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Understanding the synthesis of anthropometric diversity and workspace dimensions in ergonomic design of light armored vehicle

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Abstract

Background and objective: To ensure effective carrying, scouting, patrolling, and large-scale combat operations, the workspace design of light armored vehicles (LAVs) should be compatible with anthropometry and range of motion (ROM) measurements of the soldiers. This study examines the extent of mismatch between the anthropometric dimensions of the Ethiopian army and existing workspace dimensions of the LAV. Predictive equations have been formulated for design dimensions considering anthropometry and ROM of the target population to avoid possible incompatibility.

Method: The assessment was conducted on three existing Ethiopian LAVs, and mathematical equations were framed to predict the vehicular design dimensions. Anthropometric and ROM data of Ethiopian soldiers ($n = 310$) from an earlier reported survey by the authors were utilized. The accommodation capacity of existing LAVs was evaluated using a one-way or two-way (mis)match criterion, based on individual workspace characteristics. Along with the predicted dimensions, key vehicular dimensions were compared with other globally accepted vehicular standard dimensions.

Results: Twenty-two basic design dimensions that comply with ergonomics principles were proposed. A high mismatch (in terms of the accommodating capacities of the three LAVs) between the existing and predicted design dimensions indicates the incompatibility of the existing design dimensions in their accommodation of most Ethiopian army personnel. The predicted dimensions comply with different global vehicular standards, thus validating the results.

Conclusion: The research findings indicate that the incompatibilities between vehicular space dimensions and army personnel's anthropometry must be addressed to evade the adverse consequences on occupational health. The LAVs should be redesigned according to the anthropometry and ROM dimensions of Ethiopian soldiers.

KEYWORDS
anthropometric measurement, army vehicle, ergonomic evaluation, predictive equations, workspace design

1 | INTRODUCTION

As protection capabilities in both heavily armored vehicles and light armored vehicles (LAVs) are generally given priority, ergonomic considerations are often ignored (Madhu & Bhat, 2011). The design mismatch in the army vehicular workspace is predominantly associated with musculoskeletal discomfort (Berkowitz et al., 1999), in addition to operational inefficiency and pain related to postural dysfunctions (Lee et al., 2020; Ross, 2011) and work-related musculoskeletal disorders (WMSDs) while performing the task (Punchihewa & Gyi, 2016). Therefore, operating armored vehicles without considering the standard dimensions in a combat environment may adversely affect the health and performance of soldiers (Belmont et al., 2016). The seating arrangement of the crew and driver, equipment positioning, interior workspace, and ventilation are important factors that can directly or indirectly affect the performance and health of the crew.

The vehicle workspace should be designed considering different user anthropometry to facilitate maximum accommodation to reduce the prevalence of WMSDs and improve operational efficiency (Karmakar et al., 2012, 2014). The accommodation in this instance is defined as the convenient settlement of the users (military personnel) to be seated, see, reach, and actuate controls (Zehner, 2000). A vehicular workspace designed based on user anthropometry will ensure comfort, safety, and performance during any mission. Lesková (2014) noted that designing workspaces to accommodate a wide range of body sizes (specific population) has always been challenging for engineers and ergonomists. Ethiopian ergonomists (Beshah et al., 2014; Odhuno-Otieno, 2016) also stated that ergonomic design concepts are challenging to implement in Ethiopia since they always require up-to-date anthropometry databases. Therefore, designing army vehicles for the Ethiopian army will require documentation and utilization of large-scale anthropometric data of the military population. In Ethiopia, the anthropometric and biomechanical database of army personnel is yet to be devised for designing suitable equipment and workspaces.

The workspace dimensions (D_W) of a vehicle depend on the static (structural) anthropometry and ranges of motion (ROM) (Stoudt, 1973). It is also related to the dynamic or functional anthropometry of working positions (Hertzberg, 1960). The dynamic anthropometry can be evaluated for both static anthropometry (link length) and joint angles between the links (ROM) (Yadav et al., 2017). However, most research (Ismaila et al., 2013; Tetteh et al., 2017) used static anthropometry for estimating D_W (like seat dimensions). Moreover, the vehicular workspace dimensions mostly depend on static anthropometry and ROMs for designing controlling units on the turret handle, sight device, steering wheel, pedal, and control dashboard. Therefore, to address critical ergonomic issues, the design analysis of vehicular workspaces must consider both static anthropometric dimensions and ROM measurements (Arunachalam et al., 2020).

However, the mathematical equations for establishing the relationship between D_W and anthropometric variables are formulated in limited ergonomics studies (Castellucci et al., 2010; Fidelis et al., 2018; Ghaderi et al., 2014; Halder et al., 2017; Mehta et al., 2008; Parvez et al., 2018; Parvez et al., 2019; Rahman et al., 2019; Yadav et al., 2017), mostly for designing school furniture. Among these studies, Halder et al. (2017) and Yadav et al. (2017) examined the mismatch between the dimensions of driver seats and anthropometric characteristics of the targeted user populations (truck and tractor drivers) and proposed suitable design dimensions. Another study (Tetteh et al., 2017) established the dimensional mismatch between the few locally fabricated vehicle seats and anthropometry of Ghanaian people. They also formulated and compared the predicted dimensions with national and international standards.

The ergonomic characteristics of workspaces are primarily determined by the accommodating space clearance, visual needs, reaching distance, manipulative needs, and postural and biomechanical loads. This ergonomic need influences users to select a comfortable and functional workspace (Verriest & Alonzo, 1986). For practicing effective ergonomic workspace design, the 5th, 95th, or 5th–95th percentile (p) values of anthropometric variables (of users) are usually considered (Reed & Flannagan, 2000; Khaspuri et al., 2007).

The ergonomic compatibility assessment is an iterative process that typically involves two ways of evaluation: subjective and objective (Kolich & Taboun, 2004). Subjective evaluation is not always preferable because of its higher cost, completion time, error-rates (Tan et al., 2008), and risky environments (Koradecka et al., 2010; Singh, 2019), and is susceptible to biased results due to of the influence of personal preferences (Annett, 2002; Singh et al., 2019). Therefore, an objective evaluation was conducted in this study. Different objective evaluation methods have been employed by several researchers to assess comfort and discomfort while studying the ergonomics of specific equipment/workspace (Tan et al., 2008). One of the simplest dimensional compatibility evaluation methods, "match or mismatch evaluation technique" (Assunção et al., 2013; Castellucci et al., 2010; Dianat et al., 2013), was used in this study.

The match/mismatch evaluation can only be conducted by adopting design limits. To select the most appropriate percentile values (p) from a population distribution, Wagner et al. (1996) pointed out the following design limits associated with the ergonomic design of facilities:

- The clearance dimensions that accommodate or allow passage of the body (or body parts) shall be based on the 95th p of the male data in general for applicable body dimensions.
- Reach distances, control movements, display and control locations, test point locations, and handrail positions that restrict or are limited by body or body part size shall be based on the 5th p of female data for applicable body dimensions.
- Any equipment dimensions that require adjustment for comfort or performance of the user should be adjustable over the range of the 5th to 95th p.

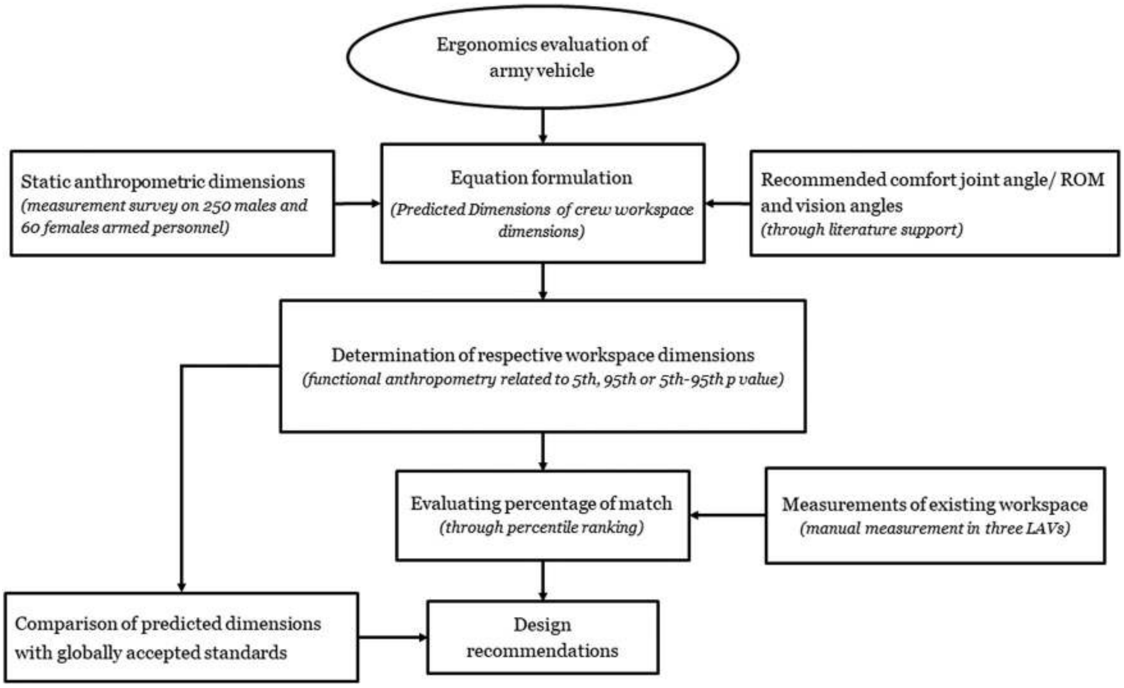


FIGURE 1 Dimensional compatibility evaluation strategy adopted in the present study

- Workspace dimensions of hardware (facility design) for the specific users' population shall be based on the functional anthropometry of the necessary working positions.
- The 50th p or mean is rarely used as design criteria because it accommodates only half of the users.

The current research aimed to investigate the mismatch between the workspace dimensions (of LAVs) and anthropometry/ROM measurements of Ethiopian armed personnel. In addition, the study proposed 22 design dimensions and compared them with globally accepted standards to ascertain their ergonomic compatibility. It is demonstrated that the predictive equations formulated in the present study would help designers and engineers to bridge a network between the interior design of the vehicle and crew/driver comfort.

2 | METHODOLOGY

Primarily, to propose suitable vehicle workspace design dimensions (in terms of body dimensions and ROM), combinational equations requiring the minimum and maximum (design) limits of static anthropometric data were formulated. The results of the static anthropometric survey of Ethiopian soldiers conducted in a prior survey was used in this study (Wibneh et al., 2020). Since the recommended ROM and vision angles have strong literature support, globally accepted ROM measurements were adopted because of their limited use in our study. The wide range of user populations (5th, 95th, or 5th-95th *p* values) of functional anthropometries was considered. The basic workspace dimensions from existing LAVs were also measured to determine the percentage match between the existing and predicted workspace dimensions. Finally, the predicted design dimensions (D_P) for the driver workspace were compared with different global vehicular dimension standards to ensure the reliability of predictive equations. Figure 1 shows the schematic representation of the proposed study design for evaluating the army vehicular workspace.

2.1 | Anthropometric data

We used the anthropometric dimensions (Figure 2 and Table 1) of Ethiopian armed personnel (250 males and 60 females) developed by Wibneh et al. (2020) in our study. ISO 7250-1:2017 standard (ISO, 2017) was used for adopting basic human body measurements for technological design. The participants were randomly selected from the ground forces, and their age and ethnicity distributions were also documented during data collection. The male participants, were aged between 18 and 52 years (mean = 30.86; SD = 6.7) and female participants between 18 and 30 years (mean = 24.21; SD = 3.26). The normality of the data distribution was checked before further analysis. The measured data (static anthropometry, Table 1) and recommended ROM and vision angles (Table 2) were used to compute the suitable design dimensions discussed later in the text.

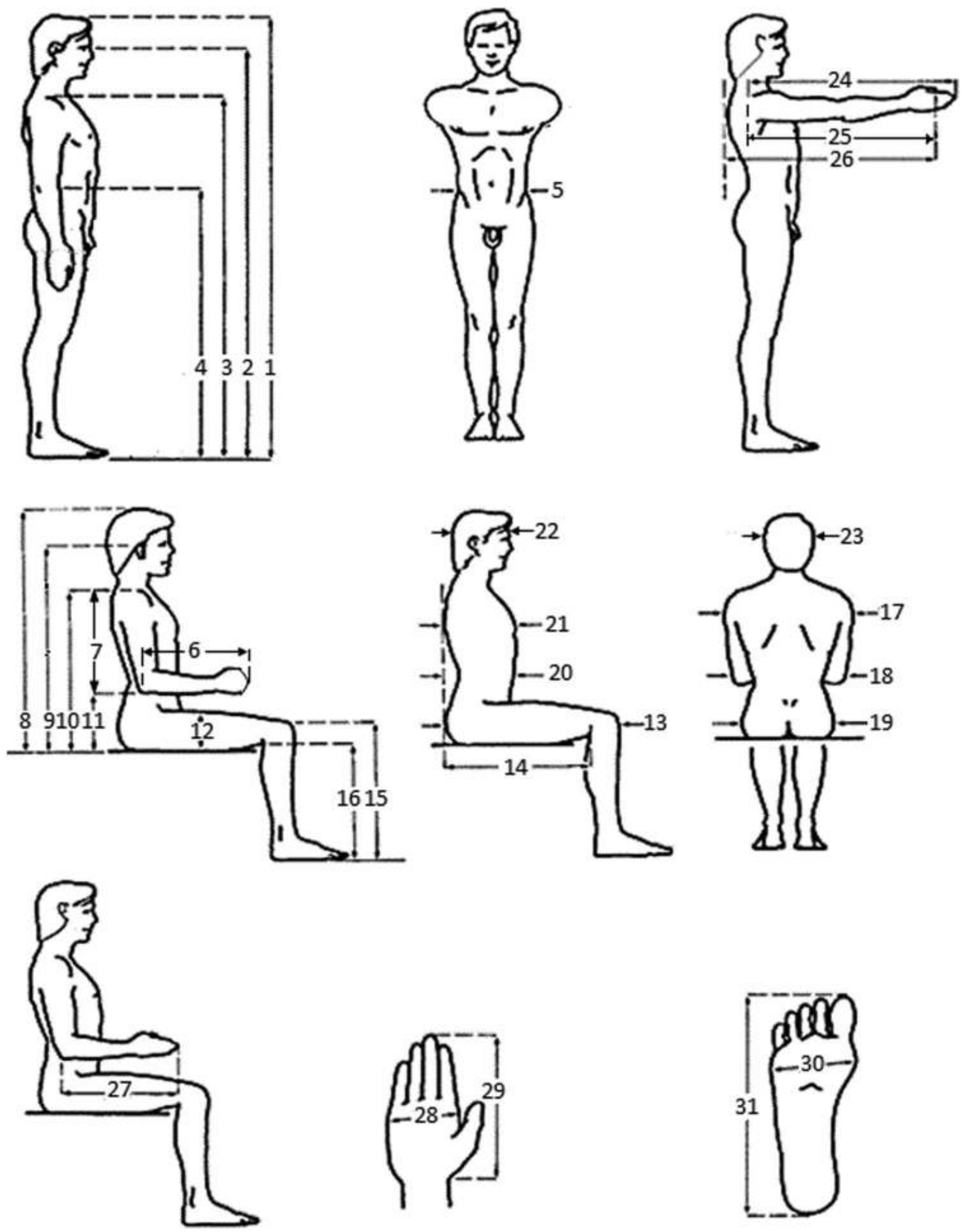


FIGURE 2 Anthropometric variables in standing and sitting posture (Adapted from: Guan et al., 2012; Pheasant & Haslegrave, 2005).

1	Stature	9	Sitting eye height	17	Bideltoid breadth	25	Grip arm length
2	Eye height	10	Sitting acromial height	18	Elbow to elbow breadth	26	Thumb tip reach length
3	Acromial height	11	Elbow rest height	19	Hip breadth	27	Forearm length
4	Elbow height	12	Thigh thickness	20	Abdominal depth	28	Hand breadth
5	Waist breadth	13	B. to popliteal length	21	Chest depth	29	Hand length
6	Forearm grip length	14	Buttock to knee length	22	Head length	30	Foot breadth
7	Upper arm length	15	Sitting knee height	23	Head breadth	31	Foot length
8	Sitting height	16	Popliteal height	24	Arm length		

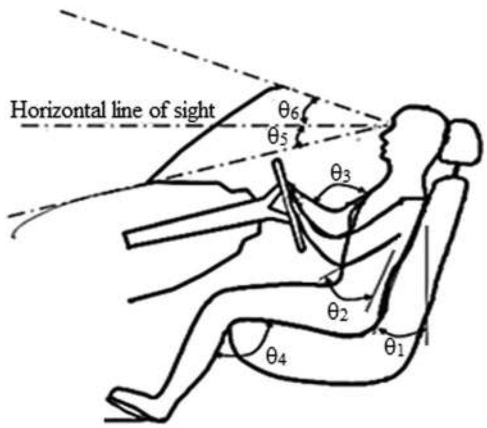
TABLE 1 Static anthropometric data for Ethiopian army population (aged 18–52 years for males and 18–30 for females

Male, *n* = 250; Female, *n* = 60	Percentiles					
	Female			Male		
Anthropometric variables	5th	50th	95th	5th	50th	95th
Standing posture						
Stature	150.80	158.00	169.20	161.00	169.50	179.90
Eye height	142.30	147.50	156.86	150.60	159.00	168.90
Acromial height	120.80	131.81	139.68	132.50	140.00	149.00
Elbow height	96.07	101.00	107.51	101.00	108.00	116.00
Arm length	64.70	69.75	73.38	70.00	75.50	81.90
Grip arm length	59.60	64.20	67.80	64.20	69.50	75.50
Sitting posture						
Sitting height	75.48	78.26	83.82	79.77	84.60	90.86
Eye height	63.44	67.08	72.48	67.48	73.35	80.20
Acromial height	47.54	51.42	58.52	52.71	58.18	64.15
Elbow rest height	14.76	17.20	22.10	17.20	21.75	26.31
Upper arm length	32.78	34.2	36.42	35.51	36.45	37.84
Forearm length	40.41	45.00	46.37	42.10	46.50	50.40
Grip forearm length	35.31	39.45	40.79	36.3	40.5	44.00
Head breadth	13.94	14.63	15.3	14.7	15.3	16.06
Head length	17.4	18.8	20.5	19.1	19.9	21.7
Bideltoid breadth	36.50	39.50	43.68	42.34	45.00	48.58
Elbow-elbow breadth	38.40	42.41	48.00	46.21	49.77	54.55
Chest depth	17.60	20.77	24.60	23.38	26.03	30.02
Abdominal depth	16.49	20.41	26.04	19.53	22.60	28.44
Waist breadth	25.02	27.60	31.30	27.10	29.00	32.90
Hip breadth	32.43	35.96	41.67	34.50	36.50	40.90
Popliteal height	34.30	39.09	42.61	40.35	42.58	47.81
Knee height	49.55	52.70	54.83	50.83	54.16	57.16
Buttock-popliteal length	42.83	47.05	49.84	44.99	48.90	50.86
Buttock to knee length	53.64	58.28	60.51	57.35	60.71	64.25
Thigh thickness	12.34	14.77	17.72	14.33	15.74	17.68
Forward thumb tip reach	69.74	74.91	78.70	75.33	80.82	87.27
Hand length	16.88	18.09	18.68	16.52	18.29	20.70
Hand breadth	7.41	8.33	9.50	7.41	8.33	9.50
Foot length	21.84	22.75	24.12	23.50	25.00	26.50
Foot breadth	7.37	8.12	9.04	7.41	8.33	9.50
Mass (kg)	45.00	53.00	63.80	55.00	65.00	84.00
BMI (kg/m^2)	19.8	21.2	22.3	21.2	22.6	25.4

Note: All measurements are in cm unless specified.

TABLE 2 Body joint angles (ROM) and vision angles with the mode/median values

Joint angles (ROM) and vision angles	Comfortable angle (ROM)	Recommended literatures
θ_1: Torso orientation	20°	Mircheski et al. (2014) *and* Ruiz Castro (2015)
θ_2: shoulder joint	22°	
θ_3: elbow joint	127°	
θ_4: knee joint	119°	
θ_5: down vision angle	15°	Van Cott and Kinkade (1972)
θ_6: up vision angle	15°	



Abbreviation: ROM, range of motion.

FIGURE 3 The existing widely used Ethiopian light armoured vehicle (photos taken from Bishoftu Motorization Engineering Complex, Ethiopia)

2.2 | Existing vehicular workspace dimensions and measuring techniques

Three different models of locally fabricated or assembled LAVs (Figure 3) were used to determine the existing vehicular workspace. Although all LAVs were weaponized, two of them (Veh-2 and Veh-3) adopt firing in the sitting posture, whereas Veh-1 adopts firing in the standing posture. The LAVs consist of four workspaces (Gillingham & Patel, 2013): infantry troop (W1), gunner (W2), driver (W3), and commander (W4) (Figure 4). These workspaces were considered to investigate the match/mismatch between the vehicular workspaces and target user (Ethiopian army). Although an effective vehicular workspace design may require the prediction of many dimensions, the scope of this study was limited to evaluating 22 basic dimensional variables for the three LAVs. The basic D_W of the infantry troop, driver, gunner, and commander are presented in Figure 5a, 5b,

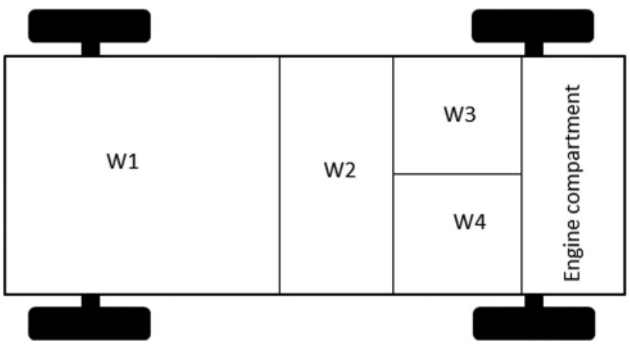


FIGURE 4 Workspaces layout with actual workspace arrangements of LAV (adapted from Gillingham & Patel, 2013). *W1 = infantry troop workspace; W2 = gunner workspace; W3 = driver workspace; W4 = commander workspace*

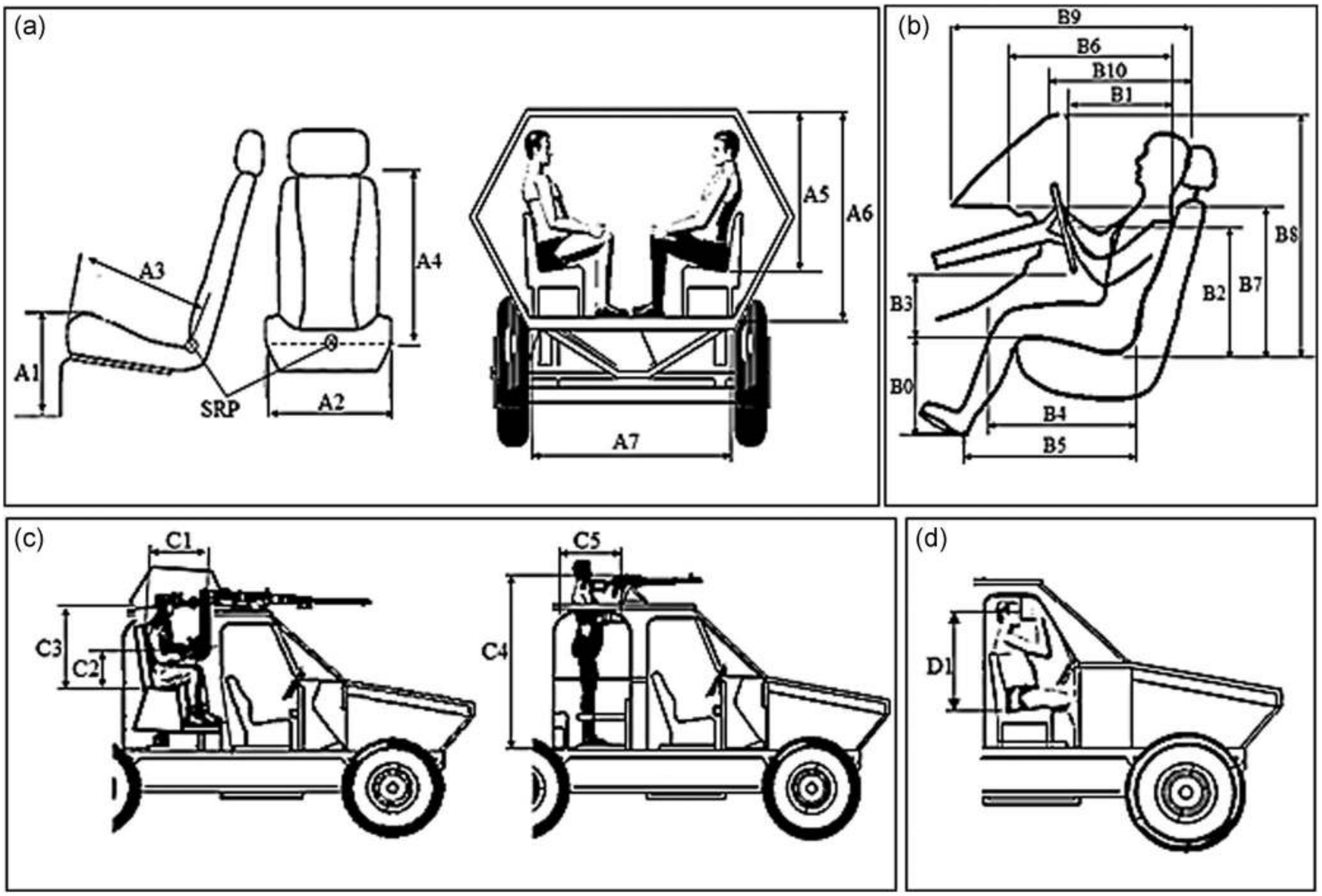


FIGURE 5 Relevant workspace dimensions of army vehicles (a) crew seat; (b) driver workspace; (c) gunner workspace in sitting posture and standing posture; (d) commander workspace. Adapted and compiled from Reed (2000); Halder et al. (2017); Tank archive (2013). A1 = crew seat height (other than driver seat height); A2 = seat width; A3 = seat depth; A4 = backrest height; A5 = headroom height; A6 = roof height; A7 = base width; B1 = steering wheel distance; B2 = steering wheel height; B3 = steering wheel clearance; B4 = control dashboard clearance; B5 = pedal distance; B6 = control dashboard distance; B7 = cowl point height; B8 = Daylight opening height; B9 = Cowl point distance; B10 = Daylight opening distance; B0 = driver seat height; C1 = turret handle distance; C2 = turret handle height; C3 = height of sight device for seated gunner; C4 = height of sight device for stood gunner; C5 = top hatch diameter; D1 = height of sight device for commander

5c, and 5d, respectively. The measured D_W with its corresponding descriptions is presented in ANNEXURE I.

The crew seat dimensions such as seat height, width, depth, and backrest height were included as essential parameters for comfortable seating (Halder et al., 2017). The base width and roof height dimensions (in the interior space) are essential to ensure comfort in a two-seater workspace (people either sitting face-to-face or back-to-back) (Gillingham & Patel, 2013). Driver workspace dimensions, such as the steering wheel center distance and height, control dashboard distance, steering wheel clearance, control dashboard clearance, pedal distance, cowl point height, and daylight opening height, should be designed per functional anthropometry. It will ensure comfortable posture, accessibility, and minimum fatigue (Yadav et al., 2017). The design of the gunner and commander workspace viz. height of sight device for a seated gunner and commander, the height of the sighting device for a stood gunner, top hatch diameter, turret handle distance, and turret handle height are required to increase the comfort and operational efficiency of gunners during patrolling, and large-scale combat operations (Tank archive, 2013).

All the fixed dimensions and most of the clearance dimensions were readily available from the assembly drawings provided by the manufacturer. Dimensions such as B1, B6, and C1 require special considerations such as identifying the scapular resting position. Based on previous literature (Ghaderi et al., 2014; Mehta et al., 2008), 80% of the sitting acromial height for 5th p females was used to define the scapular resting position before the measurement was performed. Hence, the scapular resting position was set at 38 cm based on the anthropometric measurement of acromial height (see Table 1). The workspace measurements were performed without crew members, with the scapular resting position marked on the vehicle seat. Similarly, the dimensions such as B9 and B10 require the identification of the headrest position, which is the point of the headrest along the horizontal line of sight. B9 and B10 measurements were performed at the height of the design eyepoint for the 5th and 95th p values, respectively. The seat dimensions (A1–A4) were physically verified. The measurements were made either vertically or horizontally between the two reference points (Tetteh et al., 2017). All dimensions are expressed in centimeters and were measured using a metal tape, as in Herga and

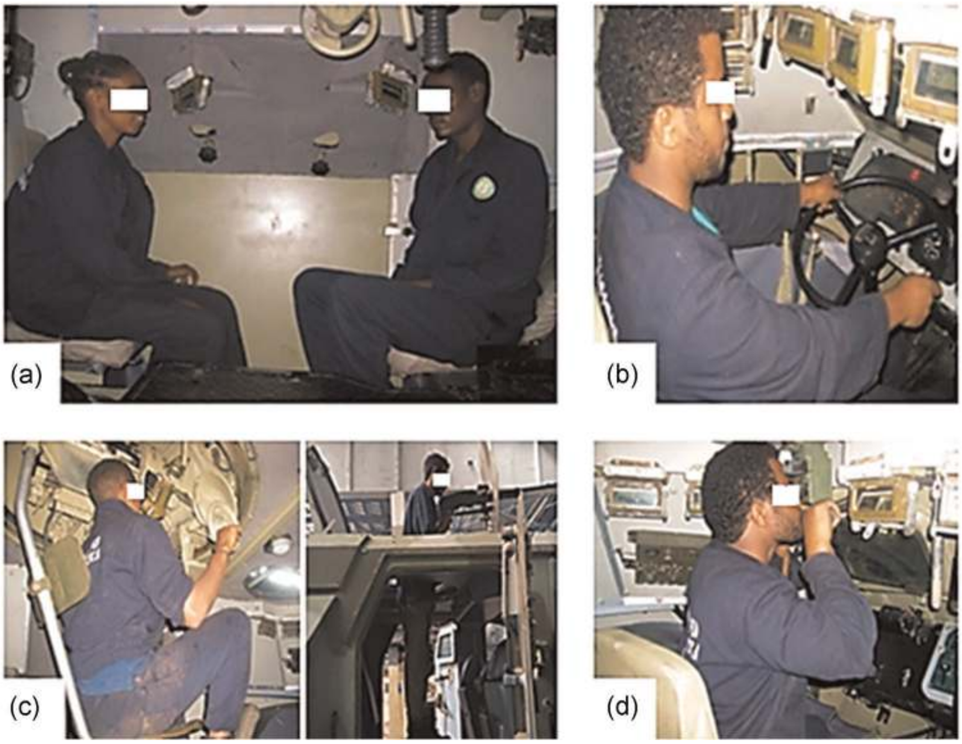


FIGURE 6 Postures adopted during (a) normal crew sitting; (b) driving; (c) gunner firing in siting and standing posture; (d) commander sighting operation (*Photos taken from Bishoftu Motorization Engineering Complex, Ethiopia*)

Fošnarič (2017). The plumb line and crosspiece were used to define the horizontal and vertical lines, respectively, along which the measuring tape lies during the measurement. A weighted pendulum was suspended freely to define the vertical line, while the crosspiece was fixed at the right angle to the pendulum (plumb line) to define the horizontal line (Paul & Whyte, 2012).

2.3 | Evaluation techniques

Before the assessment, the mathematical equations were formulated to predict the most suitable design dimensions of anthropometry and preferred ROM (Peng et al., 2018) to establish the relationship between vehicular workspace dimensions and anthropometry of the Ethiopian army.

For assessing the most suitable dimensions, two types of match/mismatch criteria, "one-way criterion" or "two-way criterion," were used (Castellucci et al., 2015; Wagner et al., 1996). The one-way criterion uses either the minimum value limited by the maximum body sizes or 95th *p* values or maximum value limited by the minimum body sizes or 5th *p* values (Anjani et al., 2013), while the two-way criterion uses both maximum and minimum values limited by 5th and 95th *p* values, respectively, as adjustable units to define suitable vehicle dimensions (Taifa & Desai, 2017). The measurement criteria were decided by the three ergonomic design principles (Taifa & Desai, 2017; Wagner et al., 1996), that is, designing for the maximum individual size considering the 95th p male, designing for the minimum individual size considering 5th p female, and designing for an adjustable range considering both 5th p female and 95th p male.

During the ergonomic assessment, four occupant spaces–infantry troop seat, commander, driver, gunner (standing and sitting), and workspaces were considered (Figure 6; all images were taken from the existing Ethiopian LAVs). D_W was evaluated considering the postures adopted by military personnel inside the LAV. The ergonomic characteristics of each workspace were evaluated by measuring the fundamental dimensions that define the vehicle interior ergonomic characteristics.

The workspace design must account for this wide range of body sizes in the user population (NASA, 1995). Therefore, 22 relevant workspace dimensions were categorized for individual workspace characteristics, such as clearance, reach, control units, visual needs, and adjustment units. Suitable design criteria were proposed for each workspace characteristic. Many match/mismatch related studies attempted to identify the workspace design criterion (Evans et al., 1988; Ismaila et al., 2010). Table 3 presents the workspace dimensions and justification regarding design approaches (designing for percentile values).

2.4 | Predictive equations

The fundamental design dimensions of vehicle workspaces can be predicted in terms of static anthropometry and ROM (Yadav et al., 2017). The equations for predicting design dimensions, D_p followed

TABLE 3 Design criteria corresponding to vehicular workspace dimensions (D_W)

Design criteria	Workspace dimensions	Descriptions
Designing for 5th percentile female value	Crew seat other than driver seat height (A1)	Smaller crew member can easily rest their foot.
	Seat depth (A3)	Smaller crew member can support their back on the back rest.
	Backrest height (A4)	Smaller crew member can get backrest at scapula portion and for full mobility to the arm and shoulder without blocked.
	Driver seat height (B0)	Smaller driver can easily reach pedal control for non-adjustable height.
	Height of steering wheel (B2)	Reduces arm extension for smaller driver.
	Control dashboard distance (B6)	Smaller gunner can easily reach in to control dashboard.
	Cowl point height (B7)	Visual needs in to the road for smaller driver.
	Turret handle distance (C1)	Smaller gunner can easily reach in to the turret handle horizontally.
	Turret handle height (C2)	Smaller gunner can easily reach in to the turret handle vertically.
Designing for 95th percentile male value	Seat width (A2)[a]	Adequate size for larger crew member.
	Head room height (A5)	Adequate clearance for larger user.
	Steering wheel clearance (B3)	
	Roof height (A6)	
	Base width (A7)	
	Control dashboard clearance (B4)	Knee clearance for larger driver.
	Daylight opening height (B8)	Reduces neck and trunk flexion for visual needs above horizontal line of sight.
	Top hatch diameter (C5)	Adequate opening clearance for free rotation during firing operation by the larger gunner in standing posture.
Designing for wide ranges of 5th percentile female to 95th percentile male values	Steering wheel distance in horizontally adjustable seat (B1)	To accommodate and fulfill adjustability requirements in wide ranges of army population
	Foot pedal distance in horizontally adjustable seat (B5)	
	Height of sight vision device for seated gunner (C3).	
	Height of sight vision device for stood gunner (C4).	
	Height of sight vision device for seated commander (D1).	

[a]The seat width designed for 95th percentile female.

three key considerations viz. maximum individual size (commonly referred to as the 95th p male), the minimum individual size (5th p female), or an adjustable range (both 5th female and 95th male) (Khaspuri et al., 2007). However, for ROM, the mean values that the majority of the population shared were used (Kyung & Nussbaum, 2009; Mircheski et al., 2014; Porter & Gyi, 1998). Table 4 shows the mathematical relationship to predict design dimensions w.r.t. anthropometric measurements and ROM. The most relevant 22 dimensions (see Table 3) of the four workspaces were considered for mathematical formulation and dimensional compatibility evaluation. These dimensions with the corresponding descriptions are indicated in ANNEXURE I.

The predictive equations for all clearance dimensions modeled by the 95th p value provided the minimum design value. The workspace dimensions (on LAVs) that exceeded the minimum design value were considered matched, otherwise mismatched. Conversely, the equations for reach distances modeled by the 5th *p* value provided the maximum design value. The dimensions (on LAVs) lower than the maximum value were considered matched, and mismatched otherwise (Castellucci et al., 2015). Therefore, to design a non-adjustable workspace, suitable design dimensions were predicted using appropriate percentile values of anthropometric variables of the military population.

The following assumptions were made while formulating the predictive equations:

TABLE 4 Equations for defining vehicular workspace dimensions in terms of anthropometry and ROMs aiming to accommodate a wide range of army population

Predictive equations for design dimensions	Descriptions
$A1 = PH + 2cm$ (1)	2 cm added to 5th p female value of the upright positioned popliteal height (PH) for shoe allowance (Gouvali & Boudolos, 2006)
$A2 = 1.1HBorHB + 5cm$ (2)	At least 110% of 95th p of female hip breadth (HB) is mostly used (Castellucci et al., 2010; Kahya, 2019) or 95th p of female hip breadth and 5 cm clearance (Mehta et al., 2008)
$A3 = BpL - 5cm$ (3)	Seat depth should be 5 cm shorter than 5th p female value of female buttock-popliteal length (BPL) (Poulakakis & Marmaras, 1998)
$A4 = 0.8AH$ (4)	At most 80% of 5th p of female acromial height (AH) for full mobility to the arm and shoulder without blocked (Ghaderi et al.,2014; Mehta et al., 2008)
$A5 = SH + 5cm$ (5)	The minimum head room height should be 5 cm greater than 95th p male value of male sitting height (SH) (Dreyfuss, 1967)
$A6 = (SH + 5cm) + (PH + 2cm)$ (6)	Roof height shall be the sum of seat height (A1) and head room height (A5) (Gillingham & Patel, 2013), and approximated from the combination of sitting height (95th p male) and the mean popliteal height (mean of 50th p male and female)
$A7 = 2(BPL + FL + 6cm)$ (7)	Base width of interior space shall be approximated from the combination of buttock to popliteal length and foot length (of 95th p male) (Gillingham & Patel, 2013). To accommodate two soldiers (sitting face-to-face or back-to-back), the dimension should be multiplied by 2. Back rest space and foot rest allowance (3.5 cm and 2.5 cm) were added
$B0 = (PH + 2cm)sin\theta_4$ (8)	Pedaling operation at $\theta_4{}^* = 119^0$ is comfortable for driver so that driver seat height is less than the normal seat height (Mircheski et al., 2014)
$B1_{max} \leq X1 + X2 - X3 \leq B1_{min}$ (9) Where, $X1 = TRL - GAL$ $X2 = UAL\sin(\theta_1 + \theta_2)$	Ranges of 5th p female to 95th p male values of thumb tip reach length (TRL), grip arm length (GAL), upper arm length (UAL), grip forearm length (GFAL), torso orientation ($\theta_1{}^* = 20^0$), shoulder joint angle ($\theta_2{}^* = 22^0$) and elbow joint angle ($\theta_3{}^* = 127^0$) shall be used (Mircheski et al., 2014; Ruiz Castro, 2015)
$X3 = (GFAL)\sin(\theta_1 + \theta_2 - \theta_3)$	Refer ANNEXURE II for X1, X2 and X3.
$B2 = Y1 + Y2 + Y3$ (10) Where, $Y1 = ELH$ $Y2 = UAL(1 - \cos(\theta_1 + \theta_2))$	Non-adjustable height was preferred for armoured vehicle to reduce jerking during off-road moving. 5th p female values of elbow rest height (ELH), upper arm length (UAL), grip forearm length (GFAL), torso orientation ($\theta_1{}^* = 20^0$), shoulder joint angle ($\theta_2{}^* = 22^0$) and elbow joint angle ($\theta_3{}^* = 127^0$) shall be used (Mircheski et al., 2014; Ruiz Castro, 2015)
$Y2 = (GFAL)\cos(\theta_1 + \theta_2 - \theta_3)$	Refer ANNEXURE II for Y_1, Y_2 and Y_3
$B3 = TT + 2cm$ (11)	Steering wheel clearance should ideally be 2 cm larger than 95th p male value of thigh thickness (TT) (Halder et al.,2017)
$B4 = BKL + 5cm$ (12)	The knee clearance shall be 5 cm larger than 95th p value of buttock to popliteal length (BPL) (Poulakakis & Marmaras, 1998)
$B5_{max} \leq BPL - (PH + 2cm)cos\theta_4 \leq B5_{min}$ (13)	Ranges of 5th p female to 95th p male values of buttock to popliteal length (BPL), popliteal height (PH) and knee joint angle ($\theta_4{}^* = 119^0$) shall be used (Mircheski et al., 2014). The driver seat surface was assumed to be in the horizontal plane
$B6 = TRL$ (14)	5th p female value of thumb tip reach length (TRL) shall be used (Bullock, 1974)
$B7 = SEH - (B9 - HL)tan\theta_5$ (15)	5th p female value of sitting eye height (SEH), head length (HL), horizontal distance of windshield cowl point from the eye (B9- HL) and down vision angle ($\theta_5{}^* = 15^0$) (Fostervold et al., 2006; Peacock & Karwowski, 1993) shall be used. The cowl point distance (B9) may not be restrictedly dependent on anthropometric variable
$B8 = SEH + (B10 - HL)tan\theta_6$ (16)	95th p male value of eye height (SEH), head length (HL), horizontal distance of daylight opening point from design eye reference point (B10 – HL) and up vision angle ($\theta_6{}^* = 15^0$) (Fostervold et al., 2006; Peacock & Karwowski, 1993) shall be used. The daylight opening distance (B10) may not be restrictedly dependent on anthropometric variable
$C1 = TRL - GAL + UAL\sin(\theta_1 + \theta_2) + GFAL$ (17)	5th p female value of thumb tip reach length (TRL), upper arm length (UAL), grip forearm length (GFAL), grip arm length (GAL), backrest angle for the gunner shall be kept minimum at torso orientation of $\theta_1{}^* = 10^0$ (Mehta et al., 2008) unlike to the driver's seat backrest angle and shoulder joint angle at $\theta_2{}^* = 22^0$ shall be used (Mircheski et al., 2014) and forearm position is assumed to be horizontal

TABLE 4 (Continued)

Predictive equations for design dimensions	Descriptions
$C2 = ELH - UAL(1 - \cos(\theta_1 + \theta_2))$ (18)	5th p female value of elbow rest height (EH), upper arm length (UAL), shoulder joint angle (θ_2* = 22^0) torso orientation (θ_1* = 10^0) and shall be used (Ruiz Castro, 2015) and forearm position is assumed to be horizontal
$C3_{max} \leq SEH \leq C3_{min}$ (19)	Ranges of 5th p female to 95th p male values of sitting eye height (SEH) for firing in sitting posture shall be used (Tank archive, 2013)
$C4_{max} \leq H + 2cm \leq C4_{min}$ (20)	Ranges of 5th p female to 95th p male values of standing eye height (EH) for firing in standing posture shall be used (Tank archive, 2013), and 2 cm is added for shoe allowance
$C5 = EEB + 25cm$ (21)	It shall be determined by 95th p male values of elbow to elbow breadth (EEB) with 25 cm side clearance (Woodson et al., 1992)
$D1_{max} \leq SEH \leq D1_{min}$ (22)	Ranges of 5th p female to 95th p male values of sitting eye height (SEH) for commander in sitting posture shall be used (Tank archive, 2013)

Note: Subscript "max" denotes maximum value of D_W usually limited by 5th percentile of female value; "min" denotes minimum value limited by 95th percentile of male value (except the hip breadth of female). A1 = crew seat height other than driver seat height; A2 = seat width; A3 = seat depth; A4 = backrest height; A5 = headroom height; A6 = roof height; A7 = base width; B1 = steering wheel distance; B2 = steering wheel height; B3 = steering wheel clearance; B4 = control dashboard clearance; B5 = pedal brake distance; B6 = control dashboard distance; B7 = cowl point height; B8 = Daylight opening height; B9 = Cowl point distance; B10 = Daylight opening distance; B0 = driver seat height; C1 = turret handle distance; C2 = turret handle height; C3 = height of sight device for sit gunner; C4 = height of sight device for stood gunner; C5 = top hatch diameter; D1 = height of sight device for commander.

*The angles of θ_1 to θ_6 are the mean values of ROM that majority of population shared.

TABLE 5 Match/mismatch decision rule of workspace dimensions in comparison with dimensions predicted by percentile values

Characteristics of dimensions	Match/mismatch decision rule	
	Match	Mismatch
The workspace dimension (D_W) related to "one-way criterion" or 5th *p* predicted value (D_P)	$D_W \leq D_P$ is matched	$D_W > D_P$ is mismatched
The workspace dimension (D_W) related to "one-way criterion" or 95th *p* predicted value (D_P)	$D_W \geq D_P$ is matched	$D_W < D_P$ is mismatched
Ranges of workspace dimensions (D_{Wmax} to D_{Wmin}) related to "two-way criteria" or wide ranges of 5th to 95th *p* predicted values (D_{Pmax} to D_{Pmin}) for adjustable units	$D_{Wmax} \leq D_{Pmax}$ and $D_{Wmin} \geq D_{Pmin}$ is matched	$D_{Wmax} > D_{Pmax}$ and/or $D_{Wmin} < D_{Pmin}$ is mismatched

Note: D_{Wmax}, maximum workspace dimension; D_{Wmin}, minimum workspace dimension; D_{Pmax}, maximum predicted design dimension determined by 5th percentile of value; D_{Pmin}, minimum predicted design dimension determined by 95th percentile of value.

- The ergonomic evaluation was performed by adopting two percentile values (5th percentile female and 95th percentile male).
- Since the anthropometric measurements are documented with light clothes and barefoot (ISO, 2017), considerable allowances for shoes and normal clothing were added in the predictive equations of key dimensions.
- The predictive equations were formulated for fixed (non-adjustable) seats for the infantry troop. However, predictive equations for the driver seat were designed for horizontal adjustability with respect to the control units. The commander and gunner seats were presented with vertical adjustability.
- Except for the driver seat height, all the seat dimensions, including headroom height and roof height, were considered the same for all crew (infantry troop, driver, gunner, and commander) workspaces.
- Some design dimensions, such as cowl point distance, B9, and daylight opening point distance, and B10, do not directly depend on anthropometric variables; therefore, the measurements were performed assuming a headrest position at the height of the design eyepoint.

2.5 | Match/mismatch criteria

Table 5 describes the match/mismatch decision rule while comparing existing D_Ws with D_P. The D_W grouped under the design criteria of maximum design value (limited by lower extreme value or 5th p) (e.g., seat height) will be considered mismatched if D_W is greater than D_P. Similarly, the adjustable D_W grouped under a wide range of 5th–95th p will be considered mismatched if the maximum measurement value (D_{Wmax}) is greater than the dimensions predicted by the 5th p (D_{Pmax}) and/or the minimum measurement (D_{Wmin}) is less than the dimensions predicted by the 95th p (D_{Pmin}) (Wagner et al., 1996).

2.6 | Match/mismatch analysis

Match/mismatch and accommodation capacity of existing DWs for the Ethiopian army population were thoroughly analyzed. The

TABLE 6 The descriptive of existing vehicular workspace measurements and corresponding predicted design dimensions (D_P) at extreme limit levels

	Predicted design dimensions		Existing workspace measurements		
Workspace type	**Analytical relationship**	**Predicted design values**	**Veh-1**	**Veh-2**	**Veh-3**
Infantry troop seat	A1 = PH + 2 cm	36.3	41	35	49.5
	A2 = 1.1HB	46	46	38	41
	A3 = BPL-5cm	37	44	39.5	42
	A4 = 0.8AH	39.6	55	40	45
	A5 = SH + 5 cm	96	99	92	96.5
	A6 = PH + SH + 7 cm	136	150	130	135
	A7 = 2(BPL + FL + 6 cm)	165	220	195	215
Driver workspace	B0 = (PH + 2 cm) sin119^0	32	38	35	36
	A2 = 1.1HB	46	47	41	40.5
	A3 = BPL-5cm	38	48	41	42
	A4 = 0.8AH	39.6	55	45	50
	A5 = SH + 5 cm	96	108	91	96.5
	A6 = PH + SH + 7 cm	136	150	125	135
	B1 = TRL-GAL+UALsin42^0 + GFALsin(85^0)	65–80.5	56–64	52–60	59–71
	B2 = ELH + UAL(1-cos42^0) + GFALcos(85^0)	31	35	28	30
	B3 = TT + 2 cm	19.68	21.5	20.5	20.5
	B4 = BKL + 5 cm	70	72	70	75
	B5 = BPL-PHcos119^0	62.5–74.5	75–86	82–92	64–76
	B6 = TRL	65–87.5	82–91	84–95	72–84
	B7 = SEH-(B9–HL)tan15^0	41	50	48	49
	B8 = SEH + (B10– HL)tan15^0	93.5	96	85	86
Gunner workspace	A1 = PH + 2 cm	36.3	41	27.5	46
	A2 = 1.1HB	46	46	38	42
	A3 = BPL-5cm	37	44	36	38
	A4 = 0.8AH	39.6	55	40	45
	A5 = SH + 5 cm	96	99	92	96
	A6 = PH + SH + 7 cm	136	150	130	135
	C1 = TRL - GAL + UALsin32^0 + FAL – AL + GAL	61	NA	64.5	63
	C2 = ELH + UAL(1 - cos32^0)	19.66	NA	31	29
	C3 = SHE	63.5–80	NA	68	74.5
	C4 = EH	141–171	154	NA	NA
	C5 = EEB + 25 cm	79.5	81	NA	NA

TABLE 6 (Continued)

Workspace type	Predicted design dimensions: Analytical relationship	Predicted design values	Existing workspace measurements: Veh-1	Veh-2	Veh-3
Commander workspace	A1 = PH + 2 cm	36.3	39	33	45
	A2 = 1.1HB	46	47	41	40.5
	A3 = BPL-5cm	37	48	41	42
	A4 = 0.8AH	39.6	60	45	50
	A5 = SH + 5 cm	96	108	92	96
	A6 = PH + SH + 7 cm	136	150	125	135
	D1 = SHE	63.5–80.2	NA	72	74

Note: All measurements are in cm unless specified.
Abbreviations: NA, not applicable.

percentile ranking method was employed to calculate the accommodation capacity (percentage match) of the army personnel in the existing vehicular workspace (for veh1, veh2, and veh3) using the match/mismatch decision rule (refer to Table 5). The percentile ranking method allows to set a reference (5th, 95th, or 5th to 95th p) and determine whether a dimension can accommodate 95% or 90% of the user population. All computations were performed using the Microsoft Excel spreadsheet software package (Microsoft Corporation, version 2016). The calculation involves three steps:

1. The data set of the respective functional anthropometry was set in decreasing order.
2. The percentile scale was determined by assigning the 0th p to the minimum value and 100th p to the maximum value.
3. Each dimension was assigned a percentile value based on their respective distribution (sorted in decreasing order) and compared with the match/mismatch decision rule.
   - The percentage match for the maximum size accommodation was determined as the number of data values below the relative percentile value of functional anthropometry to the measured value of the existing D_W.
   - The percentage match for the minimum size accommodation was determined as the number of data values above the relative percentile value of functional anthropometry to the measured value of the existing D_W.

For checking the compatibility of existing army vehicles with a wide range of army populations, several graphical comparisons were performed using OriginPro software (OriginLab Corporation, version 8).

3 | RESULTS

This section evaluates the dimensional compatibility between the existing and predicted workspace design dimensions of the LAVs. The anthropometric data of army personnel (250 males and 60 females) and workspace dimensions (of three LAVs) were collected for compatibility evaluation. Four (infantry troops, drivers, gunners, and commanders) seats/workspaces for each of the three existing vehicle models were evaluated in this study. The subsections also include the results related to match/mismatch verification and comparison of recommended vehicular dimensions with other globally accepted vehicular dimensions. Table 6 presents the predicted and existing workspace measurements of Veh-1, Veh-2, and Veh-3.

3.1 | Match and mismatch verification of existing dimensions

The match/mismatch dimensions are verified in this section. The existing and predicted workspace dimensions (D_W and D_P) are plotted graphically to visualize the match/mismatch between them (Figures 7–9). Out of the 39 workspace dimensions (of the 22 relevant dimensional variables), 16, 17, and 6 correspond to the design criteria of the 5th p, 95th p, and wide ranges of the 5th to 95th p values for the adjustable unit.

3.1.1 | Comparison of dimensions for reach and control units with 5th p predicted value

Reaching distance, control movements, and field of view (FOV) are restricted according to the body extensions (Verriest & Alonzo, 1986). These dimensions were evaluated using the one-way criterion of the maximum design limit (limited by lower extreme value or 5th p), as shown in Figure 7. The coordinate points drawn below the line of the 5th p predicted values are considered acceptable measurements; the remaining points need modifications.

Figure 7 shows that the majority of D_W values are greater than the 5th p predicted values, and therefore, not considered acceptable because of the difficulty in accommodating smaller body sizes. Particularly, the level of mismatch of dimensions in Veh-1 was higher than that in Veh-2 and 3. Only fewer vehicular dimensions were less than the 5th p values, viz. infantry troop and gunner seat dimensions (A1, A3, and A4) of Veh-2

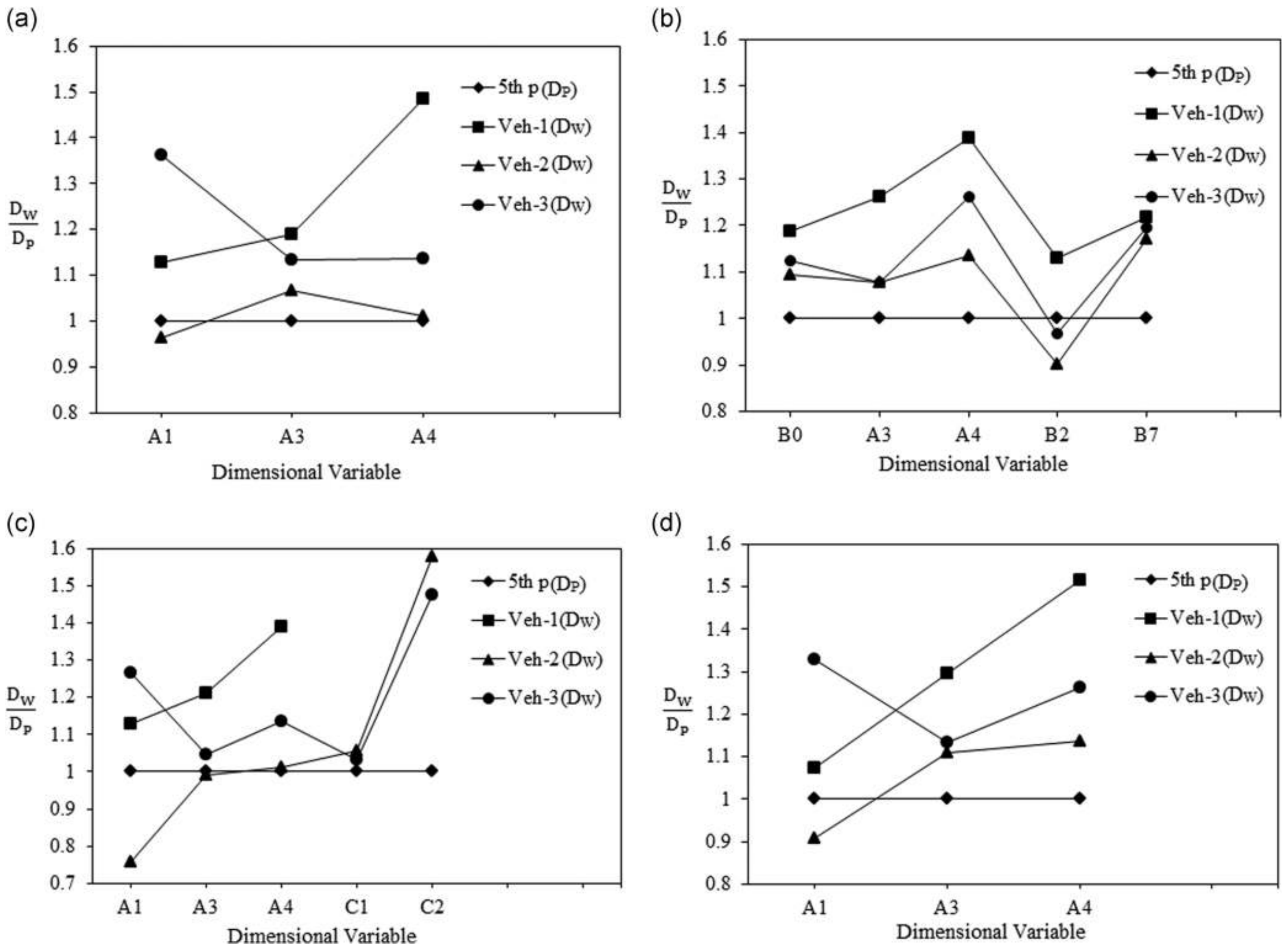


FIGURE 7 Comparison between the predicted vehicular workspace dimensions associated with the 5th percentile female anthropometry and dimensions of existing (a) crew seat (b) driver workspace (c) gunner workspace (d) commander workspace. *A1 = crew seat height other than driver seat height; A3 = seat depth; A4 = back rest height; B2 = steering wheel height; B7 = cowl point height; B0 = driver seat height; C1 = turret handle distance; C2 = turret handle height.* $D_W \leq D_P (D_W/D_P \leq 1)$ *is matched otherwise mismatched. Vehicle 1 has no gunner workspace dimensions in* 5th*percentile comparison*

and steering wheel height (B2 of Veh-2 and Veh-3). In contrast, the existing reachability, control units, and FOV controlling needs (D_W) of Veh-1 and Veh-3 do not accommodate the recommended body sizes.

3.1.2 | Comparison of dimensions for clearance units with 95th p predicted value

Dimensions such as manhole/hatch, head, and side room shall be based on a one-way criterion limited by the minimum design limit (limited by higher extreme value or 95th p) of the user body dimensions. Therefore, the coordinate points above the 95th p (reference line) of the anthropometric measurements (Figure 8) were considered acceptable; otherwise, modifications were required.

The dimensions of Veh-1, A7, B3, and B4 of Veh-2 and 3, and A5 of Veh-3 are found acceptable. All other vehicular dimensions are less than the 95th p design dimensions (larger body size) in each workspace, as shown in Figure 8, and therefore, considered unacceptable. In particular, the level of mismatch dimensions for accommodating the 95th p in Veh-2 and 3 is higher than that of Veh-1. The headroom height (A5) and roof height (A6) of Veh-2 are not adequate to enable sitting in a normal up straight posture. The daylight opening height is also less than the 95th p values in both Veh-2 and 3, and therefore, not compatible for army personnel with larger anthropometry.

3.1.3 | Comparison of dimensions for adjustable units with wide ranges of 5th to 95th p predicted value

Workspace dimensions such as seat height (for gunner and commander), pedal distance, steering wheel distance, or any equipment shall be adjusted using a two-way criterion limited by minimum and maximum design limits of workspace dimensions. To accommodate a wide range of user population, the maximum limit for an adjustable

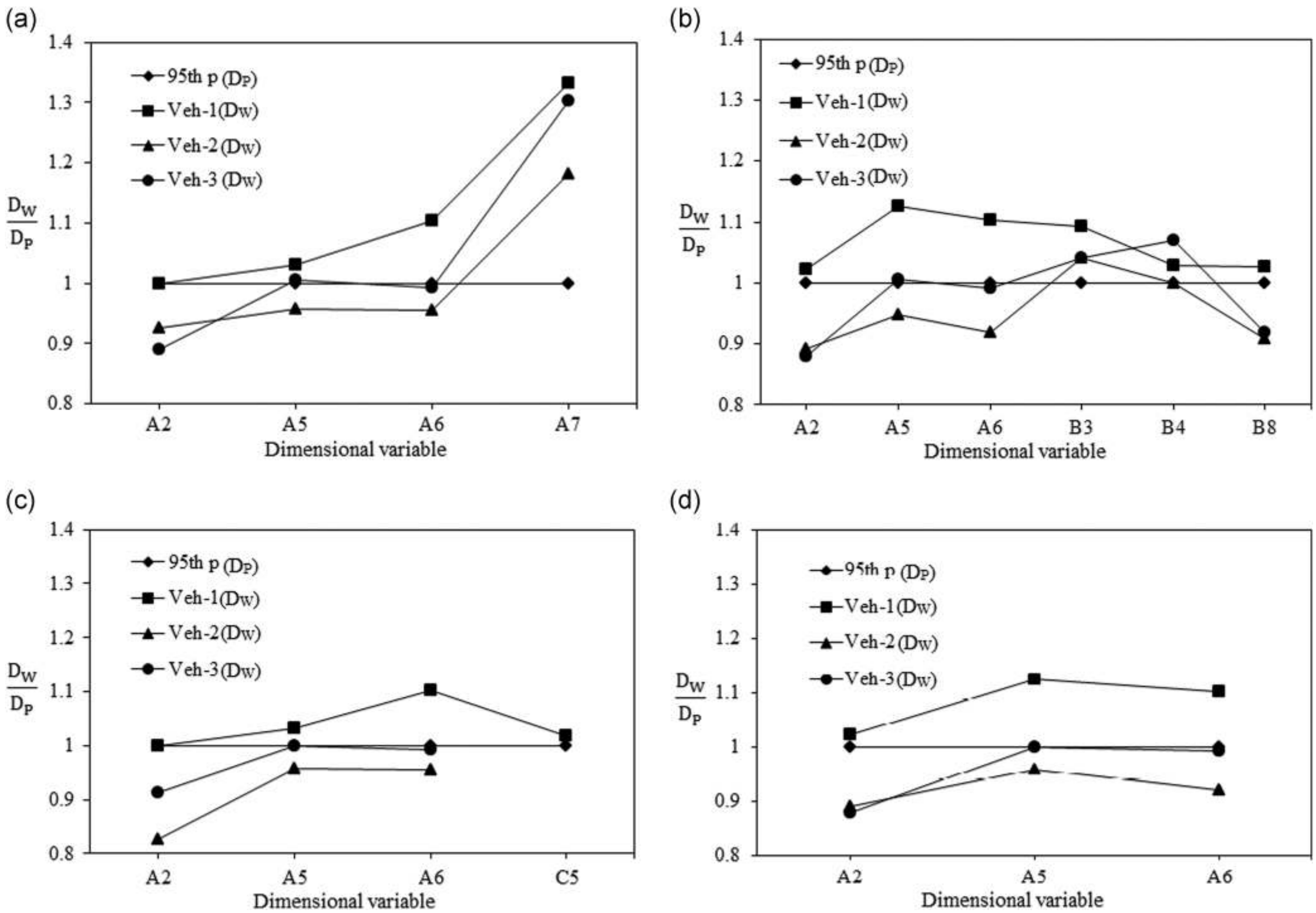


FIGURE 8 Comparison of the workspace clearance dimensions associated with 95thp values of the anthropometry for (a) crew seat (b) driver workspace (c) gunner workspace (d) commander workspace. A2 = seat width; A5 = headroom height; A6 = roof height; A7 = base width; B3 = steering wheel clearance; B4 = control dashboard clearance; B8 = Daylight opening height; C5 = top hatch diameter. $D_W \geq D_P(D_W/D_P \geq 1)$ *is matched otherwise mismatched. Vehicle 1 has only one gunner* workspace *dimensions in* 95^{th}*percentile comparison*

unit should be less than the 5th p value, and the minimum limit shall be greater than the 95th p value of anthropometric measurements (Dianat et al., 2013). If either of the two conditions are violated, the workspace measurements could not be accepted and need modification (Figure 9).

None of the existing vehicle workspace dimensions satisfied the condition of adjustment over the range 5th to 95thp (Figure 9). Presently, for C3, C4, and D1, there is no provision of adjustability to accommodate the wide ranges of the users during the gun firing, sighting, and driving tasks in the existing vehicles.

3.2 | Match percentage

Along with the accommodating capacity of the predicted design dimensions, the percentage match of the existing workspace dimensions (D_W and D_P) for the Ethiopian army (both male and female) in each of the three existing vehicles are presented in Table 7. In our study, we emphasize the boundary values (5th and 95th p) for predicting design dimensions to accommodate at least 90% of the army population.

As shown in Table 7, the percentage match for most D_W is substantially less and has a comparative discrepancy with the predicted anthropometric design values. It was unexpected that some workspace dimensions were also inappropriate for almost all army population, viz B5 on Veh-1 and 2, C2 on Veh-2 and 3, C3 on Veh-3, and commander seat height (A1) in Veh-3. Similarly, the variation in the percentage match between males and females is substantially high. Seat height (A1) of the crew for Veh-1, for example, could only accommodate 26% of the females while accommodating 82% of the males. As evident from Tables 6 and 7, Veh-1 is more suitable for users with large anthropometric dimensions, while Veh-2 and Veh-3 are more suitable for users with smaller body dimensions. Furthermore, the interior space dimensions (A6 and A7) for Veh-1 are too high when compared with the predicted dimensions and those of Veh-2 and Veh-3.

3.3 | Comparison of predicted design dimensions of driver workspace with other vehicular standards

Some of the newly predicted army vehicle dimensions for driver workspace obtained in this study were compared with other

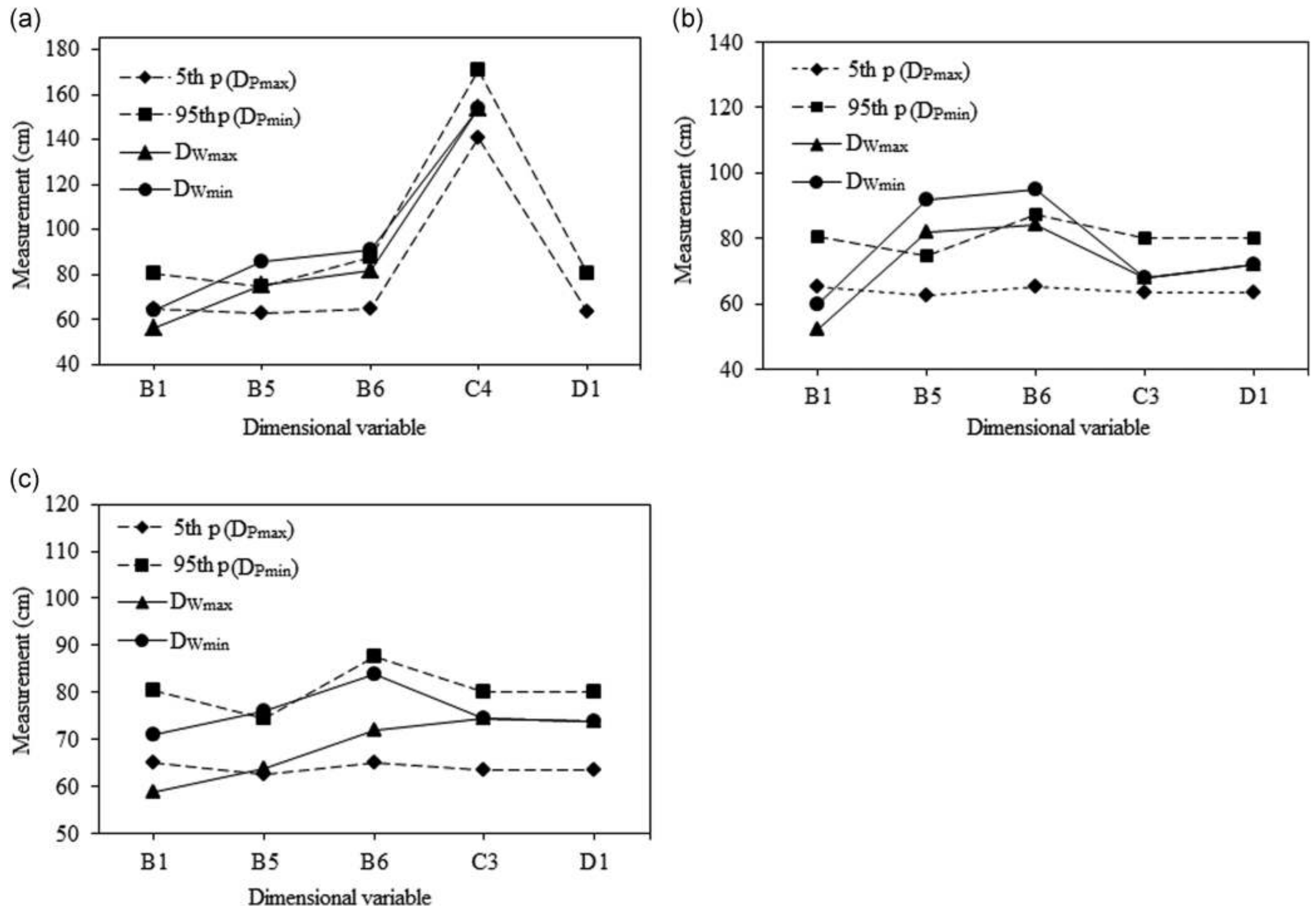


FIGURE 9 Comparison of the adjustment vehicular workspace dimensions associated with 5thp and 95thp values of anthropometric measurements in (a) Veh-1 (b) Veh-2 (c) Veh-3. B1 = steering wheel distance; B5 = pedal distance; B6 = control dashboard distance; C3 = height of sight device for seated gunner; C4 = height of sight device for stood gunner; D1 = height of sight device for commander. $D_{Wmax} \le D_{Pmax}$ and $D_{Wmin} \ge D_{Pmin}$ *is matched otherwise mismatched. Veh-2 and Veh-3 adopt firing in sitting posture whereas; Veh-1 adopts firing in standing posture. None of the existing vehicles have the provision of adjustability for dimensions C3, C4, and D1*

vehicular dimensions used in Dreyfuss standards (1967) and other popular four-wheeler brands, such as ISUZU, ASHOK LEYLAND, and TATA (Halder et al., 2017), as shown in Figure 10.

In Figure 10, most of the expected driver seat parameters, except for the backrest height (A4) and driver seat height (B0), can be traced somewhere between the other vehicle dimensional standards. The user parameters targeted (for ISUZU, ASHOK LEYLAND, and TATA) by Halder et al. (2017), found that the backrest height was relatively higher than the Ethiopian army personnel (in the present study). Perhaps this could be a possible reason for the discrepancy in the A4 dimension. Moreover, Halder et al. (2017) proposed a new backrest height dimension of 40.3 cm. Our predicted design dimension (A4) was 39.6 cm, which is in line with the dimension proposed by Halder et al. (2017). Similarly, we have considered 5th p female anthropometry for designing the minimum size of driver seat height (B0), while Halder et al. (2017) used 5th p male anthropometry. Nevertheless, Porter and Gyi (1998) recommended vehicular seat height between 28.3 and 33.5 cm. Our predicted design dimension (B0) was 32 cm, in line with the recommended size.

4 | DISCUSSION

This study presents the match/mismatch of the existing workspace dimensions for the three Ethiopian LAVs (Veh-1, Veh-2, and Veh-3). The results revealed that the majority of physical dimensions were mismatched when compared with predicted dimensions (targeting the Ethiopian armed personnel). In Veh-1, most of the dimensional mismatch was found with smaller user anthropometry, while the dimensions in Veh-2 and Veh-3 were mismatched for larger user anthropometry. Since mismatched workspaces are directly linked to the prevalence of WMSDs and reduced operational efficiency among users (Belmont et al., 2016; Punchihewa & Gyi, 2016), further longitudinal work is needed to explore the ergonomic design of LAVs. For instance, when the seat height (A1 and B0) is too high, shorter people will find it difficult to touch their feet on the floor; hence, they may try sliding forward to gain stability and perceive discomfort due to stretching of the lower limbs (De Looze et al., 2003).

The vehicle driver should be comfortable while performing driving tasks, and should not be subjected to driving fatigue due to prolonged static muscular tension (Tan et al., 2008). Unlike taller drivers, the shorter drivers have problems with reaching controls, and obstruction of FOV (Gilad & Byran, 2015). Moreover, a lower vision angle (below the horizontal line of sight) may result in neck extension and obstructed vision of the front road (Fostervold et al., 2006). The FOV can also be obstructed when the cowl point height is too high. This study found that the cowl point height (B7) was higher than the predicted value in all three vehicles (Veh-1, Veh-2, and Veh-3), thus leading to unsafe driving. Parkinson et al. (2007) correctly pointed out that for drivers with eye locations lower or more rearward, ground visibility can be restricted by the cowl point. Moreover, the ground visibility among the shorter drivers may also be restricted by the front hood. These problems can be reduced by correcting the

TABLE 7 Percentage of match estimation for the individual dimensions of existing vehicular workspace measurements in comparison with predicted dimensions

		Percentage of match						
			Existing vehicular dimension					
	Workspace	Accommodation of predicted	Veh-1		Veh-2		Veh-3	
Workspace type	Dimensions	dimension (%)	Female (%)	Male (%)	Female (%)	Male (%)	Female (%)	Malev
Infantry troop seat	A1	95	26	82.5	100	100	0	1
	A2	95	98	96.5	20	5.5	70	62
	A3	95	10	44	90	98	50	70.5
	A4	95	4	55	97	100	45	94.5
	A5	95	100	100	100	92	100	100
	A6	95	100	10	100	86	100	98
	A7	95	100	100	100	100	100	100
Driver workspace	B0	95	0	45	41	93	26	85
	A2	95	98	96.5	20	5.5	70	62
	A3	95	10	44	90	98	50	70.5
	A4	95	4	55	97	100	45	94.5
	A5	95	100	100	100	93	100	100
	A6	95	100	100	100	72	100	98
	B1	90	53	63	97	22.5	6	84
	B2	95	4	41	28	93.5	13	80
	B3	95	100	99.5	98	96	98	96
	B4	95	100	98.5	100	95	100	100
	B5	90	0	3	0	0	88	96
	B6	95		41	0	26	12	74
	B7	95	10	70	15	86	10	76
	B8	95	100	98	56	34	67	43
Gunner workspace	A1	95	26	82.5	100	100	0	1
	A2	95	98	96.5	20	5.5	70	62
	A3	95	10	44	90	98	50	70.5
	A4	95	4	55	97	100	45	94.5
	A5	95	100	100	100	94	100	100
	A6	95	100	100	100	86	100	98
	C1	95	NA	NA	53	98.5	9.5	100
	C2	95	NA	NA	0	1	0	5
	C3	90	NA	NA	9	4	0	4
	C4	90	6	4.4	NA	NA	NA	NA
	C5	95	100	98	NA	NA	NA	NA

(Continues)

TABLE 7 (Continued)

Workspace type	Workspace Dimensions	Percentage of match: Accommodation of predicted dimension (%)	Existing vehicular dimension: Veh-1 Female (%)	Veh-1 Male (%)	Veh-2 Female (%)	Veh-2 Male (%)	Veh-3 Female (%)	Veh-3 Malev
Commander workspace	A1	95	26	82.5	100	100	0	1
	A2	95	98	96.5	20	5.5	70	62
	A3	95	10	44	90	98	50	70.5
	A4	95	4	55	97	100	45	94.5
	A5	95	100	100	100	94	100	100
	A6	95	100	100	100	72	100	98
	D1	90	NA	NA	12	13	18	22

Note: Accommodation capacity of individual dimension for adjustable and non-adjustable unit was considered to be 90% and 95% respectively regardless of anthropometric diversity considerations.

Abbreviation: NA, not applicable.

position of the design eye reference point with respect to the cowl point and front top hood. It can maximize the FOV and minimize discomfort due to neck extension (Parkinson et al., 2007).

Similarly, a taller driver may face the obstruction to the FOV above the horizontal line of sight (Broniecki et al., 2010). Veh-2 and Veh-3 revealed a noticeable mismatch in the daylight opening height (B8) dimension for the 95th percentile values, not complying with the larger user anthropometry. One report (Tank archive, 2017) suggested that the adequate headroom height (A5) of the tank for a sitting crewman should be approximately 97 cm, which is fairly similar to our predicted value (96 cm). However, the headroom height of the existing Veh-2 is 92 cm resulting in trunk flexion during the normal sitting posture. The height adjustability of the sighting device at the eye level is also important (Bhattacharjya & Kakoty, 2020); otherwise, the gunner or commander might face excessive body flexion or extension that may lead to MSDs (MoD Std 00-25-17, 2004). Fixed-eye-point design is quite important for the sighting and control units (Hogberg, 2009; Vogt et al., 2005). Overall, the sighting system and controlling units should be compatible with the anthropometric range of specified users (5th to 95th p) (Wibneh et al., 2020).

The percentage matches for most workspace dimensions are below 75% (Table 7). Few workspace dimensions (B5 on Veh-1 and Veh-2, C2 on Veh-2 and Veh-3, C3, and A1 on Veh-3) were observed as inappropriate for almost all anthropometric dimensions of the army population. Fernandez (1995) recommended that while designing a particular workspace, the task demands should ideally be accommodating at least 75% to 95% of the user population. However, based on the predictive equations, it seems necessary to propose a new ergonomically designed workspace to accommodate 90–95% of the Ethiopian army.

The present workspace dimensions in Veh-1 and Veh-3 showed a substantially high mismatch to accommodate females as compared with the male army population (Table 7). Because the biological and anthropometric characteristics of females are quite distinct from

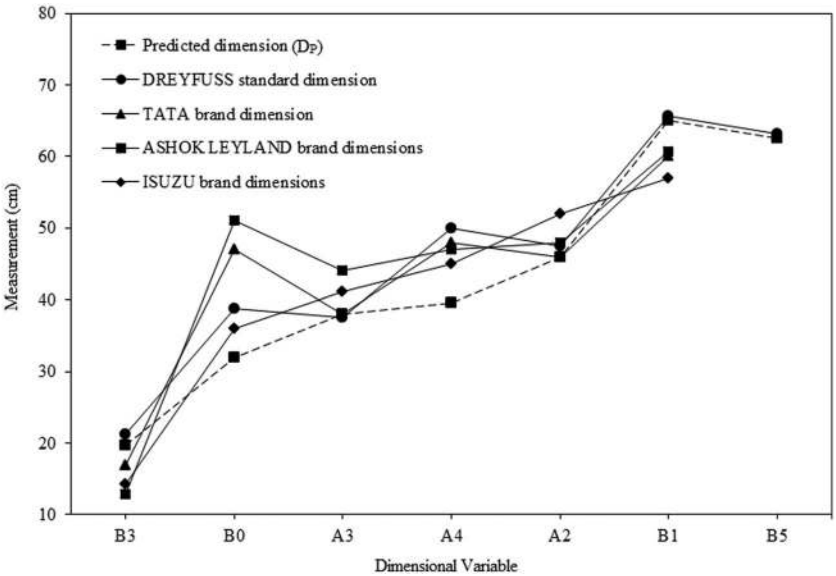


FIGURE 10 Comparison of the predicted driver workspace design dimensions with other various brands. *B3 = steering wheel clearance; B0 = driver seat height; A3 = seat depth; B1 = steering wheel distance; A4 = back rest height; A2 = seat width; B4 = control dashboard clearance*

males (Rudan et al., 1986), ergonomists should always consider gender while designing workspaces. Rima and Karen (2012) also pointed out that understanding gender diversity can lead to successful interventions to ensure better health for all workers.

In general, the reason for the high workspace variation among the LAVs could be the difference in workspace configurations by different manufacturers, without considering Ethiopian anthropometry (Beshah et al., 2014; Qutubuddin et al., 2012). However, if the anthropometric data are considered while designing the vehicular interior, the workspace dimensions closely match each other, even for different models of LAVs (Yadav et al., 2017). Therefore, we propose redesigning the vehicles based on the Ethiopian body size to accommodate the army population adequately. The newly predicted army vehicle dimensions (Table 6) are considered compatible with user dimensions and verified by comparing the obtained driver workspace dimensions with globally accepted standards (Dreyfuss standards, 1967; Halder et al., 2017).

Although the anthropometric data were collected from specific (Ethiopian army personnel) users, the body ROM measurements were not performed due to time and budget constraints. Nevertheless, we have referred to standard data (comfort joint angle) available from previous literature. Kyung and Nussbaum (2009) correctly pointed out that specifying comfortable ROM is equally important for ergonomic design and evaluation of the vehicle workspace. Because no anthropometry or ROM database is currently available for the Ethiopian army population, we propose conducting larger surveys to develop a comprehensive database to facilitate the ergonomic design and evaluation of a vehicular workspace and other equipment. The objective evaluation was performed by measuring and comparing both anthropometry and vehicular dimensions. However, more reliable results can be achieved if further research is conducted based on subjective evaluation. The proposed design dimensions (empirical equations) in the present study can also be validated using virtual (digital human modeling) or physical ergonomic evaluation techniques to reduce the uncertainty of acceptance of design solutions.

Except for a few similar ergonomic studies to evaluate the driver workspace in trucks and tractors (Halder et al., 2017; Yadav et al., 2017), to the best of our literature search, there has been no other reported research for predicting design dimensions in LAVs. Therefore, the proposed baseline predictive models and design methods are the first of its kind that can help ergonomists and designers to understand the synthesis of anthropometric diversity and workspace dimensions in the ergonomic design of the LAVs.

In the present study, the ergonomic evaluation was performed by adopting two percentile values (5th percentile female and 95th percentile male) to compensate for anthropometric diversity. However, the workspace/product design can be influenced by the combined effect of diverse anthropometric variables (Roebuck et al., 1975). For instance, people with larger legs and shorter trunks may also affect the design ergonomics of the workplace. A multivariate statistical approach (multivariate graphical analysis or PCA) can also be employed to create principal components with high correlation. These principle components may accommodate larger variations of the targeted population while designing a workstation (Bertilsson et al., 2011; da Silva et al., 2020). Even though the fundamental design parameters are considered in this study, future studies can consider other parameters, such as seat headrest height, position of clutch and gear shift lever, design eye reference point, and FOV, related to the facility design of vehicle interiors for the overall ergonomic design of LAVs.

Overall, the effective design of vehicular workspaces should consider user anthropometry and ROMs (Hsiao, 2013). Since the anthropometry of the Ethiopian army varies significantly across geographic and ethnic affiliation (Wibneh et al., 2020), it has an ergonomic impact on the design of LAV workspaces. If the workspace cannot accommodate the overall army population, it can adversely affect the health and performance of soldiers (McDonald et al., 2016). Therefore, the workspaces should be designed to curtail static and dynamic muscular tension while performing a task (Ross, 2011). The higher mismatch in the accommodating capacity of existing vehicles indicates that the vehicular workspace dimension should be considered as a critical issue, and design modification should be carried out for LAVs.

5 | CONCLUSION

This paper examined the mismatch between the body dimensions of Ethiopian army personnel and the workspace dimensions of three existing Ethiopian LAV. It also describes an approach to formulate predictive equations for workspace design dimensions associated with the anthropometric and ROM variables of the users. This study is the first to propose an ergonomically constructed LAV interior workspace of LAV according to the anthropometric measurements of the army personnel. Furthermore, existing workspace dimensions were compared to the predicted design dimensions. The findings from the match/mismatch evaluation indicated that the accommodating capacity of most of the workspace dimensions was relatively less than the predicted design dimensions. The Ethiopian defense vehicle manufacturers should fabricate LAVs considering the comfort and safety of the soldiers. The measurement predicted from the present research could serve as a reference for designing the interior workspace of Ethiopian LAVs.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ANNEXURE I:

***The relevant workspace dimensions (refer** Tables 3 and 4**) with their corresponding descriptions:**

Seat height (A1)*:* It is the distance measured vertically from the foot resting surface to the midpoint of the front edge of the seat surface.

Seat width (A2)*:* It is the distance measured horizontally between the lateral edges of the seat

Seat depth (A3)*:* It is the horizontal distance measured from the seat reference point (SRP) to the front edge of the sitting surface of the seat.

Backrest height (A4)*:* It is the distance measured from SRP to the upper edge of the backrest

Headroom height (A5)*:* The vertical distance from SRP to the hull roof.

Roof height (A6): the vertical height from the base where the foot rests to the roof of the hull.

Base width (A7): It is the hull space width usually measured on the foot resting surface.

Distance from steering wheel (B1): It is the horizontal distance from a point where it is assumed that the scapula rests to the steering wheel center.

Height of steering wheel (B2): It is the distance measured vertically from SRP to the steering wheel center.

Steering wheel clearance (B3): the distance measured vertically from the top front edge of the seat to the lowest point on the steering wheel.

Control dashboard clearance (B4): It is the horizontal distance from SRP to the dashboard position along the knee.

Foot pedal distance (B5): It is the f horizontal distance in the case of horizontal adjustable seat from SRP and to the pedal position at which the heel resting usually called acceleration heel point.

Control dashboard distance (B6): is the distance from a point where it is assumed that the scapula rests to control dashboard.

Cowl point height (B7): is the vertical distance from seat reference point (SRP) to cowl point.

Daylight opening height (B8): is the vertical distance from SRP to daylight opening.

Cowl point distance (B9): is the horizontal distance from the head rest to cowl point.

Daylight opening distance (B10): is the horizontal distance from the head rest to daylight opening.

Driver seat height (B0): It is the vertical distance from acceleration heel point on the pedal to the midpoint of the top front edge of the seat.

Turret handle distance (C1)*:* It is the horizontal distance from the back of the seat, at a point where it is assumed that the scapula rests, to the turret handle.

Turret handle height (C2)*:* It is the vertical distance from SRP to the turret handle.

Height of sight vision device for seated gunner (C3)*:* It is the vertical distances from seat reference point to display of sight device.

Height of sight vision device for stood gunner (C4)*:* It is the vertical distances from standing platform (pedestal) to the sight device.

Top hatch diameter (C5)*:* The opening diameter at the top for hatch of the gunner during firing task.

Height of sight vision device for commander (D1)*:* It is the vertical distances from seat reference point to the sight device.

ANNEXURE II:

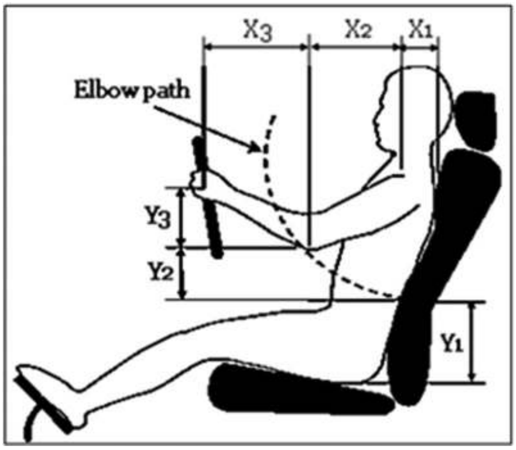

FIGURE A1 Segmentation of steering wheel position for driver workspace