmarks, indicating whether the system is correctly positioned on the body (Choi & Zehner, 2009). Together, ease and line provide a conceptual framework for understanding the physical characteristics of static fit.

However, while these objective descriptors are useful for quantifying the body–equipment interaction, they do not fully capture how the system is experienced by the user. As a result, identifying the specific factors contributing to poor fit remains challenging in applied settings. Accordingly, the present study focuses on the subjective evaluation of fit, emphasizing the user's perception of whether the equipment feels too tight, perfect, or too loose, and how these perceptions contribute to overall acceptability.

2.4 Comfort

Comfort is a critical factor in the evaluation and sustained use of LCSs, particularly in military contexts where equipment is worn for extended durations. In contrast to fit, which describes the structural alignment between the body and the equipment, comfort reflects the user's cumulative physical experience arising from the body–equipment interaction, including factors such as pressure, restriction, and thermal load (Wettenschwiler et al., 2015).

Although closely related, comfort and fit are not interchangeable. A system may be considered well-fitted in terms of alignment and positioning yet still be perceived as uncomfortable if it generates localized pressure, restricts natural movement, or contributes to heat accumulation during prolonged use. Conversely, poor fit often exacerbates discomfort by introducing instability, uneven load distribution, or excessive compression. This relationship highlights that fit provides the structural basis of body–equipment interaction, while comfort represents the cumulative experience of that interaction during use.

In the context of LCSs, discomfort can directly affect a soldier's performance, safety, and injury risk in demanding military environments (Choi & Zehner, 2009; Gruevski et al., 2024). Research has shown that discomfort increases progressively with duration, particularly when systems impose uneven loading or restrict natural movement patterns (Knapik et al., 2004; Majumdar et al., 2010). For instance, these effects may impair movement, resulting in a quantifiable decrease in a soldier's range of motion (ROM) and hindering their ability to perform essential tasks such as aiming a weapon (Choi et al., 2016, 2019). In addition, localized discomfort has direct health and safety consequences, ranging from localized issues (i.e., pressure points and chafing) to altered biomechanics that increase the risk of MSK injuries, such as rucksack palsy resulting from poorly adjusted straps (Andersen et al., 2016; Coltman et al., 2020).

Because comfort reflects an individual and perceptual experience, its evaluation relies heavily on subjective assessments. Traditionally, surveys and qualitative feedback have offered initial insights into how military personnel perceive their PPE's fit (Coltman et al., 2020; Dāboliņa & Lapkovska, 2019). Further, methods such as cross-sectional surveys on self-reported pain or injury (Runge et al., 2021), and focus groups on equipment experiences (Coltman, Brisbine, & Steele, 2021), help identify user-reported discomforts and design flaws (Coelho et al., 2020; Coltman et al., 2022b; Dāboliņa & Lapkovska, 2019); thereby providing us important information relating to how comfort is experienced in applied military settings.

An important concept relating to subjective comfort, is equipment acceptability. Equipment perceived as uncomfortable is less likely to be accepted by the user (Gruevski et al., 2024). This is especially relevant for female soldiers, who have reported greater discomfort due to issues such as improper sizing, excessive pressure, and limited accommodation of sex-specific anthropometric characteristics (Coltman, Brisbine, & Steele, 2021; Coltman et al., 2022a). Furthermore, discomfort may be compounded by poor integration between equipment components, such as improperly sized body armour, failing to integrate effectively with critical equipment such as load carriage belts, weapons, packs, and helmets (Coltman, Brisbine, & Steele, 2021). Within the CAF, subjective evaluations have demonstrated that comfort is a key factor influencing overall equipment acceptability, with poorly fitting or uncomfortable systems consistently receiving lower ratings (Gruevski et al., 2024). This highlights that comfort is not only an outcome of fit, but a central criterion in the evaluation of LCSs. As a cumulative and dynamic construct, shaped by equipment design and duration of its use, comfort is essential for evaluating how LCSs are experienced in practice and for identifying design features that support sustained, effective use in operational environments.

2.5 4D Technology

While subjective assessments are essential for capturing perceived fit and comfort, they do not fully describe the physical interaction between the body and the equipment. As a result, objective approaches that quantify body–equipment relationships have gained increasing attention, particularly with the development of advanced 3D and 4D body scanning technologies. These tools offer the potential to complement subjective evaluations by providing detailed, reproducible measurements of human shape and movement. One such technology is Move4D (Fig. 2.2), a modular photogrammetry-based 4D body scanner developed by the Institute of Biomechanics of Valencia (IBV, Spain).

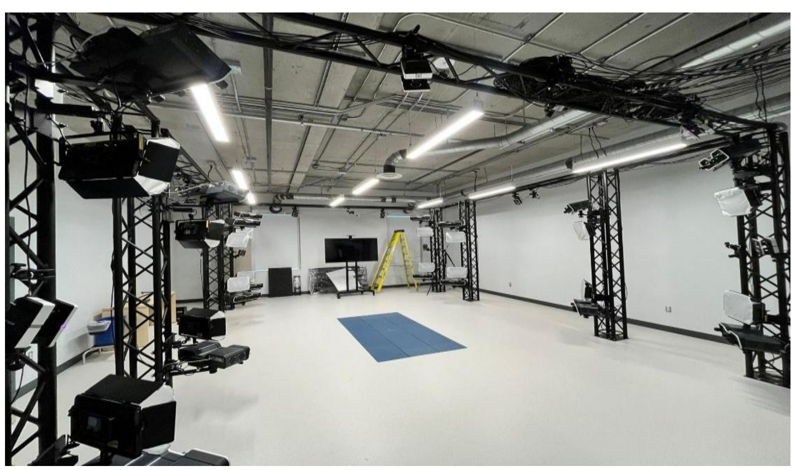


Figure 2.2. *Move4D at the University of Ottawa*

Move4D consists of a set of synchronized modules-individual hardware units designed to scan full bodies with texture in motion, along with a control unit and processing software; the system utilizes a modular photogrammetry approach (Kyosev et al., 2023). Each module (Fig. 2.3) typically comprises a pair of infrared (IR) cameras, an IR projector, a color (RGB) camera, and a processing unit.

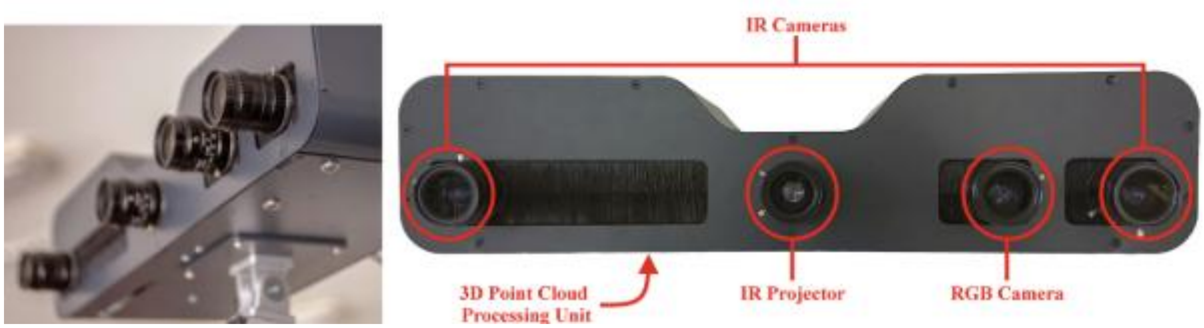


Figure 2.3. *Detail of Move4D Model Unit. From (Parrilla et al., 2020).*

Depending on the specific configuration (Fig. 2.4), Move4D can capture data at rates of up to 180 frames per second (Parrilla et al., 2020). A critical technical advantage of the Move4D system is its ability to generate homologous meshes, which maintain consistent point-to-point correspondence across all captured frames and between subjects. This advanced output is achieved through a highly automated processing pipeline that avoids the need for manual landmarking or revision for scans captured under non-loaded (i.e., minimally clothed) conditions (Parrilla et al., 2020).

Characteristics	Values	Notes
Optic unit resolution	1–2 mm	Corresponding to high – medium resolution
Maximum captures frequency	90–180 fps	Corresponding to high – medium resolution
Scanning time	1 ms	
Footprint	5.5 × 5.5 m	Corresponding to 12 units configuration
External synchronism	I/O	Trigger and synchro input/output (I/O)
Capture		3D data and corresponding color (texture)
Lighting		Inbuilt lighting system

Figure 2.4. *Move4D Technical Specifications. From (Parrilla et al., 2020).*

The system's software utilizes deep learning and a sophisticated data-driven models to process the raw 3D point cloud sequences. This model is designed to account for complex variations in human shape, pose, and soft-tissue deformation. The final output for each frame is a noise-free, watertight, and dense mesh that can be rigged with a skeleton for further analysis. For compatibility with other software, this data can be exported in standard formats such as OBJ, FBX, and BVH (Kyosev et al., 2023; Scataglini & Truijen, 2022). Examples of homologous mesh outputs generated from the Move4D scanning process are presented in Appendix C.

The practical utility and robustness of these technical capabilities are underscored by Move4D's demonstrated versatile applications. For instance, it has been utilized for analyzing changes in airgaps during movement within firefighter protective clothing (Muenks et al., 2023) and quantifying breast shape during running (De Rosario et al., 2023). Furthermore, the Move4D system's performance has been validated against established inertial motion capture systems (Xsens), demonstrating moderate to excellent reliability for temporal parameters such as cycle, stance, and swing time (ICC = 0.60–0.90), alongside acceptable agreement in joint kinematics, with RMSE values ranging from approximately 5° to 11° during gait (Meletani et al., 2024). While these capabilities highlight the system's potential for advanced analysis, in the context of the present research, Move4D was used specifically to obtain participant anthropometric characteristics. These measurements provide anatomical context for interpreting subjective fit perceptions and establish a foundation for future work integrating scan-derived metrics with perceptual outcomes.

Chapter 3: Purpose

The objective of this thesis is twofold: 1) to identify which aspects of perceived fit and comfort most strongly influence overall equipment acceptability, thereby establishing a subjective baseline for evaluating static fit; and 2) to compare perceived fit, comfort, and acceptability across LCS configurations, specifically between the current in-service CTS and the newer BACS system. To achieve this, subjective assessments provided by CAF soldiers were collected across multiple configurations. While 4D human body scanning technology (Move4D, IVB, Spain) was used to capture participant anthropometrics, its role in this study was to provide anatomical context rather than define fit outcomes. Together, these approaches provide insight into user perception and a foundation for future integration with objective, scan-derived metrics.

Chapter 4: Hypothesis

The assessment of static fit in LCSs relies on understanding how equipment is perceived by the user, particularly in relation to fit, comfort, and overall acceptability. Accordingly, subjective evaluations were central to this study, as they capture the functional aspects of equipment that directly influence user acceptance in military contexts. These outcomes were assessed through participant surveys to examine both the determinants of user perception and differences across equipment configurations. It was hypothesized that BACS configurations would demonstrate significantly higher perceived fit and comfort scores compared to CTS configurations. It was further hypothesized that perceived fit and comfort would be positively associated, such that configurations rated as better fitting would also be perceived as more comfortable. Building on this relationship, both variables were expected to predict overall equipment acceptability significantly. Finally, total system weight was expected to negatively influence perceived fit, comfort and acceptability, with stronger effects anticipated for comfort and acceptability.

Chapter 5: Methods

5.1 Participants

Sixteen soldiers (9 M, 7 F) from the CAF were recruited, and average participant demographics can be seen in Table 5.1. To ensure that subjective fit evaluations reflected operational experience, inclusion criteria required a minimum of 15 days (≥100 cumulative hours; within the previous three years) wearing body armour while carrying fighting loads ≥18 kg. Participants were also required to have completed the Basic Military Qualification–Land (DP1) course, and the FORCE Combat Fitness Test within the last year. Participants were eligible for study participation if they were medically cleared for duty. Exclusion criteria included any current medical condition (e.g., acute MSK injury) that could impair safe task performance or use of standard-issue equipment. Following approval from the University of Ottawa (2025-048) and Defence Research and Development Canada (DRDC) ethics committees, participants provided written informed consent prior to demographic data collection (age, sex, years of service).

All equipment configurations were fitted under the supervision of an Infantry Subject-Matter Expert (SME) to ensure technical accuracy and operational validity. Each participant completed two conditions per session, with the full protocol distributed across up to six non-consecutive days to manage scheduling constraints and the cumulative physical load. One participant withdrew before completing all equipped conditions; however, their completed trials were retained for analysis, resulting in three missing observations. Additionally, one participant omitted a single post-condition survey.

Table 5.1

Participant Demographics

Age groups (years)	Number of participants	Service years (Range)	Weight (kg)	Height (cm)	Chest Cir. (cm)	Waist Circ. (cm)
			Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
18-24	7 (4 M, 3 F)	0-9	77.81 (20.37)	179.91 (12.21)	102.00 (11.94)	83.51 (12.55)
25-34	7 (3 M, 4 F)	7-10+	79.50 (17.39)	176.11 (5.09)	102.54 (11.09)	86.66 (14.80)
35-44	2 (2 M, 0 F)	7-10+	96.31 (22.19)	179.01 (6.68)	114.79 (14.61)	109.59 (18.70)
Total	16 (9 M, 7 F)	0-10+	82.86 (18.96)	178.02 (8.43)	103.96 (11.76)	88.46 (15.85)

Note. SD = Standard deviation; kg = kilograms; M = Male; F = Female; cm = centimetres; Circ = circumference.

5.2 Study Design

A within-subjects repeated-measures design was employed to evaluate subjective fit, comfort, and acceptability across 11 total experimental conditions. The protocol consisted of one baseline "Slick" condition (i.e., testing protocol performed in skin-tight clothing with no LCSs or other body-borne equipment) and ten equipped conditions representing varying levels of encumbrance. The remaining conditions incorporated configurations using PPE and Full Fighting Order (FFO), where FFO is defined as clothing combined with PPE and a combat fighting load. The Slick condition was always performed during the first session to establish baseline anthropometric measurements and inform equipment sizing. The ten equipped configurations were presented in a randomized counterbalanced order across participants to minimize potential order and fatigue effects. Images representing the various kit configurations examined in this study can be seen in Figure 5.1. Configurations included both CTS and BACS equipment, representing varying levels of encumbrance with combinations of soft and hard components. For example, condition C2 used the CTS FPV, while the BACS configurations ranged from base armour only (C4) to extended coverage including the neck guard and shoulder brassards (C8). The FFO configurations integrated these armour systems with specific fighting load carriers, such as a chest rig (C5), belt kit (C6), or plate carrier alone (C7). A detailed breakdown of each equipped configuration, including component composition and total system weight, is provided in Appendix B.

Figure 5.1

Front View of the Eleven Configurations

Note. Panels (a) through (k) represent configurations C1 through C11, respectively: (a) C1: Slick (baseline); (b) C2: CTS PPE; (c) C3: CTS FFO; (d) C4: BACS PPE; (e) C5: BACS with chest rig; (f) C6: BACS with belt kit; (g) C7: BACS plate carrier; (h) C8: BACS extended coverage; (i) C9: BACS extended coverage with chest rig; (j) C10: Hybrid BACS–CTS; (k) C11: BACS chest rig combined with CTS soft armour. Configurations are presented to highlight differences between CTS and BACS systems and the modular versatility of the BACS system.

Subjective ratings were collected only following the equipped conditions; no survey was administered after the Slick baseline condition. Each condition involved completion of a standardized movement battery prior to survey administration. Anthropometric data were captured using the Move4D scanning system (IVB, Spain), previously validated for comparable anthropometric research applications (Kyosev et al., 2023; Meletani et al., 2024; Muenks et al., 2023; Uriel et al., 2022). Although objective 3D metrics were collected, the present thesis focuses exclusively on modelling subjective evaluations of the body–equipment interface.

5.3 Data Collection

Upon arrival, participants received a standardized briefing outlining the study objectives and testing sequence. Participants wore freshly laundered, form-fitting attire (spandex pants and long-sleeve shirt) to ensure accurate surface capture. During the initial Slick session, participants were scanned in a standardized standing A-pose using the Move4D system to obtain baseline anthropometric measurements (Appendix E). These measurements, together with manufacturer sizing guidelines, were used to determine equipment sizing for all equipped conditions. All equipment fitting and adjustments were conducted under the supervision of the SME to ensure operational accuracy.

Across all 11 conditions, participants completed a standardized movement protocol at the Move4D test stand. Static captures included a standing A-pose and a seated posture; each held for approximately two seconds per scan. Dynamic transitions were performed between prone, kneeling, and standing positions, including both high port and low port weapon carriage postures. Exposure to these postures ensured that participants experienced potential mechanical restriction, pressure redistribution, and sensory irritation before reporting subjective evaluations. Detailed descriptions of each pose are provided in Appendix C.

Immediately following completion of each of the ten equipped conditions, and while still wearing the configuration, participants completed the adapted fit-comfort survey on an iPad. The survey assessed three domains: regional fit, sensory discomfort, and overall acceptability (Appendix D). This approach was adapted from previously established fit and comfort assessment frameworks used in military equipment evaluation (Coltman et al., 2020; Gruevski et al., 2024). Regional fit at anatomical landmarks (e.g., neck opening, chest circumference) was rated using a 10 cm Visual Analogue Scale (VAS) anchored at 0 ("Way too small"), 5 ("Perfect"), and 10 ("Way too big"). In addition, a standalone Static Fit score was collected using a 10 cm VAS ranging from 0 ("Completely unacceptable") to 10 ("Completely acceptable"). Sensory discomfort was captured using binary indicators (0 = absent, 1 = present) for rubbing/friction, pressure, bruising, and thermal discomfort at the shoulders, arms, chest, waist, neck, back, front plate, and back plate regions, followed by a standalone Comfort Score using a 0–10 scale anchored from "Completely unacceptable" to "Completely acceptable". Participants also identified specific postures, including kneeling, prone, and seated positions, that were associated with discomfort using binary responses. Overall acceptability was evaluated using three additional 10 cm VAS ratings representing static fit, static comfort, and overall fit and comfort, anchored from 0 ("Completely Unacceptable") to 10 ("Completely Acceptable").

5.4 Data Processing

Following data collection, survey responses collected via SurveyMonkey (Momentive Inc., USA) were exported to Microsoft Excel (Microsoft Corp., USA) and were organized into a long-format dataset, where each row represented a unique participant–condition combination across the ten equipped configurations. Standard data cleaning procedures were performed, including verification of entries and handling of missing values, which were addressed during statistical modelling (see Section 5.6). ISO 7250-1:2017–compliant anthropometric measurements were automatically extracted from each participant's Slick A-pose scan using the Move4D system

(Section 6.1). While these objective measurements were retained for contextual and future analyses, they were not included as predictors in the present modelling of subjective outcomes. Regional fit ratings and the standalone Fit Score were collected on a 10 cm VAS where the ideal fit corresponded to the midpoint value of five. To quantify misfit magnitude independent of direction, ratings were transformed into deviation scores using the absolute difference from the midpoint (|Rating − 5|). The transformation produced a continuous variable ranging from 0 (perfect fit) to 5 (maximum deviation) and allowed departures from ideal fit—whether perceived as too small or too large—to be modelled as a single continuous error metric. Deviation scores were used as predictors in subsequent analyses. Sensory discomfort variables were initially collected as individual binary indicators (0 = absent, 1 = present) for rubbing/friction, pressure, bruising, and thermal discomfort across multiple anatomical regions. To avoid issues related to multicollinearity and overfitting, these variables were grouped by anatomical region to create composite binary indicators indicating whether any discomfort was present in a given area. For example, reports of rubbing, pressure, bruising, or thermal discomfort at the shoulder region were combined into a single "Shoulder Affected" variable. This approach reduced the total number of discomfort predictors to a smaller set of region-specific indicators while preserving the presence or absence of discomfort within each anatomical location. These composite indicators were subsequently used as predictors within the comfort modelling framework.

5.5 Subjective Variables and Metrics

Survey-derived variables were grouped into three categories: deviation-based fit measures, binary sensory indicators, and global acceptability ratings. Regional fit at ten anatomical landmarks (i.e., neck opening, arm opening, shoulder breadth, chest circumference, waist circumference, plate carrier length, front plate length and width, and back plate length and width), were evaluated using a 10 cm VAS anchored at 0 (“Way too small”), 5 (“Perfect”), and 10 (“Way too big”). To quantify deviation from the ideal fit state, these variables were transformed into deviation scores as described in Section 5.4, yielding continuous scores ranging from 0 to 5, where higher values indicated greater agreement with the ideal fit perception. These transformed variables served as predictors in the regional fit model. A separate overall Fit Score was also collected using a 10 cm VAS ranging from 0 (“Completely unacceptable”) to 10 (“Completely acceptable”). Sensory discomfort perceptions were captured using binary indicators (0 = absent, 1 = present) of rubbing, pressure, bruising, and thermal discomfort across the shoulders, arms, chest, waist, neck, back, front plate, and back plate regions. These binary indicators were used as predictors within the comfort model. In addition, a standalone Comfort score was collected from 0 (“Completely unacceptable”) to 10 (“Completely acceptable”) and was treated as a continuous dependent variable. Standalone Static Fit, Static Comfort, and Overall Fit and Comfort scores, representing subjective post-condition evaluations, were treated as continuous dependent variables ranging from 0 to 10. Additionally, binary posture indicators identifying discomfort during specific positions (i.e., A-pose, seated, high port, low port, kneeling with aiming, and prone with aiming) were incorporated as fixed effects within the comfort modelling framework. Frequencies of reported discomfort across anatomical regions and equipment configurations were summarized descriptively and visualized using heatmaps. Establishing a hierarchical evaluation framework allowed subjective perception to be examined across three interconnected levels: regional fit deviation, localized sensory discomfort, and overall acceptability. By identifying these variables, the analysis provides a comprehensive understanding of the body-equipment interface that transcends the limitations of a singular score.

5.6 Statistical Analysis

The primary objective of the analysis was to evaluate differences across equipment configurations and to examine the predictive relationships between regional fit deviations, sensory discomfort, and overall equipment acceptability. Linear Mixed-Effects Models (LMMs) were implemented in R (R Core Team, USA) using the *lme4* and *lmerTest* packages, with statistical significance set at $p < 0.05$. Participant was included as a random intercept to account for inter-individual variability in perception and tolerance. Because some observations were missing due to participant withdrawal and an incomplete survey response, models were estimated using the *na.exclude* option in R. This approach excludes missing observations during model fitting while retaining their positions in the dataset for the calculation of residuals and fitted values, allowing consistent handling of incomplete repeated-measures data.

Modelling followed a hierarchical framework aligned with the conceptual structure of the subjective measures. Two complementary modelling approaches were implemented to address different analytical objectives. Configuration-level models (Sections 6.2–6.4) evaluated differences in perceived fit and comfort across the ten equipped conditions, and their overall relationship. Because equipment configuration directly determines total system weight, the two variables are structurally linked. Weight was therefore excluded from the configuration comparison models to avoid collinearity and preserve the interpretation of configuration-level effects. In contrast, predictor-based models (Sections 6.5–6.7) replaced configuration with total system weight as a continuous covariate. This approach allowed evaluation of whether perceptual outcomes were influenced by overall load magnitude independently of structural misfit or sensory discomfort.

Following configuration-level analyses, predictor-based models were implemented in three stages. For all models, participant was specified as a random intercept to account for repeated measures and inter-individual variability. Total system weight was included as a continuous covariate in all models to account for the potential influence of load magnitude on subjective perceptions. First, the Overall Fit Score was modelled using regional deviation scores from the ten anatomical landmarks as fixed effects alongside total system weight (Section 6.5). In the second stage, Overall Comfort Score was modelled using composite binary regional discomfort indicators representing whether any discomfort was present within a given anatomical region (i.e., shoulders, arms, chest, waist, neck, back, front plate, and back plate), which were entered as fixed effects together with total system weight (Section 6.6). An additional mixed-effects model following the same analytical structure was performed using binary posture discomfort indicators (i.e., seated, prone, kneeling, high port, and low port positions) to evaluate the influence of posture-specific discomfort on perceived comfort. In the final stage, Overall Static Acceptability was modelled as a function of Static Fit, Static Comfort, and total system weight (Section 6.7). Given the sample size (n = 16), primary models evaluated the study population as a whole. However, an exploratory, sex-based analysis of structural predictors and their effects on perceived fit and comfort is provided in Appendix F to inform future investigations.

Multicollinearity among fixed-effect predictors was assessed using the Variance Inflation Factor (VIF) before model interpretation. VIF values greater than 5 were considered indicative of potential multicollinearity. Model performance was quantified using Marginal R^2, representing variance explained by fixed effects, and Conditional R^2, representing variance explained by both fixed and random effects. Estimated Marginal Means (EMMs) with Tukey-adjusted pairwise comparisons were calculated using the *emmeans* package to summarize configuration-level differences while accounting for repeated measures.

Chapter 6: Results

The results of the statistical analyses examining subjective evaluations of the body–equipment interface across equipment configurations are presented in this chapter. Analyses are organized in four stages. First, participant anthropometric data are summarized, followed by EMMs of perceived fit and comfort across configurations. Second, configuration-level effects on perceived fit and comfort, as well as their relationship, are evaluated using LMM. Third, regional structural deviations and localized discomfort indicators are examined as predictors of perceived fit and comfort. Finally, the relative contributions of fit, comfort, and configuration total system weight to overall equipment acceptability are evaluated.

6.1 Participants Anthropometrics

Anthropometric characteristics derived from the baseline Move4D scans are summarized in Table 6.1. These measurements provide additional context regarding participant body dimensions relevant to equipment sizing and body–equipment interaction during load carriage. All values were extracted from the baseline Slick condition scan obtained during the initial standing A-pose. Variables reported include key upper-body and torso dimensions associated with plate carrier fit and load distribution. Descriptive statistics are presented as mean ± standard deviation, with ranges provided to illustrate variability within the sample.

Table 6.1

Anthropometric Measurements from Move4D

Variable	Mean (SD)	Range
Height (cm)	178.0 (8.1)	167.1-196.0
Torso height (cm)	73.2 (4.9)	64.5-83.4
Shoulder length (cm)	14.6 (1.2)	12.4-16.7
Shoulder breath – biacromial (cm)	37.8 (2.7)	34.0-43.7

Upper arm circumference (cm)	33.8 (3.7)	25.3-39.0
Chest circumference (cm)	103.8 (11.4)	87.9-126.4
Waist circumference (cm)	88.0 (15.4)	70.2-122.8
Hip circumference (cm)	105.6 (8.3)	92.5-122.6

Note. Anthropometric measurements were obtained from Move4D body scans and converted from millimetres to centimetres.

6.2 Effect of Configuration on Fit

To examine whether perceived fit differed across equipment configurations, a LMM was conducted with configuration entered as a fixed effect, and participant included as a random intercept to account for repeated measures. Because configuration inherently determined total system weight, weight was not included in the model to avoid collinearity. A significant main effect of configuration on perceived fit was observed, F (9, 140.22) = 21.24, $p < .001$, indicating that perceived fit differed across equipment setups (Figure 6.1).

Estimated marginal means revealed three general groupings of configurations. The highest fit scores were observed for BACS PPE (C4), BACS belt kit (C6), and BACS plate carrier (C7). A mid-range cluster included BACS chest rig (C5) and BACS extended coverage with chest rig (C9), while BACS extended coverage (C8) and the hybrid BACS–CTS configuration (C10) demonstrated moderately lower ratings. CTS PPE (C2) and CTS FFO (C3) formed a distinct lower tier, with BACS chest rig combined with CTS soft armour elements (C11) positioned between the lowest and mid-range groups.

Tukey-adjusted pairwise comparisons supported these trends. CTS PPE (C2) and CTS FFO (C3) were rated significantly lower than the higher-performing BACS configurations (C4: p = .018; C6: p = .021; C7: p = .008), whereas no significant differences were detected among the highest-rated BACS configurations(C4 vs. C6, p = 1.00; C4 vs. C7, p = 1.00; C6 vs. C7, p = 1.00), nor between the mid-range BACS chest rig (C5) and BACS extended coverage with chest rig (C9) (p = .799). Overall, these results indicate a clear separation between low-, mid-, and high-performing configurations with respect to perceived fit.

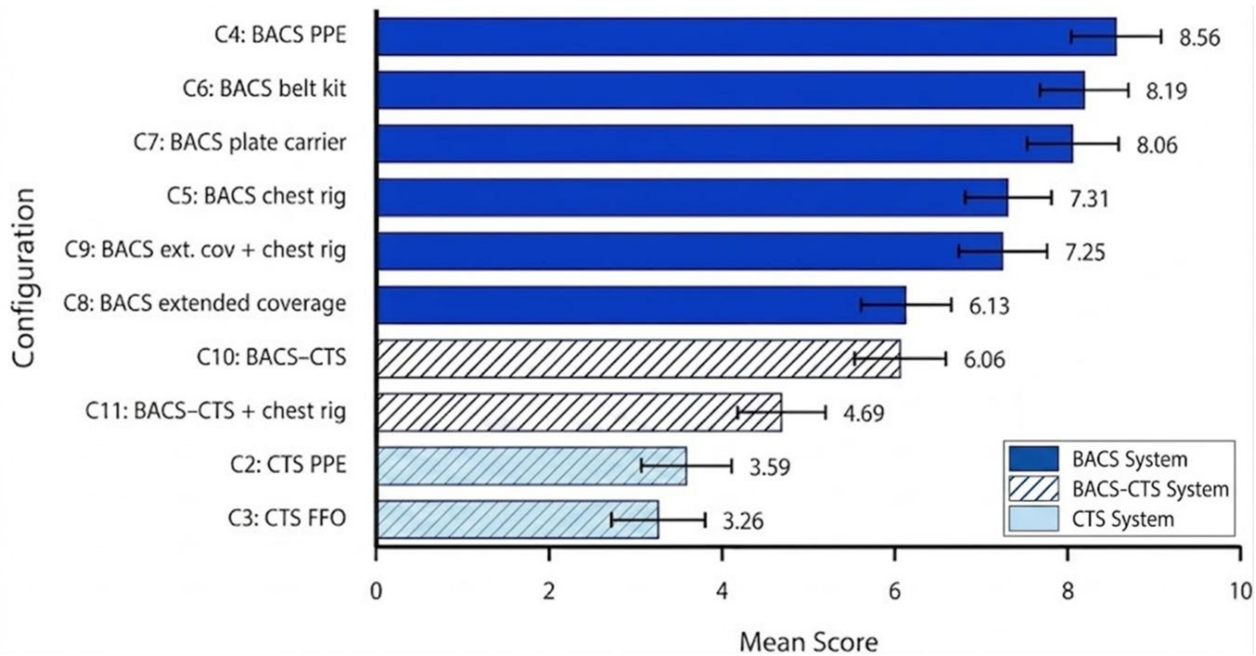


Figure 6.1

Estimated Marginal Means for Perceived Fit Across Equipment

Note. Points represent estimated marginal means derived from the linear mixed-effects model, with error bars indicating 95% confidence intervals. Configurations are ordered from lowest to highest perceived fit.

6.3 Effect of Configuration on Comfort

Perceived comfort was examined across equipment configurations using the same mixed-effects modelling structure described previously. Configuration was entered as a fixed effect and participant as a random intercept to account for repeated measures. Because configuration inherently determined total system weight, weight was not included in the model to avoid collinearity. A significant main effect of configuration on perceived comfort was observed, F (9, 140.08) = 21.84, $p < .001$, indicating that comfort scores varied across configurations (Figure 6.2).

The distribution of EMMs closely mirrored the pattern observed for perceived fit. BACS PPE (C4), BACS belt kit (C6), and BACS plate carrier (C7) received the highest comfort scores, whereas CTS PPE (C2) and CTS FFO (C3) were rated lowest. BACS chest rig (C5) and BACS extended coverage with chest rig (C9) formed a mid-range cluster, followed by BACS extended coverage (C8) and the hybrid BACS–CTS configuration (C10). BACS chest rig combined with CTS soft armour elements (C11) was positioned between the lowest and mid-range conditions. Tukey-adjusted post hoc comparisons supported these trends. CTS PPE (C2) and CTS FFO (C3) were rated significantly lower than higher-performing BACS configurations (C4, C6, and C7; all $p \leq .005$), whereas no significant differences were detected among the highest-rated configurations (C4 vs. C6, $p = 1.00$; C4 vs. C7, $p = 1.00$; C6 vs. C7, $p = 1.00$), nor between the mid-range BACS chest rig (C5) and BACS extended coverage with chest rig (C9) ($p = .860$). Overall, these results indicate that configurations perceived as better fitting were also consistently perceived as more comfortable. Given the strong correspondence between fit and comfort across configurations, subsequent analyses examined the regional factors contributing to perceived fit and comfort.

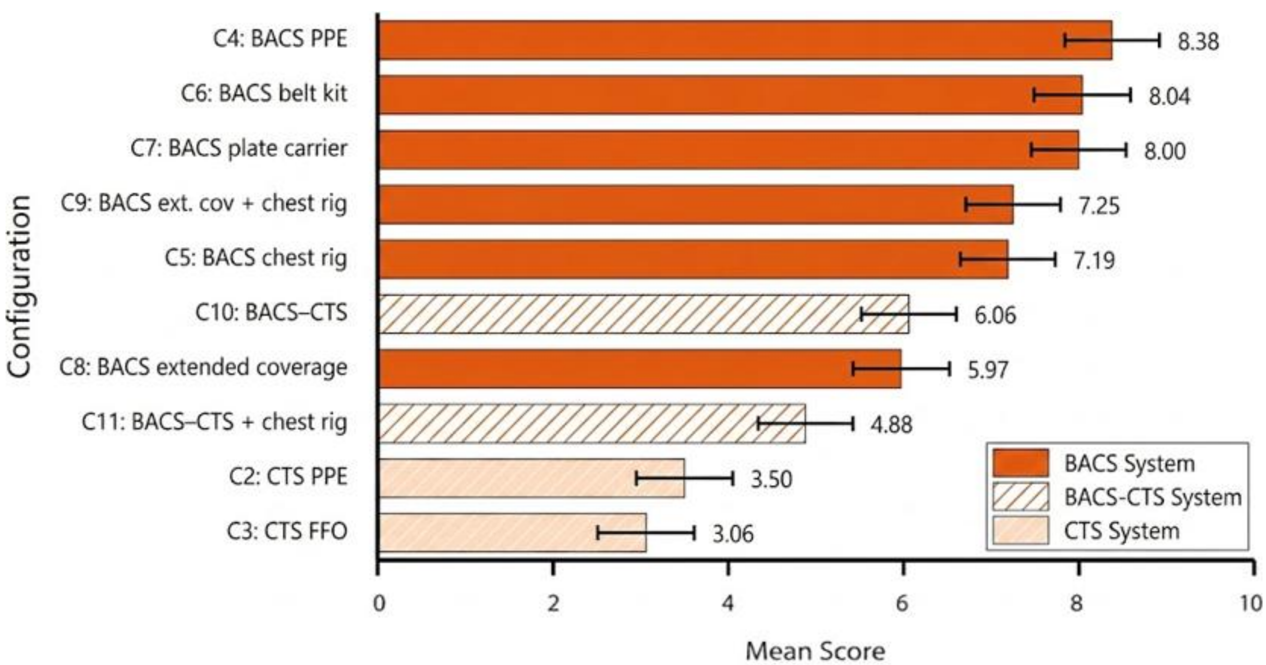


Figure 6.2

Estimated Marginal Means for Perceived Comfort Across Equipment Configurations

Note. Points represent estimated marginal means derived from the linear mixed-effects model, with error bars indicating 95% confidence intervals. Configurations are ordered from lowest to highest perceived comfort.

6.4 Relationship Between Fit and Comfort

To examine perceived fit and comfort across equipment configurations while accounting for repeated measures within participants, EMMs were computed. As shown in Figure 6.3, fit scores ranged from 3.26 to 8.56 across configurations, while comfort scores ranged from 3.06 to 8.38. Overall, configurations associated with the BACS system tended to receive higher ratings than CTS-based configurations, whereas hybrid BACS-CTS and extended-coverage systems produced intermediate scores. Patterns were highly consistent, with configurations associated with higher perceived fit also receiving higher comfort ratings. To formally evaluate this relationship, a linear regression analysis was conducted on the evaluation scores. Results confirmed a strong, significant positive association between perceived fit and comfort ($\beta = 0.43$, $p < .001$), statistically validating the visual trend across configurations.

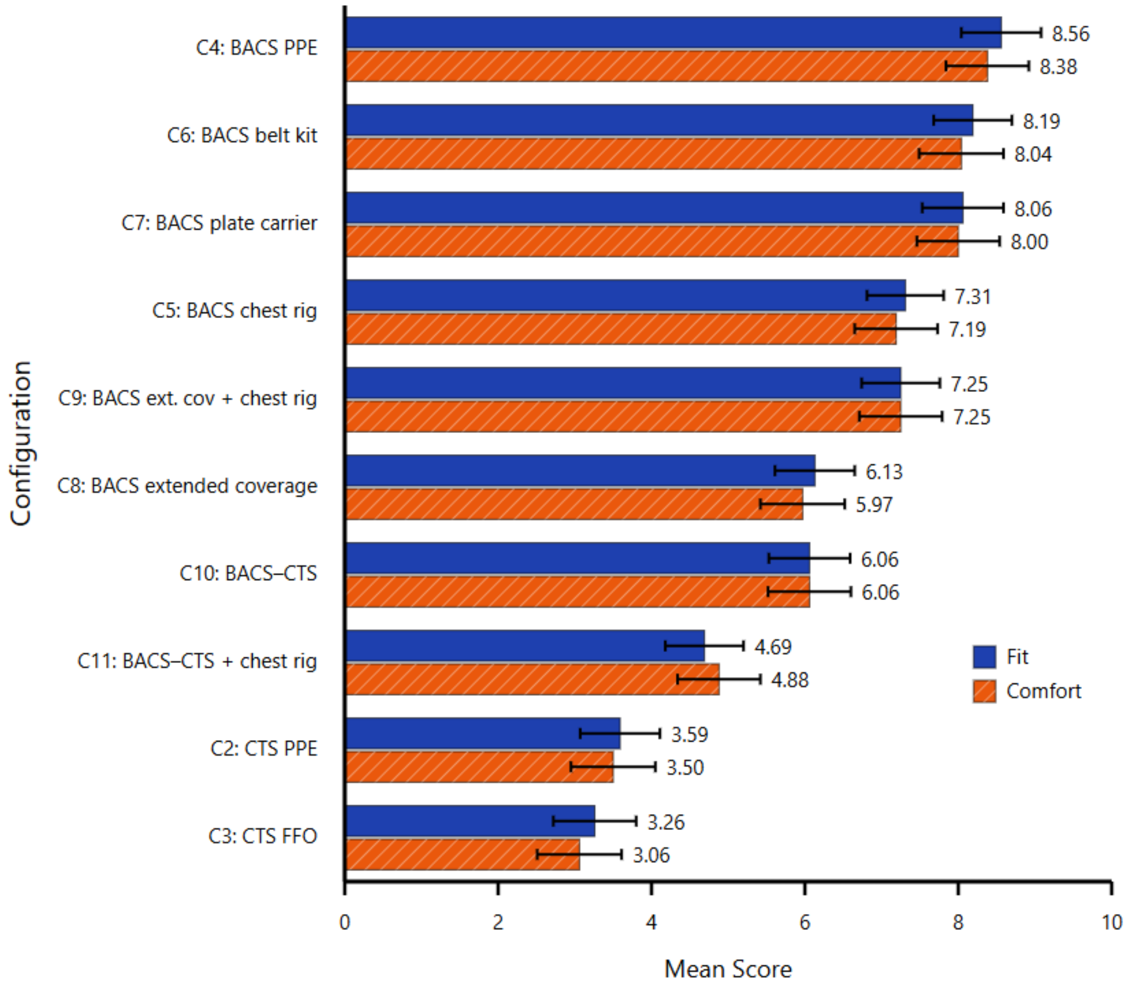


Figure 6.3

Estimated Marginal Means for Perceived Fit and Comfort Across Equipment Configurations

Note. Blue bars indicate Perceived Fit scores, and orange bars indicate Comfort scores. Data are ordered by descending Fit Score to highlight the relationship between equipment configuration and perceived performance.

6.5 Regional Drivers of Fit

Regional structural predictors were originally rated on a 10-point scale (1 = way too small, 5 = perfect, 10 = way too big). As described in Section 5.4, ratings were transformed into deviation scores (|Rating − 5|) so that larger values represented greater misfit from the ideal midpoint. Predictors of perceived fit were examined using the mixed-effects framework described previously. Prior to model interpretation, multicollinearity among fixed-effect predictors was assessed using VIF across all predictor-based models (Sections 6.5–6.7), with values ranging from 1.06 to 4.88, indicating no evidence of problematic multicollinearity.

Greater deviation from the ideal fit at several upper-body regions was associated with lower overall fit ratings (Table 6.2). Regional structural predictors were entered as fixed effects, with participant included as a random intercept to account for repeated observations. Specifically, deviation at the neck opening ($\beta = -0.43$, $p = .006$), arm opening ($\beta = -0.62$, $p < .001$), chest ($\beta = -0.63$, $p < .001$), and back plate width ($\beta = -0.73$, $p = .005$) significantly predicted reduced perceived fit. Deviation at the shoulders and waist showed marginal associations with perceived fit ($p \approx .06$–$.07$), indicating potential contributions, although statistical support was weaker. In contrast, deviation in plate length, front plate width, front plate length, and back plate length was not associated with overall perceived fit ($p > .11$). Total system weight was also unrelated to fit scores ($p = .97$). Overall, the model explained a substantial proportion of variance in perceived fit (marginal $R^2 = .67$; conditional $R^2 = .77$), indicating that regional structural alignment accounted for much of the variability in participants' fit evaluations. While regional structural deviations were associated with perceived fit, overall comfort may also be influenced by localized sensory discomfort experienced during equipment use.

Table 6.2

Mixed-Effects Model Predicting Perceived Fit from Regional Structural Deviation

Parameter	β	SE	95 % CI	*p*-values
Neck opening	-0.43	0.16	[−0.74, −0.13]	0.006
Arm opening	-0.62	0.16	[−0.93, −0.31]	<.001
Shoulder	-0.26	0.14	[−0.54, 0.02]	0.073
Chest	-0.63	0.16	[−0.94, −0.33]	<.001
Waist	-0.28	0.15	[−0.58, 0.02]	0.064
Plate length	-0.23	0.19	[−0.61, 0.15]	0.237
Front plate width	0.09	0.21	[−0.32, 0.50]	0.670
Front plate length	-0.17	0.20	[−0.56, 0.22]	0.393

Back plate width	-0.73	0.25	[−1.23, −0.23]	0.005
Back plate length	0.41	0.26	[−0.10, 0.92]	0.119
Total weight	-0.001	0.02	[−0.04, 0.04]	0.973

Note. β = regression coefficient; SE = standard error; CI = confidence interval; p-value. = significance level. Higher predictor values represent greater deviation from the ideal fit (5 = perfect).

6.6 Regional Discomfort and Postural Effects on Comfort

6.6.1 Regional Drivers of Comfort

The influence of localized discomfort on overall comfort was examined within the same modelling framework. Binary indicators representing whether discomfort was reported at each body region were entered as fixed effects, with participant included as a random intercept to account for repeated observations across configurations.

Several upper-body regions emerged as significant predictors of reduced comfort (Table 6.3). Reported discomfort at the neck ($\beta = -1.65$, $p < .001$), arms ($\beta = -1.50$, $p < .001$), and shoulders ($\beta = -1.27$, $p < .001$) was associated with significantly lower overall comfort scores. Among these predictors, discomfort at the neck showed the strongest association with reduced comfort. Discomfort reported at the back showed a marginal association with overall comfort ($p = .082$), suggesting a potential contribution but with weaker statistical support. In contrast, discomfort reported at the chest, waist, front plate, and back plate regions was not significantly associated with overall comfort scores ($p > .18$). Total system weight also did not independently predict comfort when regional discomfort variables were considered simultaneously ($p = .68$). In summary, the model results suggest that perceived comfort was primarily influenced by discomfort occurring at load bearing and mobility-related regions of the upper torso, particularly the neck, shoulders, and arms.

Table 6.3

Mixed-Effects Model Predicting Overall Comfort from Regional Discomfort Indicators

Parameter	β	SE	95 % CI	*p*-values
Neck	-1.65	0.31	[-2.27, -1.04]	<.001
Arm	-1.50	0.37	[-2.23, -0.76]	<.001
Shoulder	-1.27	0.33	[-1.93, -0.61]	<.001
Back	-0.69	0.40	[-1.48, 0.09]	.082
Chest	0.06	0.42	[-0.77, 0.90]	.882
Waist	-0.21	0.32	[-0.85, 0.42]	.507
Front plate	-0.67	0.51	[-1.68, 0.33]	.189
Back plate	-0.29	0.49	[-1.25, 0.67]	.551
Total weight	0.01	0.02	[−0.04, 0.06]	.679

Note. β = regression coefficient; SE = standard error; CI = confidence interval; p-values. = significance level. Regional predictors represent binary indicators of whether discomfort was reported at each body region.

6.6.2 Postural Effects on Static Comfort

Postural influences on static comfort were subsequently evaluated, with static comfort scores as the dependent variable and posture condition entered as a fixed effect. Participant was included as a random intercept to account for repeated measures. Using the reference posture as the baseline condition, several postures were associated with significantly reduced comfort (Table 6.4). The seated posture showed the largest reduction in comfort ($\beta = -2.11$, $p = .003$), followed by the prone position ($\beta = -1.18$, $p = .006$) and the high port posture ($\beta = -1.37$, $p = .047$). The kneeling posture showed a marginal reduction in comfort ($p = .064$), suggesting a possible effect that did not reach conventional significance. In contrast, the A-pose and low-port posture were not associated with significant changes in comfort relative to the reference condition ($p > .69$). Total system weight was again not significantly related to comfort scores within this model ($p = .87$).

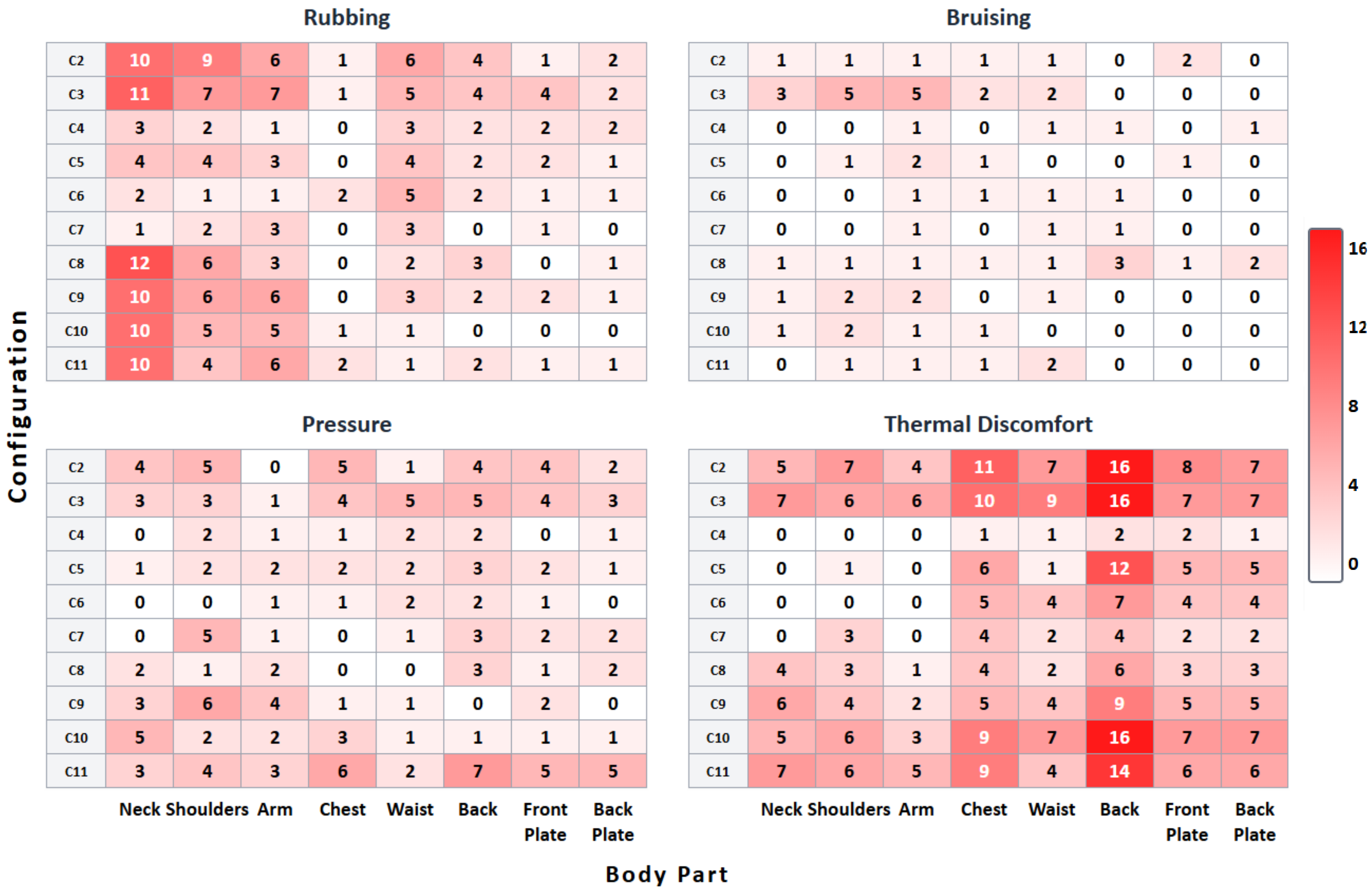
Together, these results indicate that body posture independently influences perceived comfort, with seated and prone positions producing the greatest reductions in comfort during static evaluation. Patterns of reported discomfort across body regions and equipment configurations are illustrated in Figure 6.4, which provides a global visualization of the distribution of discomfort reports.

Table 6.4

Mixed-Effects Model Predicting Static Comfort from Posture Condition

Parameter	β	SE	95 % CI	*p*-values
Lying prone	-1.18	0.42	[-2.02, -0.34]	.006
Seated	-2.11	0.70	[-3.49, -0.73]	.003
High port	-1.37	0.68	[-2.73, -0.02]	.046
Low port	-0.21	0.77	[-1.72, 1.31]	.787
Kneeling	-1.23	0.66	[-2.54, 0.07]	.064
A-pose	-0.36	0.93	[-2.19, 1.47]	.700
Total weight	-0.01	0.03	[−0.04, 0.04]	.870

Note. β = regression coefficient; SE = standard error; CI = confidence interval; p-values = significance level. Posture effects represent differences in comfort relative to the reference posture.



Rubbing

Configuration	Neck	Shoulders	Arm	Chest	Waist	Back	Front Plate	Back Plate
C2	10	9	6	1	6	4	1	2
C3	11	7	7	1	5	4	4	2
C4	3	2	1	0	3	2	2	2
C5	4	4	3	0	4	2	2	1
C6	2	1	1	2	5	2	1	1
C7	1	2	3	0	3	0	1	0
C8	12	6	3	0	2	3	0	1
C9	10	6	6	0	3	2	2	1
C10	10	5	5	1	1	0	0	0
C11	10	4	6	2	1	2	1	1

Bruising

Configuration	Neck	Shoulders	Arm	Chest	Waist	Back	Front Plate	Back Plate
C2	1	1	1	1	1	0	2	0
C3	3	5	5	2	2	0	0	0
C4	0	0	1	0	1	1	0	1
C5	0	1	2	1	0	0	1	0
C6	0	0	1	1	1	1	0	0
C7	0	0	1	0	1	1	0	0
C8	1	1	1	1	1	3	1	2
C9	1	2	2	0	1	0	0	0
C10	1	2	1	1	0	0	0	0
C11	0	1	1	1	2	0	0	0

Pressure

Configuration	Neck	Shoulders	Arm	Chest	Waist	Back	Front Plate	Back Plate
C2	4	5	0	5	1	4	4	2
C3	3	3	1	4	5	5	4	3
C4	0	2	1	1	2	2	0	1
C5	1	2	2	2	2	3	2	1
C6	0	0	1	1	2	2	1	0
C7	0	5	1	0	1	3	2	2
C8	2	1	2	0	0	3	1	2
C9	3	6	4	1	1	0	2	0
C10	5	2	2	3	1	1	1	1
C11	3	4	3	6	2	7	5	5

Thermal Discomfort

Configuration	Neck	Shoulders	Arm	Chest	Waist	Back	Front Plate	Back Plate
C2	5	7	4	11	7	16	8	7
C3	7	6	6	10	9	16	7	7
C4	0	0	0	1	1	2	2	1
C5	0	1	0	6	1	12	5	5
C6	0	0	0	5	4	7	4	4
C7	0	3	0	4	2	4	2	2
C8	4	3	1	4	2	6	3	3
C9	6	4	2	5	4	9	5	5
C10	5	6	3	9	7	16	7	7
C11	7	6	5	9	4	14	6	6

Figure 6.4

Distribution of Reported Discomfort Across Body Regions and Equipment Configurations

Note. Heatmap illustrating the relative frequency of reported discomfort across body regions for each equipment configuration. Darker colours represent a higher frequency of reported discomfort. Top left = Rubbing, Top right = Bruising, Bottom left = Pressure, Bottom right = Thermal Discomfort.

6.7 Predictors of Overall Acceptability

Predictors of overall static acceptability were examined using a LMM with Static fit deviation, static comfort, and total system weight entered as fixed effects, with participant included as a random intercept. The model explained a substantial proportion of variance in acceptability (marginal $R^2 = .76$; conditional $R^2 = .77$). As presented in Table 6.5, static comfort emerged as the strongest predictor of acceptability ($\beta = 0.82$, $p < .001$), indicating that higher comfort scores were associated with greater perceived acceptability of the equipment system. Greater deviation from ideal static fit was associated with lower acceptability ($\beta = 0.40$, $p = .003$), while total system weight showed a small negative association with acceptability ($\beta = -0.04$, $p = .027$). The relationship between static comfort and predicted acceptability is illustrated in Figure 6.5, highlighting the strong positive association between perceived comfort and overall equipment acceptability. Overall, the model results indicate that perceived comfort and fit are key determinants of equipment acceptability, with comfort emerging as the dominant contributor.

Table 6.5

Mixed-Effects Model Predicting Overall Acceptability

Parameter	β	SE	95 % CI	*p*-values
Static fit	0.40	0.13	[0.14, 0.66]	0.003
Static comfort	0.82	0.05	[0.73, 0.91]	< .001
Total weight	-0.04	0.02	[−0.08, −0.01]	0.027

Note. β = regression coefficient; SE = standard error; CI = confidence interval; p-values = significance level.

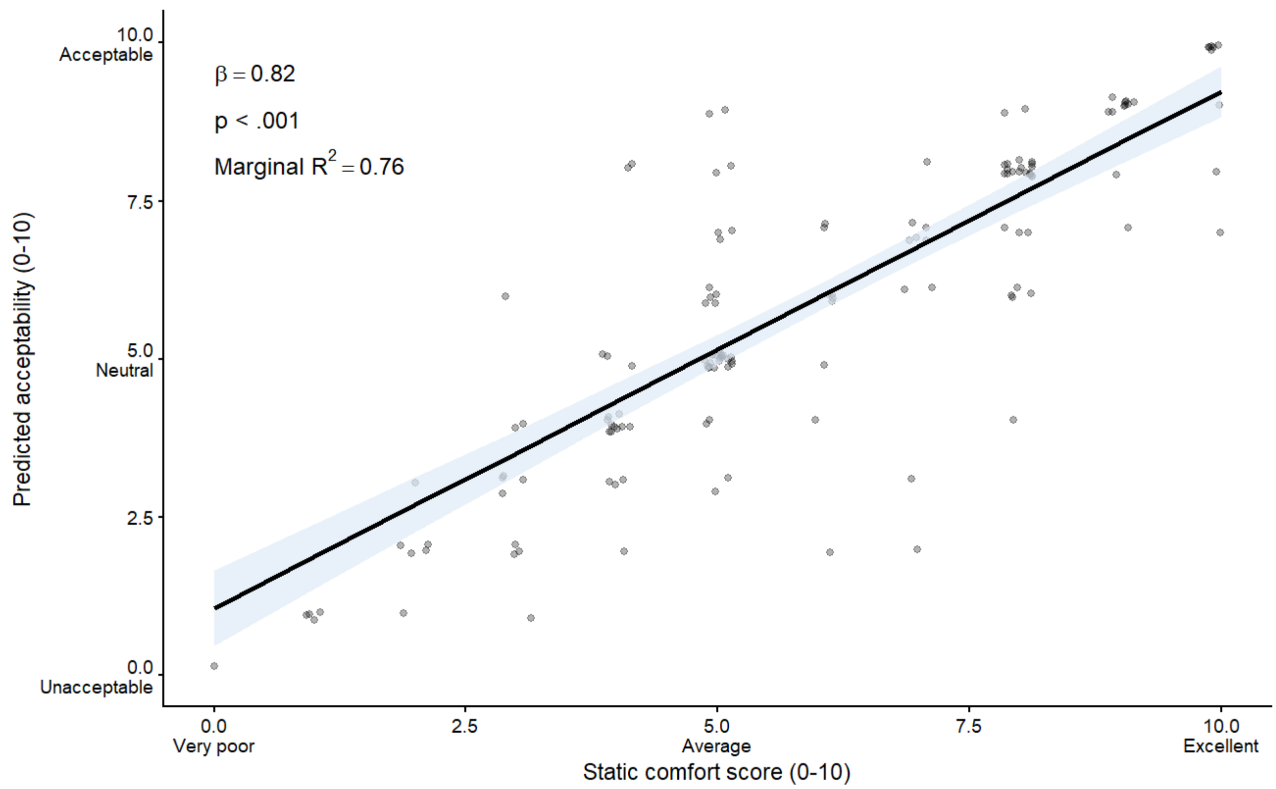


Figure 6.5

Relationship Between Comfort Scores and Overall Static Acceptability

Note. Predicted values are derived from the mixed-effects regression model, with all other predictors held at their means. Shaded areas represent 95% confidence intervals. Individual raw data points are jittered for visibility and represent specific participant observations.

Chapter 7: Discussion

This research project examined how different equipment configurations influence perceived fit, comfort, and overall acceptability, with a focus on comparing CTS and BACS systems. In addition, the study investigated how perceived fit and comfort contribute to overall equipment acceptability, identifying the key factors that shape user experience across configurations. Together, these analyses provide insight into both the relative performance of current LCSs and the perceptual drivers underlying their evaluation. Using a repeated-measures design and mixed-effects modelling approach, the findings provide a comprehensive evaluation of how LCSs are experienced by users under varying conditions.

Revisiting the primary hypotheses outlined at the outset of this study, the findings largely supported the initial expectations. The first hypothesis, predicting that BACS configurations would demonstrate significantly higher perceived fit and comfort scores compared to CTS configurations, was fully supported by the estimated marginal means (Figures 6.1 and 6.2) and subsequent mixed-effects modelling. The second and third hypotheses, which anticipated a positive association between perceived fit and comfort (Figure 6.3) and that both would significantly predict overall equipment acceptability, were also strongly supported (Table 6.5). Comfort emerged as the primary determinant of acceptability, with fit acting as a significant foundational contributor. Conversely, the final hypothesis, which posited that total system weight would negatively influence fit, comfort, and acceptability, was only partially supported. While weight demonstrated a small, statistically significant negative association with overall acceptability, it did not independently predict regional perceived fit or localized comfort when structural deviations and sensory indicators were simultaneously accounted for (Tables 6.2 and 6.3).

Overall, the results demonstrated consistent differences across configurations. Systems associated with the BACS system were generally perceived more favourably, yielding higher ratings of both fit and comfort compared to CTS configurations. In contrast, configurations incorporating CTS elements, particularly under FFO, were consistently rated lowest. Intermediate configurations, including CTS and extended-coverage systems, produced moderate ratings, suggesting that both system design and load distribution play a role in shaping user perception.

A key finding of this study is the strong alignment between perceived fit and comfort across all configurations. Conditions that received higher fit ratings (3.26-8.56) also consistently received higher comfort ratings (3.06-8.38) across configurations (Figure 6.3), indicating a strong association between perceived fit and perceived comfort in LCSs. This relationship was further supported by the mixed-effects model predicting overall acceptability, where comfort emerged as the strongest predictor, followed by fit, while total system weight showed only a comparatively small effect. Together, these findings highlight that subjective experience is driven more by how the system interacts with the body than by its absolute mass. While the present analyses focused primarily on configuration-level effects, these findings align with existing literature demonstrating that anthropometric variability is a primary driver of equipment satisfaction (Gruevski et al., 2024). For instance, Coltman et al. (2022b) indicates that specific torso and breast dimensions are significantly associated with subjective fit ratings, as equipment that is disproportionate to a wearer's stature often interferes with trunk mobility and negatively skews perceptions. Consequently, while this study provides a subjective baseline, the inclusion of anthropometric measures establishes a foundation for understanding individual variability in future work, including differences across sex. This is particularly relevant given the applied context of military load carriage, where equipment must accommodate a wide range of body dimensions.

Taken together, these findings indicate that equipment configuration plays a critical role in shaping perceived fit, comfort, and acceptability, with clear distinctions emerging between system types. More importantly, they emphasize that optimizing user experience requires consideration of both ergonomic design and individual characteristics, rather than focusing solely on load magnitude. The following sections expand on these findings by examining each primary outcome in greater detail, beginning with perceived fit, followed by comfort, and finally overall acceptability.

7.2 Perceived Fit

Fit varied significantly across equipment configurations (F (9, 140.22) = 21.24, $p < .001$), with systems associated with the BACS system consistently receiving higher ratings than those based on CTS. This distinction suggests that differences in system design may contribute to how equipment is perceived by the user, although the specific mechanisms underlying these differences cannot be determined from the present data. One likely explanation for the superior performance of BACS configurations relates to improved load distribution across key anatomical regions. Load carriage literature has consistently shown that systems which more effectively transfer weight to the pelvis, while reducing localized pressure on the shoulders and upper torso, are perceived as better fitting and less physically restrictive (Lafiandra & Harman, 2004; Wettenschwiler et al., 2015). BACS configurations, particularly those incorporating belt-based load transfer (e.g., belt kit), may facilitate a more even distribution of forces between the axial and appendicular structures, thereby reducing peak pressure points and improving overall system integration with the body.

In contrast, CTS-based configurations—especially under FFO—were consistently rated lowest (Figure 6.1). These systems may concentrate load over the shoulders and thoracic region, increasing compressive forces and restricting natural trunk and upper-limb movement, which negatively influences perceived fit (Shei et al., 2017). Previous research on military load carriage has demonstrated that excessive upper-body loading is associated with increased discomfort, altered posture, and reduced mobility, all of which contribute to poorer user perceptions of system fit (Faghy et al., 2022; Park et al., 2013).

The intermediate performance of hybrid BACS-CTS and extended-coverage configurations further supports the role of the system and structural design. While these systems may incorporate elements of the BACS platform, the addition of extended coverage or mixed components may introduce constraints that partially offset the benefits of improved load transfer. For example, increased surface contact or added stiffness from protective elements may restrict segmental movement or create localized areas of pressure, leading to moderate fit ratings. Another important consideration is the interaction between equipment design and individual anthropometrics. Although not explicitly modelled within this subsection, variability in torso length, shoulder breadth, and girth measurements likely influences how a given system interfaces with the body, with some of this variability reflecting sex-based differences in anthropometry. Systems that allow for greater adjustability or that better accommodate variation in body shape may enhance perceived fit across a broader range of users. This aligns with ergonomic principles, suggesting that equipment should be adaptable to individual morphology rather than relying on standardized sizing alone.

Overall, these findings suggest that perceived fit is not solely determined by the presence or absence of equipment, but rather by how effectively the system integrates with the user's body. Configurations that promote balanced load distribution, minimize localized pressure, and preserve natural movement appear to provide a more favourable fit experience. The following section extends this discussion by examining how these same factors influence perceived comfort.

7.3 Perceived Comfort

Comfort differed significantly across equipment configurations (Figure 6.2) and closely paralleled the pattern observed for perceived fit. Configurations associated with the BACS system consistently received the highest comfort ratings, whereas CTS-based configurations were rated lowest. While this alignment reinforces the relationship between fit and comfort, comfort reflects a broader, more cumulative user experience that extends beyond initial system interaction, consistent with prior work describing comfort as a multidimensional construct influenced by prolonged body-equipment interaction (Wettenschwiler et al., 2015).

Unlike fit, which primarily describes how well a system conforms to the body at a given moment, comfort captures how that interaction is sustained over time. It reflects the accumulation of physical sensations such as pressure, restriction, and fatigue, as well as the user's overall tolerance to the system during prolonged wear. In this context, the higher comfort ratings observed in BACS configurations suggest not only improved initial integration with the body but also a reduced rate of discomfort development during continued use. Notably, participants wore each configuration for approximately 1.5 to 2 hours, providing sufficient exposure to experience potential pressure, restriction, and thermal effects prior to evaluation. One possible explanation for these differences lies in how systems influence fatigue and perceived exertion. Load carriage research has shown that discomfort increases progressively with duration, particularly when systems impose uneven loading or restrict natural movement patterns (Knapik et al., 2004; Majumdar et al., 2010). Configurations that better stabilize the load and allow for more natural movement may reduce compensatory muscular activity, delaying the onset of fatigue and improving overall comfort. This interpretation is supported by the localized sensory discomfort data. As illustrated by the discomfort distribution (Figure 6.4), configurations relying heavily on CTS elements (e.g., C2, C3) exhibited higher frequencies of reported pressure points, rubbing, and bruising, particularly localized around the shoulders, neck, and back. Conversely, the core BACS configurations (e.g., C4, C6, C7) demonstrated a marked reduction in localized pressure reports in these load-bearing regions. This may help explain why BACS configurations, which demonstrated superior fit, also maintained higher comfort ratings.

In contrast, lower comfort ratings observed in CTS-based and extended-coverage configurations may reflect a faster accumulation of discomfort over time (Figure 6.2). Even if the initial fit is acceptable, systems that introduce movement restriction, localized pressure, or additional bulk may lead to increased muscular effort and thermal burden during prolonged use. The intermediate performance of hybrid BACS-CTS configurations further supports this interpretation. These systems may partially improve load distribution while still introducing elements that contribute to fatigue or restriction, resulting in moderate comfort ratings. This reinforces the idea that comfort is not simply determined by individual design components, but by the integrated interaction between load distribution, movement, and equipment design, as highlighted in previous military research (Coltman et al., 2020, 2022a).

Importantly, the strong association ($\beta = 0.43$, $p < .001$) observed between fit and comfort supports the conceptual framework that initial system integration plays a key role in shaping longer-term user experience. Systems that fit well are likely to reduce early sources of discomfort, which may in turn delay the accumulation of fatigue and improve overall comfort perception. This relationship is further reflected in the acceptability model, where comfort emerged as the strongest predictor, demonstrating that user acceptance of PPE is primarily driven by perceived comfort rather than isolated physical characteristics (Coltman et al., 2022a; Gruevski et al., 2024). Configurations that minimize the rate at which discomfort develops—by supporting natural movement, reducing fatigue, and limiting thermal and mechanical strain—are more likely to provide a sustained sense of comfort.

7.4 Overall Acceptability

The analysis of overall static acceptability provides a more integrated perspective on how equipment systems are evaluated, moving beyond individual outcomes to identify which factors most strongly influence user judgment. The mixed-effects model demonstrated that perceived comfort was the primary determinant of acceptability, with perceived fit also contributing significantly, while total system weight played only a minor role (Table 6.5).

This hierarchy of predictors offers an important shift in how LCSs are understood. Although total system weight is often treated as a central design constraint, the present findings indicate that users prioritize how the system feels over how much it weighs, aligning with previous findings that subjective comfort and usability are stronger determinants of PPE acceptance than absolute load magnitude (Gruevski et al., 2024; Wettenschwiler et al., 2015). In this context, comfort can be interpreted as a cumulative outcome reflecting multiple interacting factors, including pressure distribution, movement restriction, and overall system integration with the body.

Perceived fit, while secondary to comfort in the final model, appears to function as a structural foundation for comfort rather than an independent driver, indicating that proper body-equipment alignment reduced pressure concentrations and improves perceived comfort (Choi & Zehner, 2009). A system that fits well is more likely to stabilize the load, reduce unwanted movement, and minimize localized pressure, thereby indirectly enhancing comfort and, in turn, acceptability. This layered relationship helps explain why comfort emerged as the dominant predictor in the model, despite the conceptual importance of fit. An additional insight from the model is the relatively high proportion of explained variance (marginal $R^2 = .76$; conditional $R^2 = .77$), indicating that acceptability can be largely accounted for by a small set of user-centred variables. In practical terms, this implies that improving comfort and fit is likely to yield reliable gains in acceptability across a range of users, even in the presence of individual variability.

From an applied perspective, these findings have direct implications for system design and evaluation. Efforts to improve acceptability should prioritize interventions that enhance comfort—such as optimizing load transfer mechanisms, reducing pressure concentrations, and preserving mobility, rather than focusing exclusively on reducing total system weight. This is particularly relevant in operational settings where weight reductions may be constrained by protective requirements, but improvements in ergonomic design remain feasible.

Overall, the results position perceived comfort as the central driver of acceptability, supported by fit as an underlying structural factor. Together, these findings highlight the importance of user-centred design approaches that emphasize the interaction between the equipment and the body.

Chapter 8: Limitations

Several limitations should be considered when interpreting the findings of this study. The sample size represents an important consideration. Although sufficient to detect statistically significant effects within a repeated-measures framework, the relatively small sample may limit the generalizability of the findings and the ability to capture the full range of variability present in a broader population. A larger sample would likely provide a more comprehensive representation of user experiences and better reflect the diversity of responses observed in operational contexts.

Related to this, variability in participant responses was evident, particularly with respect to differences in prior experience with LCSs. Participants with greater years of service or familiarity with similar equipment tended to provide more detailed and critical evaluations, whereas less experienced participants often offered less differentiated responses. This suggests that perceptual evaluations of fit and comfort may be influenced by individual experience, with more experienced users potentially applying stricter or more nuanced criteria when assessing equipment performance. Additionally, participants may have been predisposed to evaluate the newer BACS system more favourably, given its status as a recently introduced and modernized system. This expectation bias could have influenced subjective ratings, contributing to more positive evaluations independent of actual performance differences.

An additional limitation relates to the reliance on subjective self-report measures. Although visual analogue scales and binary indicators are widely used in ergonomic research, they are inherently influenced by individual interpretation and response tendencies. Differences in how participants interpret scale anchors (e.g., “perfect fit” or “completely acceptable”) may introduce variability unrelated to the underlying physical interaction. Pertaining to, despite counterbalancing, learning and comparison effects cannot be fully excluded. Increased familiarity with the protocol and implicit comparisons across configurations may have influenced participant scores.

Another limitation concerns the study design's emphasis on static fit. Although participants wore each configuration for a sufficient duration to provide survey responses, the primary focus was on assessing fit, comfort, and acceptability under controlled, static conditions. This approach was intentionally adopted to establish a consistent baseline of subjective fit, which could be interpreted alongside objective measures of static body–equipment interaction. However, it does not capture how perceptions of fit and comfort may evolve during dynamic tasks or prolonged use, where factors such as movement, fatigue, and task-specific demands are likely to influence user experience. Accordingly, the findings should be interpreted as reflecting baseline perceptions rather than the full range of responses observed in operational contexts.

Methodological considerations related to data collection should also be acknowledged. The use of 4D body scanning required participants to wear standardized, form-fitting attire to ensure accurate surface capture. The selected attire, determined through pilot testing, optimized visibility of body contours but does not fully reflect how equipment interacts with typical operational clothing, which may limit ecological validity.

Finally, the modelling approach reflects a defined analytical scope, focusing primarily on subjective evaluations of fit and comfort, with total system weight included as a covariate. While these variables explained a substantial proportion of variance in overall acceptability, they do not fully capture the complexity of the body–equipment interaction. In particular, individual anthropometric characteristics, which may influence how load is distributed and perceived across the body, were not incorporated into the statistical models. As a result, participant-specific variability in system interaction may not be fully accounted for. Taken together, these limitations provide important context for interpreting the findings of the present study and highlight considerations related to participant characteristics, experimental design, measurement approaches, and analytical scope, while also identifying key directions for future research.

Chapter 9: Future Work

Building on the findings of the present study, a key direction for future research lies in the development of an integrated methodology for assessing static fit that combines both subjective and objective metrics. The results of this thesis demonstrated that perceived fit and comfort are central to user evaluation of LCSs, with subjective perceptions strongly influencing overall acceptability. At the same time, the study incorporated objective approaches, such as 4D body scanning, to characterize the physical interaction between the body and the equipment. However, these two domains were not formally integrated within a unified analytical framework.

The development of a combined methodology would allow for a more comprehensive characterization of static fit by linking user perception with measurable physical parameters. Subjective assessments capture the lived experience of the user, including factors such as pressure, restriction, and overall system integration, which are not always directly observable through objective measures. Conversely, objective techniques—such as 3D/4D body scanning—provide quantifiable information on body shape, equipment interface. Existing literature has highlighted the need to move beyond purely subjective evaluations of fit toward more objective and quantifiable approaches that can systematically characterize body–equipment interaction (Brisbine et al., 2022; Stirling et al., 2020).

In the context of the present study, such a methodology could involve linking subjective fit ratings to specific objective indicators derived from body scanning data, such as regional clearances, compression zones, or alignment between anatomical landmarks and equipment components. Establishing these relationships would allow for the identification of key physical predictors of perceived fit and may support the development of predictive models capable of estimating user experience based on measurable characteristics. Future work should also consider sex-based analyses, as differences in anthropometry and body composition may influence both body–equipment interaction and perceived outcomes. Incorporating sex as a factor within such models could help identify whether distinct predictors of fit and comfort exist across groups, thereby supporting more inclusive and representative evaluation frameworks. Exploratory analyses conducted in the present study (Appendix F) suggest potential differences in how specific anatomical regions influence perceived fit and comfort. For example, the effect of "back plate length" on perceived fit appeared distinct between male and female participants (Figure F.1), which may reflect sex-specific anthropometric variations in torso length and anatomical landmarks. While the present sample size limits the ability to draw robust statistical conclusions regarding these sex-based interactions, these exploratory findings support the rationale for future, adequately powered research to systematically examine how sex influences the body–equipment interface.

Building on this approach, the integration of subjective and objective measures presents an opportunity to move toward predictive applications. With the development of robust models, it may be possible to use a single body scan to estimate how a given LCSs will fit an individual and how it is likely to be perceived in terms of comfort and acceptability. Such an approach would represent a significant advancement in the evaluation of LCSs, enabling more efficient assessment processes and supporting the design of equipment that is better tailored to individual users. The integrated framework has the potential to inform the development of user-centred and potentially personalized load carriage solutions. By identifying how specific physical characteristics relate to perceived outcomes, future work can contribute to optimizing system design based on both structural compatibility and user experience. Overall, advancing toward a unified methodology that combines subjective and objective measures of static fit represents a critical step in improving the evaluation and design of LCSs.

Chapter 10: Conclusion

This thesis provides evidence that the evaluation of LCSs extends beyond traditional considerations of system weight and instead depends on how the equipment is experienced by the user. By establishing a subjective baseline of static fit, this work demonstrates that perceived comfort is the central factor shaping overall equipment acceptability, with fit acting as a structural foundation that supports this experience. The comparison between CTS and BACS configurations highlights the importance of system design in facilitating effective body–equipment interaction. Rather than isolated features, it is the integration, stability, and distribution of the system that ultimately determine how it is perceived during use. These findings reinforce the need to prioritize user-centred design approaches that account for both physical alignment and sustained comfort.

More broadly, this research emphasizes user perception as a meaningful and necessary component of LCSs assessment. Establishing a subjective baseline not only supports a more comprehensive understanding of fit but also provides a foundation for future work aimed at integrating perceptual and objective measures. Ultimately, improving LCSs requires moving beyond how systems are built to how they are experienced. By focusing on the interaction between the soldier and the equipment, this work supports the development of systems that are not only protective but also functional, acceptable, and sustainable in operational use.

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Appendix A: Informed Consent

Consent Form

Protocol No.: 2025-048
Title: Impact of personal armour and loads on soldier musculoskeletal health, mobility, and effectiveness
Principal DRDC Investigator: Linda Bossi, MSc (DRDC Toronto Research Centre (TRC)
Principal University of Ottawa Investigator: Ryan Graham, Ph.D. (University of Ottawa)
Co-Investigators: Matthew Mavor, Ph.D. (University of Ottawa); Thomas Karakolis, Ph.D. (DRDC TRC);
Research Assistants: Alexandre Mir-Orefice, Domenica Paulette Solano Ocampo, Jessica Wenghofer (University of Ottawa), Cerys McGuinness, Adrienne Sy, Suren Vahidi (TRC), Donny LeBlanc, Iain Kinkaid, Eric Kramkowski (QTAC Inc)
Project code: CVPE_Army_015 CEF3 - Clothing, Equipment Form, Fit and Function for a Diverse Force.

I,____(full name) of _________________

-- (full mailing address) hereby volunteer to be a participant in the study entitled, *Impact of personal armour and loads on soldier musculoskeletal health, mobility, and effectiveness, P*rotocol # 2025-048). I have read the information sheet and have had the opportunity to ask questions of the Investigator(s) or Research Assistants. All my questions concerning this study have been answered to my satisfaction. However, I may obtain additional information about the research project and have any study questions answered by contacting the Principal Investigator, Ms. Linda Bossi, DRDC Toronto Research Centre, telephone: (647) 924-8489, Email: linda.bossi@forces.gc.ca.

I understand that the objective of this study is to evaluate the fit, range of motion, clinical and tactical movement behaviours of soldiers wearing in-service and new armour and load carriage designs, under fighting and marching loads, and to better understand how body-borne load, equipment design, and personal characteristics affect a soldier's musculoskeletal health, mobility, as well as implications for survivability. By volunteering for this study, I will further knowledge about the coverage implications of armour design on mobility and contribute to the development of digital human modelling capabilities that may benefit myself and my colleagues in the Canadian Armed Forces.

I understand that the main exclusion criteria for the study include self-reported and currently active musculoskeletal injury accompanied by pain, or mobility impairment at the time of data collection. I acknowledge that I have completed and passed the FORCE Combat fitness test in the past year and that I am qualified to at least Basic Military Qualifications Land (DP1) course or equivalent.

I understand that my participation in this study will take up to 6 testing days, which need not be consecutive. Each test day is maximum 8 hours each (including 45-60 min lunch and hourly

15 minute rest breaks), for a total of up to 48 hrs of time commitment. I understand that the study will involve:

a. During the initial session:

    1) Participating in a briefing on the purpose, methods, risks, and safety measures being employed in the study;
    2) Having an opportunity to ask questions about the study, and have my questions answered by an experimenter (Investigator or Research Assistant);
    3) Completing a participant demographics and experience questionnaire;
    4) Being briefed about, having had a demonstration of, and having an opportunity to try myself, in a clothing only condition, the full range of tests and tasks that I will be expected to perform in the study;
    5) Being issued and wearing close-fitting athletic clothing or long underwear and being scanned (in a whole body 3D photo-based scanning lab), wearing that alone while briefly assuming standardize static posture(s); this will enable determination of my unencumbered body size and shape which will be used to relate me to the rest of the CAF population, to determine which manufacturer-recommended size of each equipment item I should initially try, and to serve as the unencumbered clothing-only baseline for eventual comparison with all other loaded/encumbered conditions; and
    6) Completing the full range of tests in a clothing only baseline condition, comprising close-fitting scanner-compatible athletic wear, boots, plus any non-torso protection I choose to wear during all equipped testing to follow (e.g., boots, knee and elbow pads, gloves, eye protection, etc.). Some tasks will require me to also wear a helmet and carry a surrogate assault rifle with sling.

b. During each of the remaining five (5) subsequent testing days:

    1) Completing all testing at the following three (3) test stands:
        i. MOVE 4D Scanner. In Armour Only and Full Fighting Order conditions of in-service and DICE gear, I will be scanned with a dynamic, 3D, whole-body, high-resolution camera/video system, while assuming static postures, performing range of motion and dynamic posture transition movements in each condition. All measures are calculated from scans.
        ii. Tactical Mobility Test Stand, I will be asked to don a helmet and carry a surrogate C7A2 weapon on a single point sling along with the armour/load carriage and load condition, and then be asked to perform several firing posture transitions, basic tactical movements (walk, run) and 3 combat tasks (react to enemy fire while advancing to contact, pepper potting, and withdraw (Aussie peel back)
        iii. 30 minutes of marching on an instrumented, split track Treadmill (at 0% grade, comfortable marching pace) in each of 5 Marching Order conditions representing in-service and DICE with 25 kg loaded packs worn over FFO (total load of 45 kg). 15 minutes of marching with armour plates worn and 15 minutes of marching with armour plates removed (and stowed in upper anterior pack).

c. Being assigned one of the 10 remaining Armour (PPE Only) or FFO conditions (to complete each of Test Stands I and II) and one of the 5 remaining marching order conditions (to complete Test Stand III) until all testing has been completed.
d. Being issued daily my assigned conditions/equipment only after it has been sanitized using a professional sports team equipment sanitizer (which employs ozone and/or UV light to kill germs);
e. Being issued and wearing daily, freshly laundered close-fitting athletic clothing in lieu of the combat uniform for most tests/ This is for compatibility with 3D whole-body camera-based scanning and motion capture and analysis systems used in the study (combat clothing is also baggy thus gives a false impression of space claim because the bulk is easily compressible).
f. Being instrumented by a research assistant (my choice of male or female) with skin pressure measurement sensors (left and right shoulders, left and right hips) prior to testing marching order conditions on the Test Stand III treadmill;
g. Completing questionnaires throughout my experience as a participant:
    1) At Test Stand I, completing a fit questionnaire
    2) at Test Stand III, being asked, every 5 minutes, for ratings of discomfort, symptoms of nerve or blood vessel constriction or occlusion, or system acceptability. I will be given an opportunity to readjust the pack to mitigate discomfort and continue marching until 15 minutes of marching and 3 rating sessions are completed. I will repeat this test for each equipment condition in 2 plate conditions (with plates worn in position for 15 minutes, and with plates stowed in the pack for 15 minutes)
    3) After completing Test Stand III in one Marching Order condition, for eacfh plate condition, I will be completing a questionnaire on the acceptability of the pack with and without armour plates.
h. returning my issued clothing and kit and having a midday 45 minute to 1 hour lunch break.
i. After lunch, being issued my next-assigned condition, confirming fit of and repeating Test Stands I and II in another test condition. Note that I will not be allowed to complete more than one treadmill march at Test Stand III on any test day;
j. signing pay and stress allowance sheets and confirming my next session date and time.
k. repeating steps c through j on subsequent test days until I have completed all 11 PPE or FFO conditions at Test Stands I and II, and all 6 Marching Order conditions at Test Stand III.
l. having high fidelity 3D whole-body photograph and video-based scans taken of me. I understand that my consent is required and must be documented by the DRDC Photo/Image Release Form (attached) as to whether these photos/videos can be used for publication or presentations or viewed beyond the study team identified by the protocol. I understand that I MAY NOT participate in the study if I decline to be photographed/videotaped as most study data, and virtually all objective data relies upon being scanned.

I am aware of the intention for secondary use of my data for machine learning analyses and digital human modelling capability development (to create morphable models of alternative body size/shape, kit design, movement patterns, etc.).

I have been told that the potential risks associated with this research protocol include, musculoskeletal injury, fatigue, and thermal strain. I understand that these moderate risks are acceptably mitigated by good physical fitness, the risk mitigation strategies listed in the participant information sheet, as well as a range of procedures being undertaken by investigators (i.e., adequate breaks, encouraged hydration, ambient temperature control, limiting loaded marching task to 30 minutes per day, to name a few). Also, I acknowledge that my participation in this study, or indeed any research, may involve risks that are currently unforeseen by Defence Research and Development Canada (DRDC).

In the highly unlikely event that I become incapacitated during my participation, I understand that emergency medical treatment will be instituted, even though I am unable to give my consent at that time. I will go with the Investigator(s) to seek immediate medical attention if either the Investigator(s) or I consider that it is required.

I understand that the information and data collected from me will be kept confidential. My name will not be included anywhere in the data files, other than this consent form or on pay and stress allowance sheets. I will be assigned a unique identification number (alpha-numeric code) linked to all data collected. All electronic data will be stored on the investigators' work on computers or encrypted server, accessible only to named investigators and research assistants; these are password protected. Hard copy data will be stored as Protected B (locked in secure padlocked cabinets accessible only to investigators. I understand that my data may be used in multiple subsequent analyses or modelling efforts in an anonymous, aggregate form.

I understand that my experimental data will be protected under the Government Security Policy (GSP) at the appropriate designation and not revealed to anyone other than the named Investigator(s) without my consent, except as data unidentified as to source.

I understand that my name will not be identified or attached in any manner to any publication arising from this study. Moreover, I understand that the experimental data may be reviewed by an internal or external audit committee with the understanding that any summary information resulting from such a review will not identify me personally.

I understand that, as a Government Institution, DRDC is committed to protecting my personal information. However, under the Access to Information Act, copies of research reports and research data (including the database pertaining to this project) held in Federal government files, may be disclosed. I understand that prior to releasing the requested information, the Directorate of Access to Information and Privacy (DAIP) screens the data in accordance with the Privacy Act in order to ensure that individual identities (including indirect identification due to the collection of unique identifiers such as rank, occupation, and deployment information of military personnel) are not disclosed.

I understand that any photos collected as part of this study will remain strictly confidential, and stored properly in a locked cabinet as protected B. If I consent to my photos being used for DND or academic presentations and publications, I understand that the photo will be edited to obscure identifiable features such as the face and visible tattoos.

I understand that participating in this study is completely voluntary, that I am free to refuse to participate, and that I may withdraw my consent at any time without prejudice or hard feelings. Should I withdraw my consent, my participation in this research project will cease immediately, unless the Investigator(s) determine that such action would be dangerous or impossible (in which case my participation will cease as soon as it is safe to do so). I also understand that the Investigator(s), or their designate, may terminate my participation at any time, regardless of my wishes.

I understand that I am entitled to stress remuneration in the amount of $75.00 per day, for a maximum of 6 days or $450 if I complete the study as described in the protocol. I understand that even if I take longer than 6 days to complete data collection, I will still only be eligible for stress renumeration of a maximum of $450. I understand also that stress remuneration is income and is subject to income tax, and that as a CAF member, my Service Number (SN) is required for remuneration.

I understand that I am considered to be on duty for disciplinary, administrative and Pension Act purposes during my participation in this study and I understand that in the unlikely event that my participation in this study results in a medical condition rendering me unfit for service, I may be released from the CAF and my military benefits apply. This duty status has no effect on my right to withdraw from the study at any time I wish, and I understand that no action will be taken against me for exercising this right. I understand that my individual performance in any of the tasks in this protocol will not be used as a professional military evaluation related to my career.

I understand that by signing this consent form I have not waived any legal rights I may have as a result of any harm to me occasioned by my participation in this research project beyond the risks I have assumed. Also, I understand that I will be given a copy of this consent form so that I may contact any of the individuals mentioned below at some time in the future should that be required

---

Release Granting Permission to use digital photo images from an Approved Human Research Study in Department of National Defence Publications and Presentations and for Analysis

Initial only one of the following:

_____ I hereby grant permission and consent to the use of digital photo images of me from the above study for analysis purposes, in DND publications and presentations, and academic publications and presentations, only if facial and distinguishing features are obscured so that I cannot be recognized in the image.

_____ I hereby grant permission and consent to the use of digital photo images of me from the above study for analysis purposes ONLY

_____ I hereby do NOT grant permission and consent to the use of digital photo images of me from the above study for analysis purposes, in DND publications and presentations, or academic publications and presentations.

Volunteer's Name: ____

Signature:_________________________ Date: ___________________________

Name of Witness to Signature: ____

Signature:_______________________________ Date: _________________________

Principal Investigator:

Signature:_______________________________ Date: _________________________

Unit Operations Office, CO or other designate (if participant is not part of a CFTPO task):

Signature:_______________________________ Date: ________________________

FOR PARTICIPANT ENQUIRY IF REQUIRED:

Should I have any questions or concerns regarding this project before, during or after participation, I understand that I am encouraged to contact the appropriate DRDC research centre cited below. This contact can be made by surface mail at this address or by phone or email to any of the DRDC numbers and addresses of individuals listed below:

Defence R&D Canada - Toronto
1133 Sheppard Avenue West
Toronto, Ontario, M3K 2C9
Principal Investigator or Principal DRDC Investigator:
Linda Bossi, telephone: (647) 924-8489, Email: linda.bossi@forces.gc.ca

For research ethics issues:
Chair, DRDC Human Research Ethics Committee (HREC)
HREC-CEESH-Toronto@drdc.rddc.gc.ca; or by phone: (416) 635-2098.

Appendix B: Configuration Description

Table B.1 *Summary of Experimental Configurations and Equipment Loading*

Label	Configuration Title	Configuration Description	Cumulative Weight (kg) Size M
C1	Slick	Baseline, clothing only, comprising close-fitting scanner-compatible clothing, boots (helmet and weapon surrogate)	4 kg
C2	CTS PPE	Clothe the Soldier (CTS) in-service Fragmentation Protective Vest (FPV) with bullet-resistant plates (BRPs) (front and back, no shoulder caps)	10 kg
C3	CTS FFO	CTS PPE + fighting load carried in Tactical Vest (TV)	18 kg
C4	BACS PPE_{base}	$BACS_{base}$ base armour only (front, back, sides soft armour, and plate in plate carrier, no combat load items or pouches on plate carrier)	6kg
C5	$BACS_{base}$ FFO1	BACS PPE_{base}(#C4) + fighting load configuration 1 (chest rig)	15.4 kg
C6	$BACS_{base}$ FFO2	BACS PPE_{base} (#C4) + fighting load configuration 2 (belt kit)	15.2 kg
C7	$BACS_{base}$ FFO3	BACS PPE_{base} (#C4) + fighting load configuration 3 (plate carrier)	14 kg
C8	BACS $PPE_{Extended}$	BACS $PPE_{Extended}$ coverage ($BACS_{base}$ plus BACS neck/nape, throat, shoulder soft armour)	6.5 kg
C9	$BACS_{Extended}$ FFO1	BACS $PPE_{Extended}$ (#C8) + FFO1	20 kg
C10	BACS PPE_{Full}	CTS soft armour in (#C2) + BACS Hard Armour in DICE FFO1, empty/no load	8 kg
C11	$BACS_{Full}$ FFO1	C10 CTS Soft Armour + BACS Hard Armour + BACS FFO1	20 kg

Appendix C: Static Poses from Move4D

Figure C.1 *A-pose scan by Move4D*

Figure C.2 *Seated pose scan by Move4D*

Figure C.3. *Low port pose scan by Move4D*

Figure C.4. *High port pose scan by Move4D*

Figure C.5 *Kneeling with an aiming pose scan by Move4D*

Figure C.6 *Lying prone with an aiming pose scan by Move4D*

Appendix D: Fit and Comfort Survey

Université d'Ottawa | University of Ottawa

Load Carriage System Survey

Current Condition (section to be completed by researcher/research team):

1. What is the current kit condition?

- ◯ Clothe the Soldier (CTS)
- ◯ Dismounted Infantry Capability Enhancement (DICE)
- ◯ Sniper System (SS)

2. What is the current configuration?

- ◯ C2: CTS PPE only
- ◯ C3: CTS PPE + FFO
- ◯ C4: DICE PPE Base only (front, back, side)
- ◯ C5: DICE PPE + FFO1
- ◯ C6: DICE PPE + FFO2
- ◯ C7: DICE PPE + FFO3
- ◯ C8: DICE PPE + extended DICE Armour (neck, throat, shoulder) PPE only
- ◯ C9: DICE PPE + extended DICE Armour (neck, throat, shoulder) PPE only + FFO1
- ◯ C10: DICE + Mod Scale an Armour PPE Only (Full torso coverage)
- ◯ C11: DICE + Mod Scale an Armour PPE Only (Full torso coverage) + FFO1
- ◯ Other (please specify)

3. Participant ID:

Please answer the following questions based on the equipment worn in the current condition (unless otherwise stated) as stated above (i.e., current equipment worn by participant).

The following fit questionnaire was adapted from (Gruevski et al., 2024)

Load Carriage System Survey

Plate Carrier - General Questions

Please answer the following questions considering only the fighting load carriage and **your experience** wearing a fighting load carriage system

* 4. Which of the following variant(s) of the fighting load carriage system you used in the last 5-years (select all that apply)

- ☐ Current in-service kit (clothe the soldier (CTS))
- ☐ Previously in service kit (i.e., 1982 Pattern)
- ☐ Non-issued (COTS)

* 5. How often have you worn the current in-service CTS tactical vest on average over the past 5-years (excluding 2020) for the following circumstances (put a checkmark for all that apply)

	Daily	Weekly	Monthly	Yearly	N/A (have not used it)
Training	☐	☐	☐	☐	☐
Deployment	☐	☐	☐	☐	☐
Other (please specify below)	☐	☐	☐	☐	☐

Specify:

* 6. What size of the following plate carrier do you typically use?

S	M	L	XL	Don't know/unsure
○	○	○	○	○

* 7. Have you ever experienced any fit related issues or discomfort?

- ○ Yes
- ○ No
- ○ Don't know/unsure

If you answered **yes** to the above question, please specify

Load Carriage System Survey

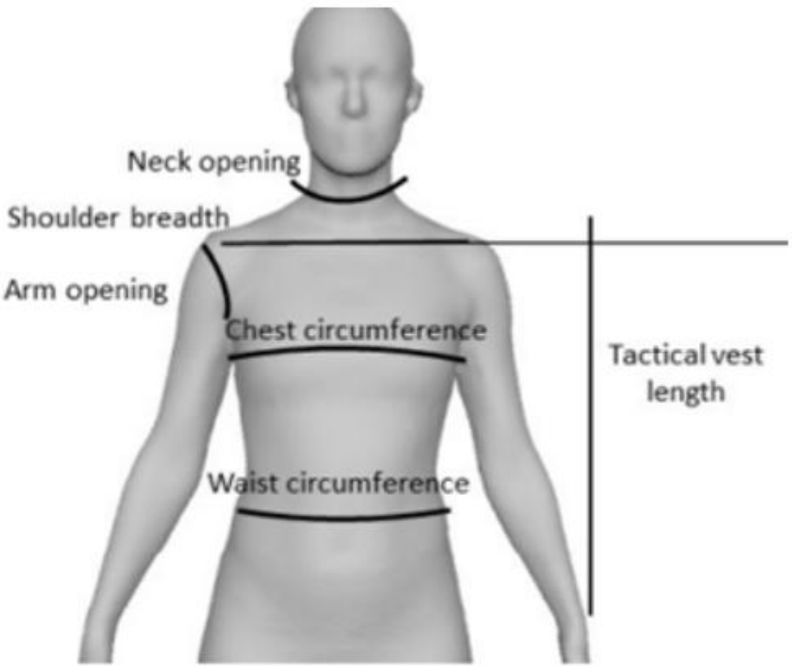
Please answer all the following questions based on the equipment worn in the current condition/configuration.

Plate Carrier Fit Related Questions

Fit: The degree to which the clothing or PPE conforms properly to the shape of the body

Please answer the following questions based on the military kit/tactical vest/ fighting load carriage system that you are currently equipped with, while standing in a stationary position.

Use the following diagram to assist in answering all subsequent questions.



Rate each section in terms of plate carrier fit using the current condition (currently worn by participant – as indicated above). Please use the 10-point visual analogue scale and use the slide to rate each region that best indicates fit.

* 8. Neck opening

Way too small   Perfect   Way too big

* 9. Arm opening

Way too small   Perfect   Way too big

* 10. Shoulder breadth

Way too small Perfect Way too big

* 11. Chest circumference

Way too small Perfect Way too big

* 12. Waist circumference

Way too small Perfect Way too big

* 13. Plate carrier length

Way too small Perfect Way too big

* 14. Front plate width

Way too small Perfect Way too big

* 15. Front plate length

Way too small Perfect Way too big

* 16. Back plate width

Way too small Perfect Way too big

* 17. Back plate length

Way too small Perfect Way too big

* 18. How do you tipically **prefer the fit** of the plate carrier?

Tight — Neutral — Loose

* 19. Please rate the **overall fit** of the plate carrier for the curret condition, using the visual analogue scale.

Completely unacceptable — Borderline — Completely acceptable

Plate Carrier Comfort Related Questions:

Comfort: A state of ease and freedom from any physical constraint, pain, irritation, and thermal discomfort

Please answer the following questions based on the military kit/tactical vest/ fighting load carriage system that you are currently equipped with, while standing in a stationary position.

* 20. Rate each section in terms of tactical vest comfort based on the current condition of equipment worn by the participant. Please select all that apply.

	Comfortable, no issues	Rubbing, chaffing, abrasion	Bruising, discolouration, and/or loss of circulation	Pressure points, hot spots	Thermal discomfort
Shoulders	☐	☐	☐	☐	☐
Arm opening	☐	☐	☐	☐	☐
Chest	☐	☐	☐	☐	☐
Waist (abdomen)	☐	☐	☐	☐	☐
Neck (collar)	☐	☐	☐	☐	☐
Back	☐	☐	☐	☐	☐
Front plate	☐	☐	☐	☐	☐
Back plate	☐	☐	☐	☐	☐

Other (please specify)

* 21. Please rate the **overall comfort** of the plate carrier for the current condition.

Completely unacceptable — Borderline — Completely Acceptable

Static Poses:

Participants will perform a series of **static poses** for each of the equipped conditions. Using the visual analogue scale, please indicate the overall fit and the comfort of the various components of the 'kit' worn in the current condition.

* 22. **Fit** relating to the **plates in the plate carrier or fragmentation vest**

Way too small	Perfect	Way too big

* 23. **Comfort** relating to the **plates in the plate carrier or fragmentation vest**

Completely unacceptable	Borderline	Completely acceptable

* 24. Please rate the **overall comfort and fit** for the **entire equipment system** worn during this condition

Completely unacceptable	Borderline	Completely acceptable

* 25. Did any of the static poses performed cause increased discomfort, please select all that apply.

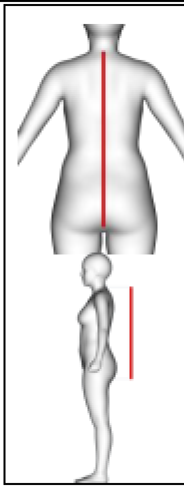
- [ ] A-pose
- [ ] Lying Prone
- [ ] Kneeling
- [ ] Seated Position
- [ ] High Port
- [ ] Low Port
- [ ] N/A

Appendix E: Anthropometric Measurements

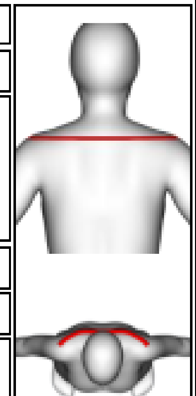
Table E.1 *Definitions of Automatic Measurements by Move4D (Move4D User Guide, 2024)*

ID:	0010
Designation:	Height
Definition:	Vertical distance from the highest point of the head in the median line to the ground (virtual stadiometer).
Source:	ISO 8559-1:2017 5.1.1
Other std.:	ISO 7250-1:2017 6.1.2, ASTM D5219-15 Height, ISO 18825-2:2016 2.2.1, ISAK:2019 Section 4.1.2
Units:	mm

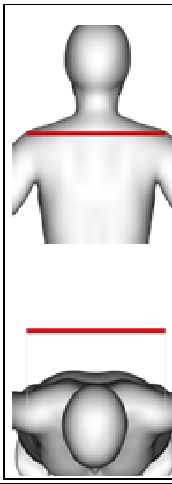
ID:	0041_I
Designation:	Torso height (abbr Torso ht)
Definition:	Vertical distance from back neck point to the inside leg level (virtual anthropometer). The back neck point (ISO 8559-1:2017 3.1.6) is the tip of the prominent bone at the base of the back neck in the mid-sagittal plane, and projected posteriorly to the surface of the skin. The inside leg level (ISO 8559-1:2017 3.1.26) is the level of highest visible point at the junction between the right and left thighs observed from the back of the subject.
Source:	ISO 8559-1:2017 5.7.3
Other std.:	ASTM D5219-15 Cervicale to crotch height
Units:	mm



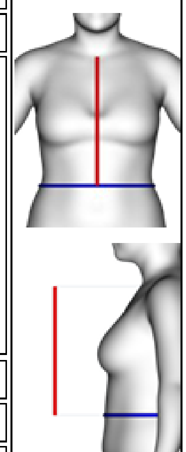
ID:	3020_mk
Designation:	Back shoulder width (abbr Back shoulder wd)
Definition:	Distance from the right to the left shoulder point along the back (virtual tape). The shoulder point (ISO 8559-1:2017 3.1.2) is the most lateral point of the edge of the spine (acromial process) of the scapula, projected vertically to the surface of the skin.
Source:	ISO 8559-1:2017 5.4.2
Other std.:	ASTM D5219-15 Accross back shoulder width
Units:	mm



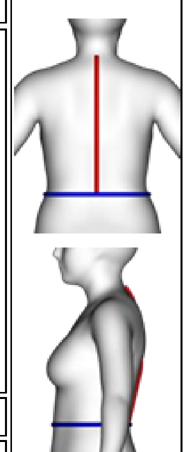
ID:	3100_I
Designation:	Shoulder (biacromical) breadth (abbr Biacromial br)
Definition:	Distance along a straight line from acromion to acromion (virtual sliding caliper). The acromion point (ISO 7250-1:2017 5.2) is the most lateral point of the edge of the spine (acromial process) of the scapula, projected vertically to the surface of the skin.
Source:	ISO 7250-1:2017 6.2.7
Other std.:	ISO 18825-2:2016 2.2.8, ISAK:2019 Section 8.2.35
Units:	mm



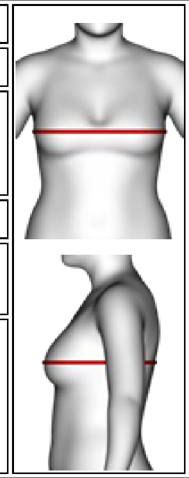
ID:	4050_mk
Designation:	Front neck to waist height (abbr Front neck-waist ht)
Definition:	Vertical distance from the front neck point to waist level. The front neck point (ISO 8559-1:2017 3.1.8) is the crossing point of the line connecting medial superior borders of the left and right clavicles and front median line. Waist level (ISO 8559-1:2017 3.1.22) is the midway level between the lowest rib point and the highest point of the hip bone at the side of the body. Lowest rib point (ISO 8559-1:2017 3.1.15) is the inferior point of the bottom of the rib cage (tenth rib) projected horizontally. The highest point of the hip bone (ISO 8559-1:2017 3.1.16) is the highest point at the side of the upper border of the iliac crest.
Source:	IBV
Other std.:	
Units:	mm



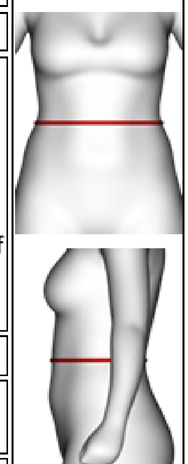
ID:	5040_mk
Designation:	Back neck point to waist (abbr Back neck-waist)
Definition:	Distance along the back, from back neck point to waist level (virtual tape). The back neck point (ISO 8559-1:2017 3.1.6) is the tip of the prominent bone at the base of the back of the neck in the mid-sagittal plane, and projected posteriorly to the surface of the skin. Waist level (ISO 8559-1:2017 3.1.22) is the midway level between the lowest rib point and the highest point of the hip bone at the side of the body. Lowest rib point (ISO 8559-1:2017 3.1.15) is the inferior point of the bottom of the rib cage (tenth rib) projected horizontally, 45 degrees from the mid-sagittal plane, to the surface of the skin. The highest point of the hip bone (ISO 8559-1:2017 3.1.16) is the highest point at the side of the upper border of the iliac crest.
Source:	ISO 8559-1:2017 5.4.5
Other std.:	ASTM D5219-15 Center back waist length, ISO 18825-2:2016 2.2.9
Units:	mm



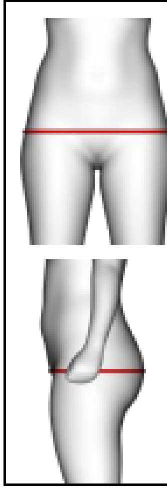
ID:	4510
Designation:	Bust girth
Definition:	Horizontal girth measured at bust point level (virtual tape). Bust point (ISO 8559-1:2017 3.1.11) is the most anterior point of the bust when wearing a bra.
Source:	ISO 8559-1:2017 5.3.4
Other std.:	ISO 7250-1:2017 6.4.10, ASTM D5219-15 Chest/bust girth, ISO 18825-2:2016 2.2.18
Units:	mm



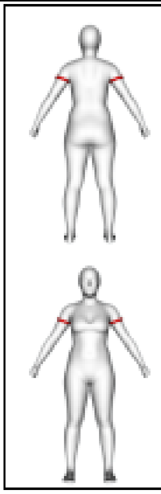
ID:	6510
Designation:	Waist girth
Definition:	Horizontal girth of the body measured at the waist level (virtual tape). Waist level (ISO 8559-1:2017 3.1.22) is the midway level between the lowest rib point and the highest point of the hip bone at the side of the body. Lowest rib point (ISO 8559-1:2017 3.1.15) is the inferior point of the bottom of the rib cage (tenth rib) projected horizontally, 45 degrees from the midsagittal plane, to the surface of the skin. The highest point of the hip bone (ISO 8559-1:2017 3.1.16) is the highest point at the side of the upper border of the iliac crest.
Source:	ISO 8559-1:2017 5.3.10
Other std.:	ISO 7250-1:2017 6.4.11, ASTM D5219-15 Waist girth, ISAK:2019 Section 6.2.20, ISO 18825-2:2016 2.2.20
Units:	mm



ID:	7520
Designation:	Hip girth
Definition:	Horizontal girth of the body measured at the hip level (virtual tape). Hip level (ISO 8559-1:2017 3.1.25) is the level of the greatest projection at the back of the body (buttocks).
Source:	ISO 8559-1:2017 5.3.13
Other std.:	ASTM D5219-15 Hip/seat girth, ISAK:2019 Section 6.2.21, ISO 18825-2:2016 2.2.22
Units:	mm



ID:	8520_LR
Designation:	Upper-arm girth
Definition:	Mean of the left and right upper arm girths, each one measured midway between the shoulder point and elbow point in the same arm. Shoulder point (ISO 8559-1:2017 3.1.1) is the most lateral point of the lateral edge of the spine (acromial process) of the scapula, projected vertically to the surface of the skin. The elbow point (ISO 8559-1:2017 3.1.10) is the most prominent point of the olecranon of ulna.
Source:	ISO 8559-1:2017 5.3.16
Other std.:	ISAK:2019 Section 6.2.15
Units:	mm



Appendix F: Exploratory Analysis of Sex-Based Differences in Perceived Fit and Comfort

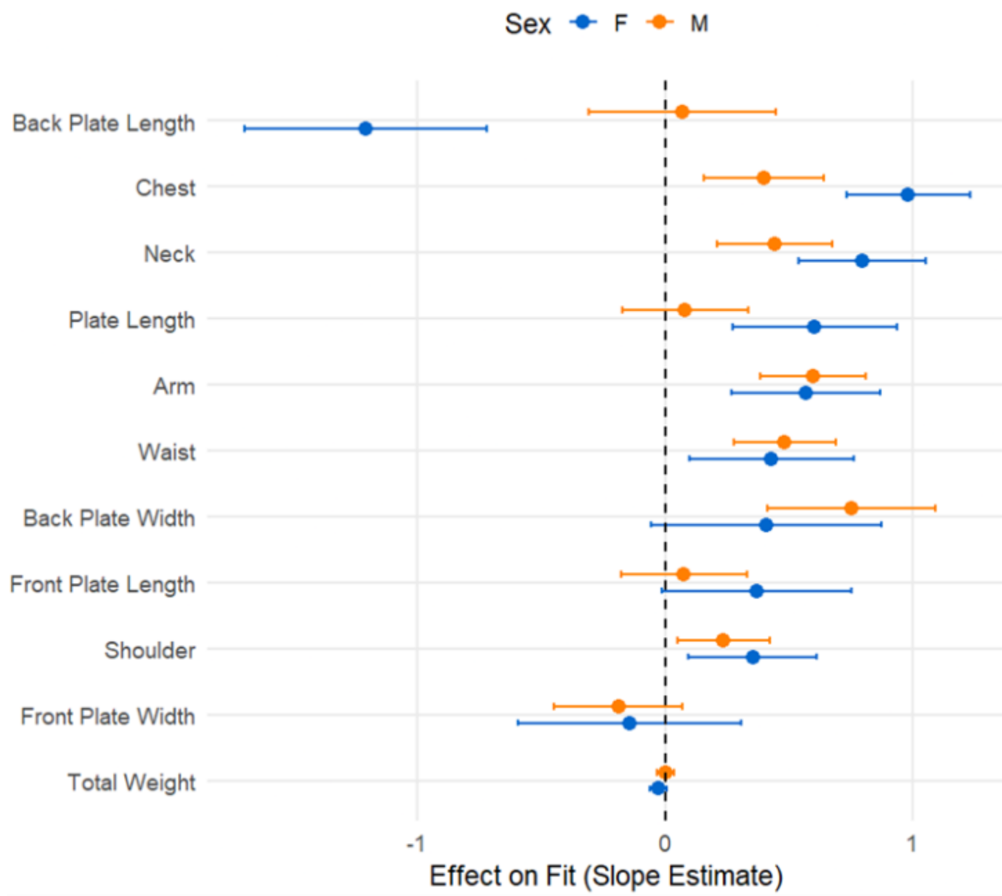


Figure F.1. *Sex-based slope estimates for the effects of regional structural deviations on perceived fit. Points represent mean slope estimates, with error bars indicating 95% confidence intervals.*

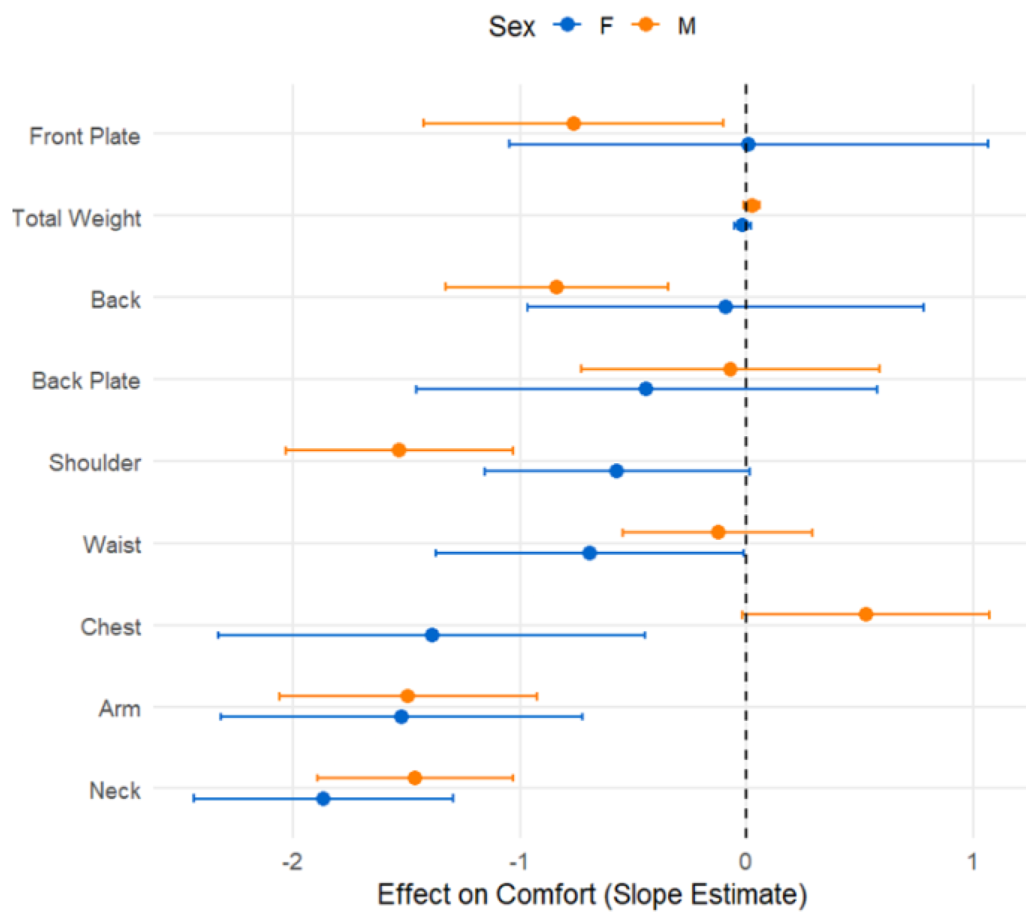


Figure F.2. *Sex-based slope estimates for the effects of regional discomfort on perceived comfort. Points represent mean slope estimates, with error bars indicating 95% confidence intervals.*