STUDY ON ERGONOMIC AND CREW PROTECTIVE INTERVENTIONS ON LIGHT ARMOURED VEHICLES FOR ETHIOPIAN ARMY

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

by

Amare Wibneh Mengistu
(Roll no.166105010)

Department of Design
Indian Institute of Technology Guwahati
Guwahati-781039
INDIA

November 2022

Department of Design
Indian Institute of Technology Guwahati
Guwahati, Assam – 781039

CERTIFICATE

This is to certify that the work contained in this thesis entitled "**Study on Ergonomic and Crew Protective Interventions on Light Armoured Vehicles for Ethiopian Army**" has been carried out under my guidance and supervision and is a bonafide work of **Amare Wibneh Mengistu**. This work, submitted for the degree of Doctor of Philosophy, is original and contains no materials previously published or written by any other person for a degree or diploma at IIT Guwahati or any other institute or university. All the requirements, including mandatory coursework as per the rules and regulations mentioned in the Ph.D. ordinance for submitting the thesis for the Ph.D. degree of the Indian Institute of Technology Guwahati, have been fulfilled.

Date: November 16, 2022

Sougata Karmakar.

Prof. Sougata Karmakar, PhD
Professor
Department of Design
Indian Institute of Technology Guwahati
Guwahati- 781039, Assam, India.

Department of Design
Indian Institute of Technology Guwahati
Guwahati, Assam – 781039

DECLARATION

I hereby declare that the work contained in this thesis entitled "**Study on Ergonomic and Crew Protective Interventions on Light Armoured Vehicles for Ethiopian Army**" is carried out by me, a bonafide student of the Department of Design, Indian Institute of Technology Guwahati, Assam, India under the guidance of Prof. Sougata Karmakar at the Department of Design, Indian Institute of Technology Guwahati, Assam. This work is done for the award of Doctor of Philosophy. **It has not been submitted elsewhere for any other degree or diploma.** The work contained in this thesis is original and has been done by me under the guidance of my supervisor. I have followed the guidelines provided by the institute in preparing the thesis. I have confirmed the norms and guidelines given in the ethical codes of conduct of the institute.

Date: November 16, 2022

Amare Wibneh Mengistu
Roll No. 166105010
Department of Design
Indian Institute of Technology Guwahati
Guwahati- 781039, Assam, India.

Dedicated to My Wife "Mrs Genet Shimels", Next to GOD

Acknowledgment

I have begun by thanking the almighty God Jesus Christ for giving me the patience to finish this thesis (It would not have been possible without his help). I would like to express my sincere gratitude towards all those who have helped me directly and indirectly during the study of my Ph.D. work at IIT Guwahati.

I would like to acknowledge the Government of Ethiopia for providing me with financial support to conduct my Ph.D. work. I must also thank the Defence Engineering College of Ethiopia and Bishoftu Automotive and Locomotive Industry for their unwavering support during data collection and field assessment studies. I also thank the Government of India and the Indian Institute of Technology Guwahati for all sorts of infrastructural facilities.

First and foremost, I would like to express my sincere gratitude to my Doctoral Supervisor, Prof. Sougata Karmakar, for his valuable guidance, patience, and encouragement during the past few years of research work. I will always be grateful to him for his consistent motivation and insightful support. His extraordinary patience and guidance inspired me to carry out and complete this research work. Regardless of his workload, he always guides me to discuss every difficult phase for my Ph.D. work with moral support. I have learned a lot, and I shall always be grateful to him and respect for the same.

I want to express my deepest gratitude to my doctoral committee members Prof. A.K. Das, Department of Design, Prof. S.N. Joshi, Department of Mechanical Engineering, Dr. Swati Pal, Department of Design and Dr. Keyur Sorathia, Department of Design, IIT Guwahati, for their time, interest and insightful comments. They consistently gave me valuable suggestions that facilitated the progress of my research work. I am also grateful to the former and present heads of the current heads of the department of design. I would also like to take this opportunity to express my thanks to the viva-voce examination board members Prof. J. Kumar, Dr. Nelson Muthu and Dr. Santosh Jagtap for providing me their precious time for thesis and viva-voce examinations I am grateful to all the faculty members of the Department of Design, IIT Guwahati, for their unrelenting support during my studies. I would like to appreciate and sincerely thank all the participants for their understanding and co-operation while performing the experimental research. My sincere thanks to all faculty, staff, and students at the Department of Design for helping me stay at IIT Guwahati. I also acknowledge the help received from Dr. Ashish Singh, who was a post doctorial member in department of design, for his strong technical support for the thesis writing. He provided his research experiences without hesitation, and he had shown his modesty to support me tirelessly. I would like to pay my special thanks to Technical Assistants of Design Workshops and Laboratories for their direct support in material acquisitions, cutting, machining and welding during the construction period of the physical mock-up. I would also like to thank all the staff members of the workshop facility at the Department of Design, IIT Guwahati, for helping me and supporting me in creating a prototype of my product. My friends and colleague at Ergonomics Laboratory, Department of Design, IIT Guwahati, have contributed immensely to completing this thesis. My special thanks go to all my friends at IIT Guwahati; their advice and co-operation during this research have helped me become a better person and stay motivated.

I express my deep gratitude to my wife "Mrs Genet Shimelis" for immense support during my Ph.D. program. Her patience, goodwill, caring nature, and encouraging words kept me driving and helped me focusing on my work. I will be grateful to her for sharing every responsibility without my presence during the Ph.D. period. My kids and close family members also contribute to success in this research work through their prayers and encouraging words. Last but not least: I am thankful to all my family members and anyone related to this work up to any extent in due course of Time.

Amare Wibneh Mengistu
IIT Guwahati

Executive summary

Light armored vehicles (LAVs) are multi-purpose type of vehicles. It can be used for reconnaissance activities such as patrolling and scouting activities, transporting and carrying troops, ambulance service, small and large scale combating activities in various army wings, and conflict cessation in streets and institutions of urban or city. From the design perspective, LAVs require maneuverability, survivability, off-road efficiency, and compact size, maintaining the adequacy of the space and comfort. Researchers have conducted various studies regarding its maneuverability, survivability/crew protection, and firing power in a compact interior space of the vehicle. However, ergonomics aspects are often overlooked while space compactness and crew protective aspects are considered. Therefore, the current research aims to investigate the design intervention of the ergonomic and crew protective aspects without affecting the space occupancy and mobility of the Ethiopian LAV to enhance crew comfort and safety.

Based on the existing problem we fixed, various results and findings were established following different systematic approaches and procedures. The results of the comprehensive study come up with design procedures/ guidelines for Ethiopian army vehicles were presented as follows:

1. The anthropometric database of 32 variables that were collected from 250 males and 60 females of Ethiopian army personnel in terms of range mean, standard deviation, and percentile values (5th, 50th, and 95th) was documented for ergonomic design of vehicular workspaces and other facilities as there is anthropometric variations comparing with other nationalities such as USA, Korea and India and as there is no reported similar database for army personnel in the Ethiopian context.
2. As there was an ergonomic mismatch of the existing vehicular workspaces, new proposed design dimensions were determined based on the predictive mathematical models which were formulated as a function of ahtropometric dimensions and ROMs.
3. Due to the contradictory effects of the various desired constriants, an optimal design and anslysis of the vehicle hull were performed to achieve the maximum crew protection capability without affecting the hull weight and space adequacy.
4. Validating the compatibility of predicted workspace dimensions of LAV employing digital and physical mockup evaluations was the part of the study to ensure the accuracy of the

predicted design dimensions that comply with ergonomic principles early in the design of new LAVs.

5. Apart from physical mockup testing, identification of key anthropometric variables (the minimum data set) that represents the rest of required large variables for a PMU testing of LAV with limited source of users for trial was done in the prior study as there is no sufficient human subjects for user trial in the institute where the physical mockup made.

The major methodological protocols that can provide visible contributions for researchers in the process of anthropometric survey consist of sample size calculation, anthropometric measurement tools, procedures and techniques, selection of the required anthropometric variables for design of army vehicles, reliability assessment of measurements to avoid errors occurred by measuring instruments and observer, and techniques for data analysis. The match/mismatch analysis of existing vehicular workspace dimensions compared to predicted design dimensions (determined by predictive equations) is considered the novel methodological contribution of its kind. Predictive equations formulated as a function of anthropometric variables and ROMs can be utilized as a design standard globally and nationally. Design intervention of ergonomic issues and crew protective aspects (such as dimensions of occupant space, hull obliquity, geometric factors, and mobility aspects) of the vehicle was considered to be design constraints to enhance crew protection without affecting space occupancy and mobility/mass so that it helps to provide as a methodological basis. Apart from digital human modeling, physical mock-up testing is also helpfull to use small sample sizes as needed to check the design intervention of both ergonomic and crew protective aspects.

Hence, the study's findings will be immensely useful to design a new or redesign an existing army vehicle to ensure better comfort and performance of the crew in working posture. Design of an obliqued hull of LAVs based on the anthropometric and ROM data for defining workspace design dimensions thereby the final proposed vehicle models would certainly reduce muscular discomfort and injury of the crew and troops from armor piercing rounds, and increase operating performances efficieny and safety of the crew during neutral posture sitting, firing, sighting and driving. Therefore, modernizing the defence vehicular technology by introducing scientifically proven better design concept according to the need of specific country is the global need.

Table of Content **Page No.**

Chapter 6: General Discussion and Conclusion 139

List of Figures

List of Tables

Nomenclature

List of abbreviations and acronym

AL	Arm length
AP	Armour piercing
APC	Armoured personnel carrier
BB	Bideltoid breadth
BKL	Buttock to knee length
BPL	Buttock to popliteal length
CV	Coefficient of variation
DHM	Digital human modeling
DMUs	Digital mock-ups
EEB	Elbow to elbow breadth
EH	Eye height
ELH	Elbow rest height
FL	Foot length
FOV	Field of view
GAL	Grip arm length
GFAL	Grip forearm length
HAV	Heavenly armoured vehicle
HB	Hip breadth
HHS	High hardness steel
HL	Hand length
LAV	Light armoured vehicle
M	Mass
MU	Mock-up
MUs	Mock-ups
PCFA	Principal component factors analysis
PL	Popliteal height
PMUs	Physical mock-ups
R	Coefficient of reliability

ROM	Range of motion
RQ	Research question
S	Stature
SD	Standard deviation
SHE	Sitting eye height
SH	Sitting height
SRP	Seat reference point
T	Actual thickness of the hull plate
TEM	Technical error of measurement
TRL	Thumb tip reach length
TT	Thigh thickness
UAL	Upper arm length
Veh	Vehicle
VHS	Very high hardness steel
W1	Infantry troop/occupant seat workspace
W2	Gunner workspace
W3	Driver workspace
W4	Commander workspace
WMSDs	Work-related musculoskeletal disorders

Mathematical notations

B_i	Width of presented hull geometries, G1, G2, G3
E_i	Mass of presented geometries, G1, G2, G3
M_i	Mass of presented geometries, G1, G2, G3
R_{Ei}	The energy required for penetration of geometries, G1, G2, G3
R_i	Penetration resistance to mass ratio of geometries, G1, G2, G3
R_{Mi}	Mass ratio of oblique to non-oblique armor plate of geometries, G1, G2, G3
t_θ	Effective thickness of the hull plate
Θ	Oblique angle of obliqued hull

Dimensional notations

A1	Seat height
A2	Seat width
A3	Seat depth
A4	Backrest height
A5	Headroom height
A6	Roof height
A7	Base width
B0	Driver seat height
B1	Distance from steering wheel
B10	Daylight opening distance
B2	Height of steering wheel
B3	Steering wheel clearance
B4	Control dashboard clearance
B5	Foot pedal distance
B6	Control dashboard distance
B7	Cowl point height
B8	Daylight opening height
B9	Cowl point distance
C1	Turret handle distance
C2	Turret handle height
C3	Height of sight vision device for seated gunner
C4	Height of sight vision device for stood gunner
C5	Top hatch diameter
C-1	Headroom clearance
C-2	Foot room clearance
C-3	Thigh room clearance
C-4	Knee room clearance
C-5	Clearance of popliteal area
C-6	Lateral seat clearance

D1	Height of sight vision device for commander
D_P	Predicted design dimensions
D_{Pmax}	Maximum predicted design dimension
D_{Pmin}	Minimum predicted design dimension
D_W	Workspace dimensions
D_{Wmax}	Maximum workspace dimensions
D_{Wmin}	Minimum workspace dimensions

1

Introduction

1.1 Background/ Present Scenario

Carrying, scouting, patrolling, and small-scale combating missions in military operations are the main activities carried out by LAVs. Therefore, designing and developing a multi-purpose LAV (Maas, 2011) is a needful action with an intervention of crew protective/safety and ergonomic aspects at minimum attainable weight and cost to achieve successful accomplishments of targeted missions. However, the armoured vehicles most often lack valid human factor/ergonomic requirements that should be defined in man-machine interaction design (Greenley et al., 1999; Wibneh et al., 2021a). Madhu and Bhat (2011) also reported that ergonomic considerations are often ignored as protection capability in fighting vehicles is generally given importance. According to a report of Madhu and Bhat (2011), the major difficulty in applying ergonomic considerations is the unavailability of valid anthropomorphic data of the target user population (Wibneh et al., 2020 and 2021a).

The workspaces of the army vehicle shall be compatible with the user's body dimensions and range of motions (ROMs) to get seat comfort and operate activities inside the vehicle successfully during carrying, scouting, patrolling, and combating missions (Todd et al., 1999). Operating armoured vehicles without considering standard dimensions in a combat environment may adversely affect the crew's health and operating performance (Belmont et al., 2016; Biebuyck et al., 1990). Inside the armoured vehicles, the crew and driver seating, equipment positioning, interior workspace, and ventilation are the crucial factors that may indirectly or directly affect the crew's performance and health (Da Silva et al., 2002; Gillingham & Patel, 2013). Therefore, human factors are considered the most important in military system design (Chatterjee et al., 2019).

In the present era, user-centric design for specific users considering anthropometric and ROM variability is highly desirable (Castellucci et al., 2010; Halder et al., 2017; Yadav et al., 2017). However, the intervention of ergonomic and crew protective aspects (through consideration of users' anthropometry and the hull obliquity) in combat vehicles had been rarely found in the previous research literature. Hence, ergonomic interventions with protection capability must be implemented to accomplish successful combat missions.

To date, the Ethiopian army vehicles are also manufactured without due consideration for individual army personnel's safety, comfort, or performance (Wibneh et al., 2020). Thus, the army vehicles especially combat vehicles are ergonomically less compatible with the wide range of Ethiopian army population because of the unavailability of required standard anthropometric data (Odhuno-Otieno, 2016). Another reason is that designers/engineers are not well expertized in ergonomics concepts. Thus, they are not giving importance to human factors as they consider the importance of lethality and protection capabilities in their design. Therefore, there is an urgent need to consider human factors issues in terms of life protection, safety, operational ease, convenience, and comfort for better performance without affecting the mobility of the LAVs.

1.1.1 Overview of the LAVs in Ethiopia

Ethiopia has a significant role in in achieving solidarity between African Union (AU) and other countries in the continent by conducting peacekeeping operations and military assistance. It is the top African contributor in military logistics for AU peacekeeping and is positioned at 4th rank in UN peacekeeping contribution (Solomon, 2013). Therefore, in addition to its high demand for the internal affair, the country supplies different military logistics for peacekeeping missions. The supply of LAVs for UN peacekeeping missions is one of the prime logistics for carrying, scouting, patrolling, and combating missions.

LAVs, sometimes called armoured personnel carriers (APCs) are usually weaponized with small arms up to 14.5 mm armour piercing (AP) guns (Madhu & Bhat, 2011). In the Ethiopian defense scenario, the most common LAVs for the aforementioned special missions are FORD-550, BRDM-2 and WMZ-551 vehicles, and listed in Figure 1.1 names with veh-1, veh-2 and veh-3. Ethiopia was initially importing these vehicles from other countries (Russia and Israel), and are/were subjected to many flaws; these include the poor ergonomic design, occupying less numbers of crew, door/hatch way flaws, low level of crew protection and high fuel consumption (Samochód, 2011). These vehicles are currently produced through successive upgrades in the Ethiopian defence industry called Bishoftu Automotive and Locomotive Industry even though the occupational ergonomic flaws persist.

Figure 1. 1: Ethiopian FORD-550, BRDM-2 and WMZ-55 LAVs

Other previous research literature related to our study were reviewed to identify the research gaps that were not yet explored. The review includes: (a) standard anthropometric database assessment (b) ergonomic design of army vehicle (c) crew protection enhancement from projectiles and mine blast.

1.2 Preliminary investigation of existing vehicular workspaces

Preliminary investigation (observational study) on existing workspaces was presented to show the extent of mismatch of the workspace with the user populations. The anthropometric compatibility testing (in terms of space occupancy, dimensional clearances, reachability, view field, operational activities, etc.) of existing workspaces of the three different Ethiopian existing LAV (locally manufactured in Bishoftu Automotive and Locomotive Industry) was conducted with the different body (small, medium and large) sizes of users. Some illustrative photos of existing workspace for observational study were captured as shown in Figure 1.2, and the ergonomic flaws observed from existing workspaces were presented in Table 1.1. The majority of adopted postures show that the various body joint angles are ranged beyond comfort zones (Krist, 1994; Porter, 1998 and Tilley, 2002).

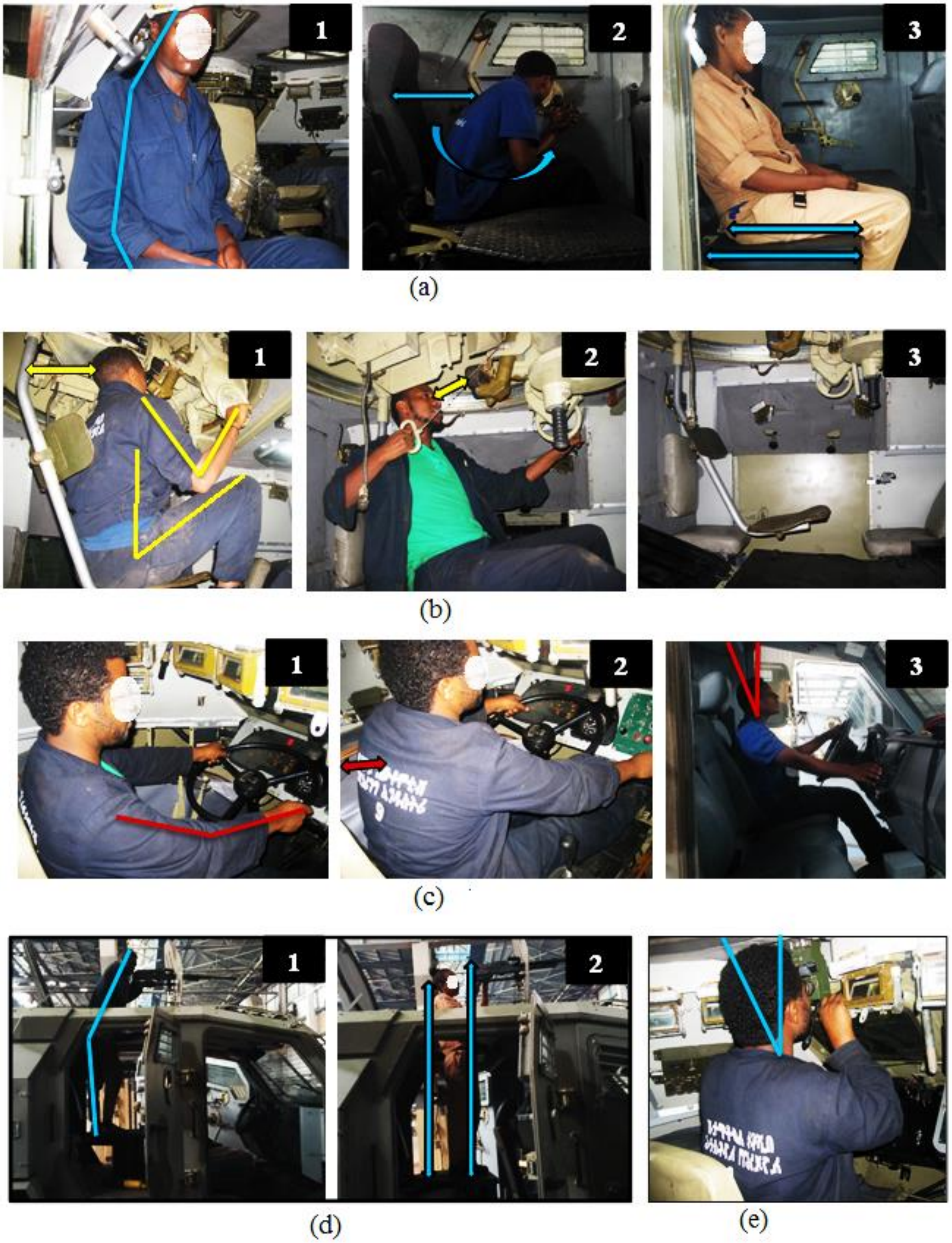

Figure 1. 2: Postures adopted in existing vehicles during a) troop/occupant sitting b) gunner firing activities in siting posture c) driving tasks along with manipulating tasks on control dashboard d) firing in standing posture by larger male and smaller gunners e) commander sighting task.

Table 1. 1: Observational results for preliminary study of anthropometric compatibility on existing workspaces referring to Figure 1.2 illustrations

Observational results of preliminary investigations (Figure 1.2)			
Workspace	**Design requirements**	**Observational results**	**Recommendations**
Squad sitting workspace	• The space shall be adequate for the user to sit with upright posture. • Requires proper seat position during firing in squad sitting posture. • The seat should have adequate clearance at popliteal area for the user to get a back support.	• Body flexion due to inadequate head room height • The improper seat position causes body twists and away from backrest support in firing posture • The smaller user cannot get back support because of inadequate clearance at the front seat for the popliteal.	• The head room height of the vehicle shall be provided with anthropometry of the larger users and adequate clearance • The seat shall be designed to accommodate the users during both traveling and firing. • The seat shall be provided with adequate clearance at its front edge.
Firing workspace for sitting posture	• Ergonomically fit with the target user population. • The turret handle shall be placed with a proper position with respect to the gunner seat.	• Firing workspace in sitting posture causes the thigh extension due to its too short seat height. • The seat design is poor and causes the seated gunner discomfort during the firing operation. • The position of the turret handle causes an elbow flexion while rotating the turret for aiming at the target. • The sight devices for aiming at the target are away from the headrest position.	• The seat shall be designed with having vertical adjustments to accommodate wide ranges of users. • The rotating handle height with respect to the seat and distance with respect to the point where the scapula rests shall be properly defined.

Firing workspace for standing posture	• The firing workspace shall be free from body awkward during operation.	• A tall gunner could experience high lumbar flexion while aiming. • The short gunner could not reach for the alignment and firing.	• The standing platform shall be adjustable as per users’ anthropometry to accommodate the wide ranges of users
Driving workspace	• The steering wheel position shall be comfortable for wide ranges of users. • The driver shall easily manipulate the control dashboard without get away from back rest • The front road shall be seen by the smaller driver adequately without obstruction and neck extension.	• The relative position of the seat with the steering wheel causes extension of the driver’s arm at shoulder and elbow joints during steering. • The reaching distance of the control dashboard for the existing vehicle is quite far from the point where the scapula rests, and thus, the driver tends to move forward and bend his body to reach into and operate the control dashboard. • Since the front compartment was too high, visual obstruction was found, and the deriver’s neck got extended to see the front .road	• The seat shall be adjustable horizontally to accommodate wide ranges of targeted users. • The reaching distance from seat point where the scapula rest to the controlled dashboard shall be defined by the smaller arm grip reach length. • The level of front compartment height shall be lowered adequately.
Commander workspace	• The sight device shall be placed/ mounted in proper position.	• As a result of exceeding height for the sighting device for FOV, the commander is forced to stretch his body and neck extension to reach into the sighting device	• The seat shall be adjustable with respect to the sight device as per users’ anthropometry to accommodate the wide ranges of users

1.3 Review of Literature

1.3.1 Standard anthropometric data

Primarily, anthropometric data of the targeted users is required for any human-centered facility design to consider ergonomic factors. Thus, previous literature reviewed the anthropometry of user populations in different countries, including Ethiopia, along with its worth and requirement for army vehicular workspace design.

1.3.1.1 Need for standard anthropometric data

Nowadays, the term “anthropometry” refers to the measurement of human body segments, ranges of motions (ROM), and strengths for bringing about human-centered design based on physical variations (Sutalaksana & Widyanti, 2016). Jeong & Park (1990) noted that anthropometric measurements are the basic requirements to predict the physical dimensions of facilities and workspaces to achieve the ergonomic compatible design. Thus, applying anthropometric data into user-specific products/workspaces design may improve users’ health and comfort (Barroso et al., 2005). Likewise, Xiao et al. (2005) noted that anthropometric data is required for designing ergonomically comfort and safe workspaces, equipment, and tools. Therefore, the requirement of anthropometric data of a targeted population of country/nation plays a vital role in product and workspace design. It is also considered an essential factor for studying physical variations of the population for health science and nutritional aspects. Developing such a database is common in many countries (Jafry & O'Neill, 2000; Karmegam et al., 2011; Mirmohammad et al., 2011). Especially in developed countries, using an anthropometric database is becoming routine in their human center design works. The objective is to provide a standard of accuracy for sizing and fitting so that designers would have a text of dimensions to construct product and workspace sizes (e.g., vehicular workspaces) with self-assurance (Odhuno-Otieno & Mehtre, 2016).

1.3.1.2 Ethiopian anthropometry

Apart from Ethiopia and the majority African countries, the anthropometric data for manipulating human-centered designs are widely used. In Ethiopia, the development and packaging of the anthropometric database have been given limited attention though Ethiopian anthropometric measurements are significantly varied as compared to other countries (Beshah et al., 2014). As it's desirable, the anthropometric data for the Ethiopian population is insufficient. Due to this, the dimensional mismatch of equipment and workspace that they utilize are predominant with their body dimensions. So far, attempts have been made to establish anthropometric data of a few body variables for Bahir Dar City's (Ethiopian City) adult men for clothing design purposes (Beshah et al., 2014). The anthropometric size chart established the 5th p, 50th p, and 95th p data of the adult men of Bahir Dar City for only making shirts and trousers. Since the study did not consider the majority of the population, the size chart only represents adult men of the Bahir Dar City of Ethiopia. The comparison test with European and US standards was also done. A significant variation was observed in its comparison result, and thus, a future study on Ethiopian anthropometric dimensions may be required.

The other hopeful attempts made so far are developing standard size charts for Ethiopian young men through the anthropometric survey in 09 different regions of Ethiopia. Similarly, the objective of the standard size charts is for clothing design of the young men having 18-26 ages only. Though large sets of variables are required in the measurement for facility design, the most required anthropometric variables were not included in the measurements to design other products and workspaces. Therefore, it can be generally said that Ethiopia still do not have its own sufficient standard anthropometric database at country level, except limited male anthropometric data for clothing designs at different age levels (Beshah et al., 2014 ; Odhuno-Otieno & Mehtre, 2016).

1.3.1.3 Anthropometry of army personnel in different countries, including Ethiopia

Nowadays, most armies produce their military clothes, weapons, and equipment according to the anthropometric characteristics of their soldiers (Brabec, 2005). Since the early 19th century, many anthropometric databases for the army population have been measured in different parts of the world. Countries like Sweden, USA, and Latin-American countries have their updated anthropometric database for their army by diversifying the effects of factors like age, gender, ethnics, geographical differences (Tomkinson, 2010; Gordon et al., 1972; Dobbins & Kindick, 1989) etc. Similarly, the development of anthropometric data for specific users of facility design in Asian countries is not new for the implementation in arm forces (Bharadwaj et al., 2014). These databases were used to design the ergonomic equipment, clothes, tools, and workspaces for the armed forces (Zachariah et al., 2001). But these previous literature studies for anthropometric data of different countries' armies might take only a few measurements or dimensions on small numbers of body variables. Therefore, such results are used only for a specific purpose of design. It is difficult to generalize to say the countries have all required standard anthropometric dimensions for their army.

Unlike other countries, the concept of ergonomics and its anthropometric database packaging in the Ethiopian defense sectors is not widely employed but is highly desired for the purpose of designing military products and workspaces. In short, attention is not yet given to developing the required standard anthropometric size chart. Thus, developing a standard anthropometric database to create ergonomically safe LAV is vital. Hence, it helps to check the compatibility of the LAV with the targeted users to achieve fitness of the vehicle from the Ethiopian army personnel context.

1.3.1.4 The required anthropometric variables for design of army vehicles

From more than 250 anthropometric variables, Chaillet et al. (1966) listed the required anthropometric variables for the interior design of army vehicle and these variables are listed in Table 1.2 and Figure 1.3. The listed variables are used depending on the design objective of LAV workspaces. The key dimensions which predict design dimensions for driver cabins simultaneously are sitting height, sitting eye height, thumb tip reach, sitting acromion height, buttock-knee length, and sitting knee height (Zehner et al. 1993). Other anthropometric dimensions that are also important for driver cabin accommodation are simply clearance dimensions and can be considered separately (Zehner et al. 1993). These clearance dimensions are deltoid breadth, sitting hip breath, buttock-popliteal length, popliteal height, thigh circumference, and foot length. Popliteal height measurement is very similar to knee height in standing measurement and can be taken from it. The buttock-popliteal length was estimated using a regression equation using the data survey of US Army 1988 (Gordon et al. 1989). Summary statistics for the 12 measurements are critical for the driver cabin.

Table 1. 2: Required anthropometric variables for army vehicle design (Source: Chaillet et al., 1966)

	Standing position			**Sitting position**	
No.	**A**	**B**	**C**	**D**	**E**
1	Stature	Nasal-root height	Chest breadth	Sitting height	Shoulder breadth
2	Eye height	Chest depth	Waist	Shoulder height	Elbow-to-elbow

			breadth		breadth
3	Ear height	Waist depth	Hip breadth	shoulder-elbow height	Hip breadth
4	Shoulder height	Buttock depth	Knuckle height	Waist height	Knee to knee Breadth
5	Nipple height	Crotch height	Wrist height	Thigh clearance height	The breadth of both feet
6	Knee cap height		Waist height	Buttock-knee height	Elbow rest height
7	Penile height		Elbow height	Back-of-knee height	Eye height
8	Substernal height		Cervical Height	Knee height	
9	Suprasternal height			Buttock- leg length	
10				Fore arm-hand length	

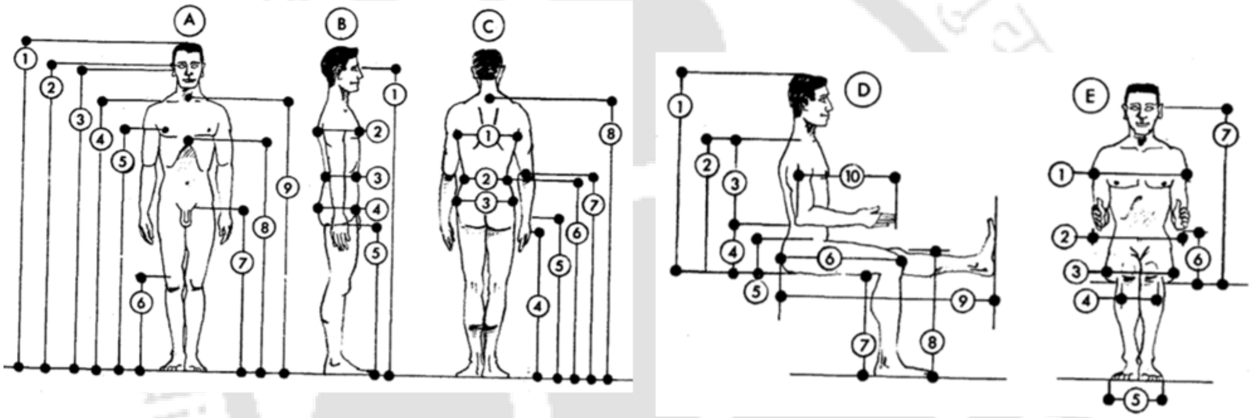

Figure 1. 3: Anthropometric measurement variables (Source: Chaillet et al., 1966)

1.3.1.5 Anthropometric measurement techniques

There are two main techniques of measuring anthropometric dimensions in data collection surveys. These two methods are hand or physical measurement techniques (direct measuring technique) and photogrammetric technique (indirect measuring technique) (Abdullah, 2011). Even though both the aforementioned techniques have their advantages, they also have their limitations in ease ability and validity. The direct measuring technique is a reliable and straightforward anthropometric method using measuring tapes and calipers It is still being utilized to measure the human body even though it is time-consuming and requires the physical presence of the compliant during recording all required measurement information.

1.3.2 Ergonomic design of vehicles in general

The large number of published articles found in the scientific literature for ergonomic design and development of different vehicles other than military vehicles. In the published literature, different vehicles like public transportation vehicles, tractors, ambulances, automobiles are suggested to be designed with consideration of complicated tasks and environment (Eyal et al., 2103). Various design constraints were considered in driver and passenger seat station like study of egress-ingress (Wang et al., 2013), reachability (Hanson et al., 2008), visual analysis (Godwin et al., 2008), spinal load analysis (Hamberg et al., 2008), head and lateral clearance (Woodson et al., 1992; Chakrabarti and Nag, 1996), comfort analysis (Porter and Gyi, 1998; Krist 1994), posture analysis (McAtamney and Corlett, 1993).

1.3.2.1 Ergonomic design of army vehicle: Global scenario

Lethality and mobility for army vehicles are generally important, but human factors are ignored in the current design process (Madhu and Bhat 2011). Most former researchers did not consider human engineering in the design aspects of the combat vehicle. The human body used to be utilized as a machine operating another machine (Sajjad, 2013). Therefore, current and future vehicle programs face significant challenges in providing adequate accommodation for soldiers while ensuring performance and safety. The army doctrine recognizes that operating in a continuous combat environment adversely affects soldier performance (Miller et al., 2011). The human body is also susceptible to the environments in which it is being employed. Crew and driver seat, positioning of a fire control system in the turret, positioning of sight devices and equipment, internal environment, vibrations due to off-road and mine explosion, noise, and other environmental factors in which the combat crew is working effects the performance and the health of the crew. According to a recent survey, 4.4 million people in the United States suffer from an ergonomics-related disease (Akbar et al., 2013).

In the case of army vehicles, there is limited published literature on ergonomics design and development of army vehicles considering anthropometric dimensions. Describing all aspects of state and human behavior in the use of any kind of military technology, for instance, human factors, have become a major aspect of interest and at the same time a study subject by itself, aimed at improving performance and reducing risks in different professional fields (Badea et al., 2014). Therefore, there is an urgent need to consider human factor issues in terms of operational ease, comfort, convenience, and safety for better vehicle performance. The safety and performance of military personnel depend, among other things, upon the fit of their protective equipment and workstations.

In the Ethiopia scenario, the ergonomics assessment of passenger seats of mini-buses was studied by Saba et al. (2013) through the subjective and objective evaluation method to check the compatibility of the seat for mini-buses with the user population. The authors stated that local manufacturers usually design or redesign the seats to suit the expectations of their customers without due consideration for the comfort and safety of the passengers. Saba et al. (2013) also noted that the question of the correct design of passenger seats with emphasis on comfort regarding the Ethiopian people arises because required anthropometric measurements are not available, and the local manufacturers assume that the manufacture of seats is an art rather than engineering.

In this particular topic, the ergonomic design for the Ethiopian army vehicle was not yet intended to design the vehicle matching with the Ethiopian army population. Among others, the unavailability of required standard anthropometric data is one of the causes for producing incompatible products and workstations for the targeted users. The reason is not only this in the defense industry; because designers/engineers are prioritizing for lethality and protection capability, but human factors are ignored in their design objectives. In general, considering an ergonomic design of crew workstations for the vehicle is too low compared to the developed countries.

1.3.2.2 General requirements of fighting vehicle workspace design

As it was stated on Defence Standard Specification of (Def Stan 00-25 PART 14/1, 2000) publication, the interior design requirements regarding body dimension and range of motion are body size, reach, posture, seating, clothing effects, and space envelops. It is essential to provide sufficient space for the different sized crew members. They will use the vehicle and equipment (i.e., the intended user population) and allow for their changes in posture or movement while carrying out tasks or simply riding in the vehicle. For these necessities, it is usually provided an adjustment in seats and some crew station components (Def Stan 00-25 PART 14/1, 2000).

The vehicular workspaces comprise firing, loading, infantry troop seat, driving, and commanding workspaces within the crew compartment. All have direct visual tasks, communication, and command links with others remote from their workplace; interactions with information on displays at their workplace, some form of controls to operate an egress/ingress comfort (Def Stan 00-25 PART 14/1, 2000). At his/her workplace, the crewman interfaces directly with the equipment around him and indirectly with other elements of the more extensive system he forms a part.

To reduce the prevalence of WMSDs and improve operational efficiency, the vehicle workspace shall be designed to consider wide ranges of target user accommodation. The accommodation, in this instance, is defined as the convenience of the user (military personnel) to get seated, see, reach, and actuate controls (Zehner 2000). Attempts to design vehicular workspace based on the user anthropometry can provide comfort, safety, and performance during any mission.

1.3.2.3 Human factor/ ergonomic evaluation

Evaluating human/machine compatibility from a traditional physical ergonomics perspective necessarily involves building actual physical mock-ups (PMUs) and subsequently trial with real human beings. Though it is typically more realistic, PMUs are time-consuming and expensive (Karmakar et al., 2012). Nowadays, computer-aided digital human modeling and simulation (DHM) technology using digital mock-ups (DMUs) has emerged as the state of art expertise for ergonomic evaluations at conceptualization stage before prototyping to save time and cost (Kumar et al., 2013). It is cost-effective and evaluates the user's posture before developing (PMUs) or prototypes. However, both DMUs and PMUs are needed to assess human factor/ergonomics and validate user requirements (Aromaa et al., 2014).

For virtual ergonomic evaluation of space occupancy, reach distance, posture, the field of view, and comfort/discomfort, the CAD models of humans called manikin and CAD model of vehicle or DMU are interfaced in appropriate positioning following various references points (H-point, design eye point, seat reference point, accelerator heel point, etc.) (Jung et al., 2009). The DHM requires the data of the users' anthropometry and ranges of motions (ROMs) to construct or create manikins. However, the fundamental difficulty in CAD manikins to accommodation evaluation is that occupant positions are affected both by anthropometric and postural variability

(Roebuck et al., 1975). Ergonomic design aspects of the army vehicles using virtual ergonomics evaluation were studied in a limited number of literature reviews to know the design model's compatibility with the users' population at the conceptual stage.

1.3.3 Crew protection of army vehicles

The level of protection for basic armour is designed to withstand at least 7.62 mm Ball and AP shots. The need to increase the protection level has led to add-on armour made from high hardness steel, very high hardness steel, ceramic, and other more effective types of armour materials that are more weight-efficient (Madhu and Balakrishna, 2011). Apart from selecting proper materials, Madhu and Balakrishna (2011) noted that the protection capability of the crew from the firing of projectiles and blasts is enhanced using passive (geometric forms/shapes), active and reactive protection technology. Active and reactive protection technologies are used more in heavy armoured vehicles (HAVs) and may also incur undesired characteristics in terms of weight and cost. For LAVs, passive protection technology is more favorable than the others because of undesired characteristics of weight and cost (Madhu and Balakrishna, 2011). Vivek.R.(2012) noted the four basic principles under which the new protection philosophy revolves. These basic principles are: (a) do not be get detected, (b) if detected, do not get hit, (c) if hit, do not get penetrated, (d) if penetrated, minimize injury.

In the words of Shergill (1997), today, casualties are a cause for alarm, and human life is taken as a very precious commodity. Though the weight factor is still in question for HAVs, various technologies are currently evaluated for external vehicle fire protection. Therefore, care should be taken not to have too thick an armor, as it will add unnecessary weight to the vehicle.

Towards enhancing the armoured protection, the commonly faced problem by the developers is the high/ enhanced weight and corresponding less mobility of the vehicle. When applied to a vehicle structure, Ahmad et al. (2012) said that sustainable product development requires a balanced approach towards technological, economic, and ecological aspects. Hence, mobility for LAV is generally given importance during designing. To enhance the hull's protection capability without affecting mobility, the research should achieve a high strength-to-weight ratio of the armoured shield.

Apart from the advancement in using different materials, the forms (geometric structures) can enhance the passive armour protection capability of the hull through an oblique angle of the plate. The obliqued armour plate has been proven to deflect away from the AP rounds' energy that comes from the horizontal direction and minimize the surface penetration as shown in Figure 1.4. In the research articles by Yap (2012), it was studied that instead of increasing thickness to resist the penetration of the armor plate, the sloping of armor can result in the simultaneous effects of increasing the effective thickness (in the horizontal) of the armor and deflection of AP projectiles and blasts. In addition to the increased effective thickness of the obliqued hull, the researcher reported that hitting a surface in any way other than head-on, a projectile is more likely to be deflected. It is increasing the sloping armor results in the loss of energy of the projectile to change its velocity in the direction of the armor's slope, thus resulting in an inability to penetrate the armor. Therefore, it needs further investigation about the direction of most projectiles to optimize the armoured material deflection angle and the thickness of the hull.

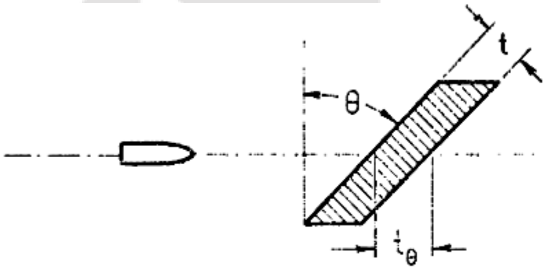

Figure 1. 4: Shows the effects of inclining armor on effective thickness (Source: Ogorkiewicz 1963, 83)

1.4 Research gaps

The following research gaps were observed from reviewing previous literature studies:

- Extensive scientific literature was published about ergonomic design and development of different vehicles, other than military vehicles. However, there is limited published literature on ergonomics design and development of army vehicles, considering the soldiers' anthropometric data (Chaillet and Honigfeld 1966, Hart et al. 1967, Karmegam et al. 2011).
- Anthropometric and biomechanical databases are available for countries with high-income, but in many instances, there is no such database for middle-income and low-income countries. Majority of the countries, especially developed countries, have their own updated anthropometric biomechanical databases for their user population to design matching equipment, clothing, tools, and workspaces. However, there is a limited number of published literature for the army population throughout the world.

- There is no anthropometric and biomechanical database for the Ethiopian army population. Thus, anthropometric and biomechanical database packaging in the Ethiopian defense sectors is not widely employed but is highly desired to design military facilities and workspaces.
- Various engineering design aspects related to blast protection and dynamic stability and crew protections are rarely reported for army vehicles (LAVs). The optimal critical design of the amour body considering crew protection, mobility, and ergonomic issues are rare even in developed countries, especially for LAV, and emerging the technique to enhance the protection capability of the hull without affecting comfort and mobility is limited. Therefore, LAVs are not secure enough in the case of the firing projectiles and mine or improvised explosive devices explosion.

1.5 Areas unexplored

Based on the literature review, the diagrammatic representation of the research gap has been prepared, as shown in Figure 1.5.

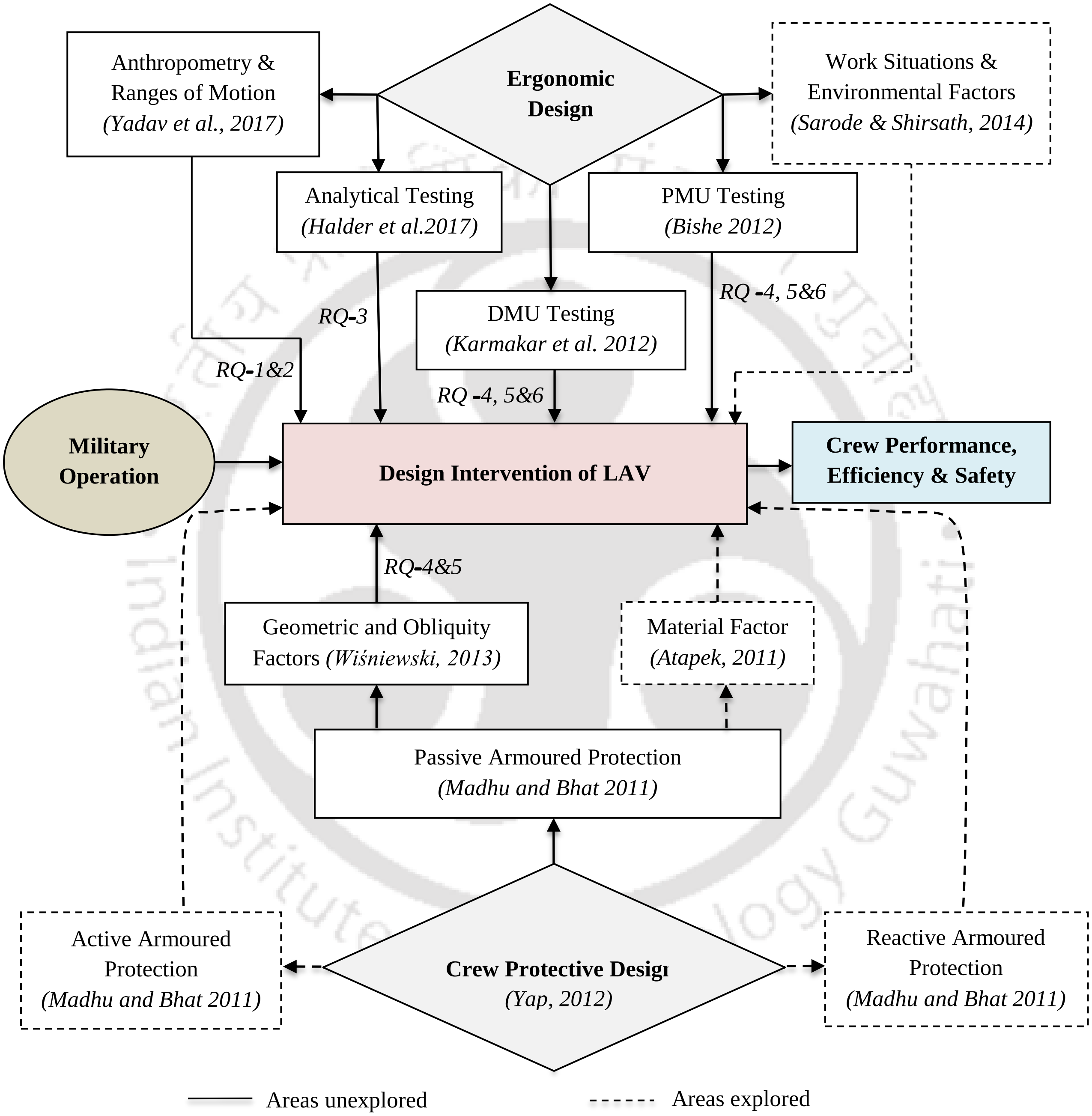

Figure 1. 5: Model of research gaps identification

1.6 Problem statement

Many of the existing LAVs used by Ethiopian army personnel are not sound in their crew safety and ergonomic design due to the ignorance of proper considerations of human and protection enhancement factors in hull designs. Operating armoured vehicles without considering standard dimensions in a combat environment may adversely affect the crew's health and operating performance (Belmont et al., 2016; Biebuyck et al., 1990). Greenley et al. (1999) reported that the weakness of applying ergonomic considerations is due to the unavailability of valid anthropomorphic data for the targeted user populations and other reasons. The unavailability of the Ethiopian army's anthropometric data also hinders conceptualizing and designing facilities for defense necessities. There is no users' anthropometric database, so developing an army vehicle for Ethiopian army personnel is a great challenge for the engineers/designers as users' physical capabilities and body dimensions vary widely. Hence, the anthropometric survey is required along with designing workspaces of LAV or equipment/ devices used by them.

Another most common problem faced by the developers to enhance the crew protection capability from gunfire is the incurred weight and the associated less mobility of the vehicle. Thus, there is an urgent need to consider human factors issues in terms of life protection, safety, operational ease, convenience and comfort for better performance without affecting mobility of the LCVs. Therefore, to enhance crew protective hull of the vehicle and ensure the compatibility of the workspaces with the targeted user population, there remains a need for the developing an anthropometric database for the Ethiopian army population following with ergonomically safe and crew protective LAV design.

1.7 Motivation and justification for choosing the present research

From its needful aspects, LAV can be used for reconnaissance activities, patrolling, scouting, forward command and control, urban and close-quarters operations, security, transporting/carrying, and used for small-scale combating activities in various army wings and missions. It can also be used for conflict cessation (with the minimum loss of human life and properties) that is usually taken place between security forces and protesters in streets and institutions of urban/city (Corps, 1998). The battle zones in defense scenarios have moved to complicated situations, including border incursion, terrorist attacks, and jungle warfare (Eliyas & Hima, 2014). Moreover, the requirements for LAVs in the future will be multi-purposive, mobile and adaptable, along with its protection and safety for the crew. To ensure such necessities, LAVs are required for the army forces to respond quickly to various incidents with effective maneuverability, survivability and combating. These unconventional situations also need the requirement of a compact, crew protective, and high-speed vehicle (Mans, 1982). The design requirements need to have off-road efficiency, compact size design without affecting adequacy of the space, comfort, etc. These supportive vehicles will need to be upgraded due to their increased multi-role capacity. Therefore, developing a LAV is a needful action with an intervention of crew protective/safety and ergonomic aspects to achieve adequate and comfortable workspaces for infantry troops/crew, maximum attainable crew protection, and minimum possible hull weight. However, as protection capability in fighting vehicles is generally essential, ergonomic issue is ignored because of the need for size compactness (Madhu and Bhat 2011). Thus, there is an urgent need to consider human factors issues in terms of life protection, safety, operational ease, convenience and comfort for better performance without affecting their mobility.

1.8 Research questions

From Figure 1.5, the following six research questions associated with the research gaps have been extracted:

RQ-1: Is the anthropometry of the Ethiopian soldiers significantly different from the anthropometry of some other countries as anthropometry is science of studying dimensions and it would remain same ($p < 0.05$)?

RQ-2: What key anthropometric variables represent the other required variables to simplify the design and analysis of the research?

RQ-3: Does Ethiopian army personnel body dimension significantly affect the ergonomic design of the Ethiopian army vehicle (accommodation capacity < 75%)?

RQ-4: Does crew protection enhancement due to hull obliquity contradict the ergonomic aspects (space occupancy) and weight of the LCVs?

RQ-5: To what extent the crew protection is improved to maintain a comfortable workspace at the lowest possible weight?

RQ-6: How much percentage of the Ethiopian army personnel can the army vehicle accommodate after an intervention has been made?

1.9 Hypothesis formulation

Hypothesis 1 (Q1, Q2, and Q3): Anthropometric difference of Ethiopian army personnel compared to other countries has a significant impact on dimensional compatibility of the army vehicular workspace that would be developed by following the standards of other countries.

Hypothesis 2 (Q4, Q5, and Q6): Proper design modifications with considerations of suitable workspace dimensions and appropriate hull obliquity would significantly increase crew protection and comfort without affecting space occupancy of the crew and mobility/weight of the vehicle.

1.10 Aim and objectives

The current research aims to investigate the design intervention of the ergonomic and crew protective aspects without affecting the space occupancy and mobility of the Ethiopian LAV to enhance crew comfort and safety.

The specific objectives to be conducted in the present research study were listed as follows:

- To develop an anthropometric database for Ethiopian army personnel for workspaces and equipment ergonomic design.
- To identify the most influential anthropometric variables representing the large sets of required variables for simplifying ergonomic design analysis of LAVs.
- To study the dimensional compatibility of LAV workspaces compared with Ethiopian army personnel's anthropometric characteristics.
- To investigate the influences of hull obliquity on crew protection, mobility, and ergonomic design of LAV using an optimal design approach.
- To evaluate an ergonomic design of the LAV workspace using DMUs and PMUs evaluation for validation purposes.

1.11 Expected outcomes

The outcomes come up with design guidelines for Ethiopian army vehicles with due consideration of ergonomics, and protection/safety are listed as below:

- Developing and packaging of anthropometric databases for Ethiopian army personnel.
- Reducing the numbers of anthropometric variables to be measured in an anthropometry survey that involves sample data of large number of variables.
- Ergonomic design guide line of Ethiopian army vehicle due consideration of Ethiopian anthropometric database.
- Providing design methods for anthropometric surveys and ergonomic evaluation packaging to reduce physical trial costs, time, and resources.
- Predicting the required design dimensions of LAV workspaces by their respective predictive equations (expressed as a function of anthropometric variables and ROMs.
- Establishment of design philosophy for the vehicle model at conceptual stage for the enhancement of crew protection capability along with ergonomic design considerations.

1.12 Research plan

In this research, initially, an anthropometric survey of Ethiopian army personnel was conducted for workspace designing of LAVs and related facilities from the perspective of Ethiopian soldiers. Following an anthropometric survey, workspace design dimensions were predicted from equation formulation (expressed as a function of anthropometric variables of Ethiopian soldiers and ROMs). The match/mismatch of the existing workspace dimensions of the vehicles in comparison to the predicted dimensions was carried out to check the compatibility of vehicle workspace dimensions with the users' body dimensions. Thereafter, an optimal design and analysis of different geometric hull structures was carried out considering various ergonomic and crew protective issues. Finally, the workspace compatibility of both DMUs and PMUs of LAV developed by the predicted design dimensions was validated by digital manikins and physical users. To check the compatibility of the workspace with the wide ranges of (5th to 95th percentiles) of targeted users (Ethiopian soldiers) would be considered. Figure 1.6 shows the overall flow of the study contents for an ergonomic and crew protective evaluation of LAVs.

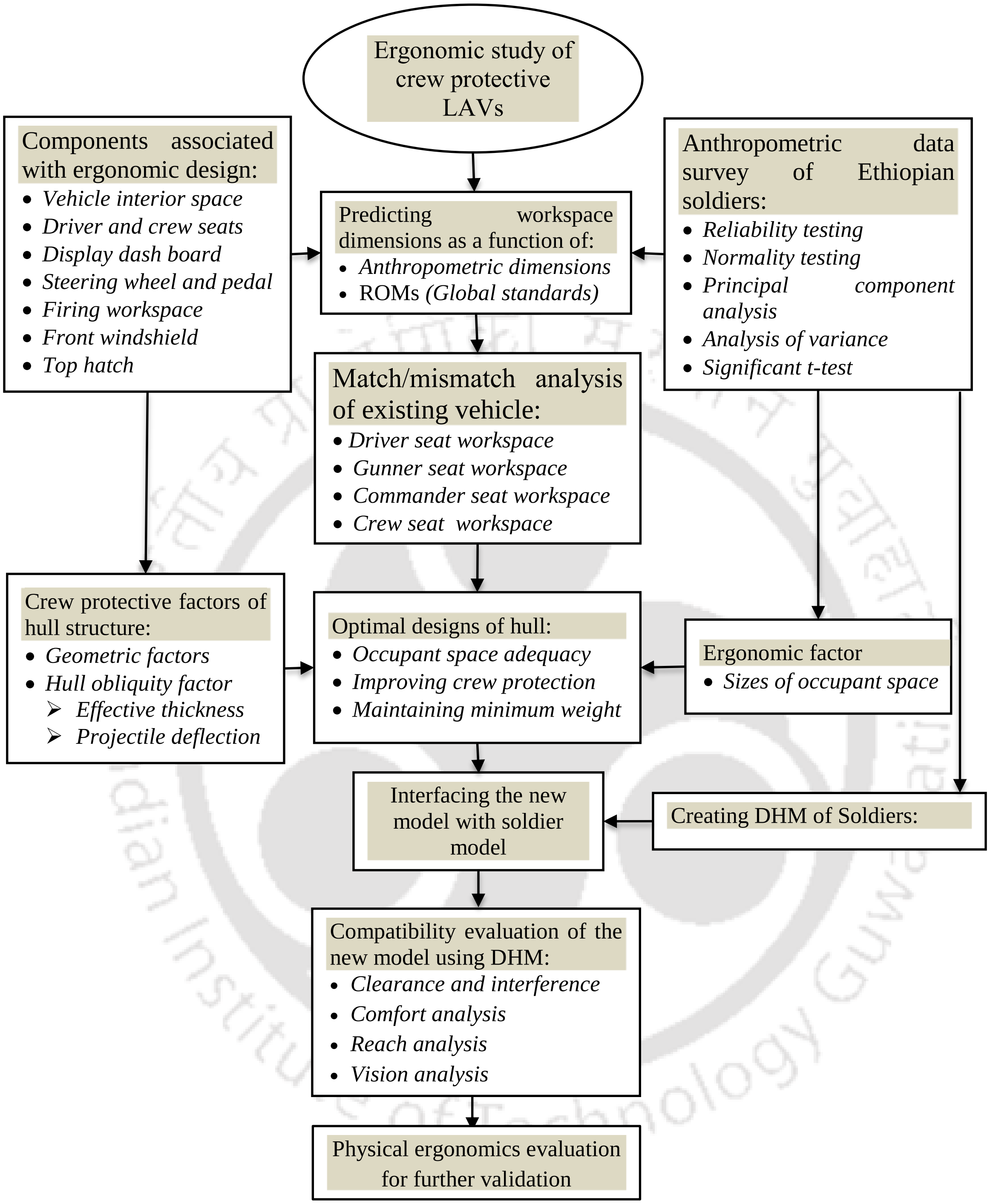

Figure 1. 6: Overall flow of the research

1.13 Framework of the thesis

Based on the study workflow, the thesis report is divided into six chapters. Figure 1.7 briefs about the thesis workflow. The research questions, objectives, and hypotheses addressed in the individual chapters, are summarized in Table 1.3. All the chapters are briefed in Subsection 1.14.

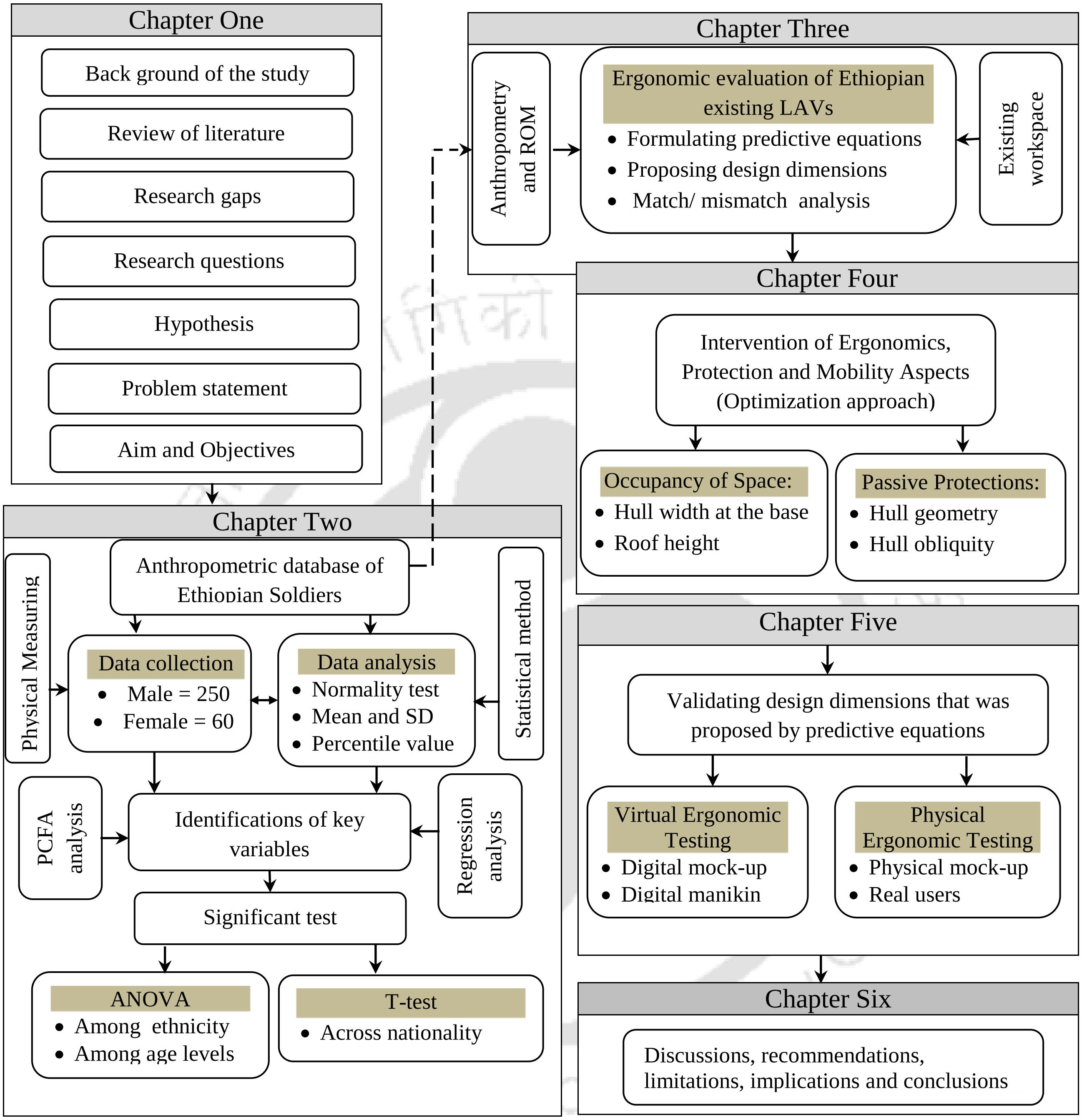

Figure 1. 7: Thesis workflow and content of various chapters

Table 1. 3: Research questions and objectives organized in various chapters and publications

Chapter	Research Questions	Objectives	Publications
2	**RQ-1:** Does the anthropometry of the Ethiopian soldiers is significantly different from the anthropometry of some other countries ($p < 0.05$)? **RQ-2:** What key anthropometric variables represent the other required variables to simplify the design and analysis of the research?	Objective 1: To develop an anthropometric database for Ethiopian army personnel for ergonomic design of workspaces and equipment. Objective 2: To identify the most influential anthropometric variables representing the large sets of required variables for simplifying ergonomic design analysis of LAVs.	Wibneh, A., Singh, A. K., & Karmakar, S. (2020). Anthropometric measurement and comparative analysis of Ethiopian army personnel across age, ethnicity, and nationality. *Defence Science Journal*, *70*(4), 383-396. [SCIE Indexed]. Wibneh, A., Singh, A. K., & Karmakar, S. (2021a). Research Design for Simplifying Anthropometric Data Collection Process Using PCA. In *International Conference on Research into Design* (pp. 71-82). Springer, Singapore.
3	**RQ-3:** Does Ethiopian army personnel body dimension significantly affect the ergonomic design of the Ethiopian army vehicle (accommodation capacity < 75%)?	Objective 3: To study the dimensional compatibility of LAV workspaces comparing with anthropometric characteristics of Ethiopian army personnel.	Wibneh, A., Singh, A. K., & Karmakar, S. (2021b). Understanding the synthesis of anthropometric diversity and workspace dimensions in ergonomic design of light armored vehicle. Hum. Factors Man. 31, 447–468. [SCI Indexed].
4	**RQ-4:** Does crew protection enhancement due to hull obliquity contradict the ergonomic aspects (space occupancy) and weight of the LCVs? **RQ-5:** To what extent does the crew protection improve to maintain a comfortable workspace at the lowest possible weight?	Objective 4: To investigate influences of hull obliquity on crew protective, mobility and ergonomic design of LAV using optimal design approach.	Wibneh, A., Singh, A., & Karmakar, S. (2021c). Effect of Hull Obliquity on Crew Protection, Mass and Space Occupancy of Light Armoured Vehicle. *Defence Science Journal*, *71*(5), 619-629. [Accepted. SCI Indexed]. Wibneh, A., & Karmakar, S. (2021). Evaluation of Crew Protection Performance and Ergonomic Design Aspects of a Light Combat Vehicle During Its Conceptualization Stage. In *Ergonomics for Improved Productivity* (pp. 547-553). Springer, Singapore.
5	**RQ-6:** How much percentage of the Ethiopian army personnel can the army vehicle accommodate after an intervention has been made?	Objective 5: To evaluate an ergonomic design of the LAV workspace using DMU and PMU evaluation for validation purposes.	Wibneh, A., Singh, A., & Karmakar, S. (2022, July). Strategy for Ergonomic Validation of a Physical Workstation Mock-Up Involving Limited User Trial. AHFE 2022 International Conference, New York, USA, July 24-28, 2022. [Accepted] Wibneh, A., & Karmakar, S. Validation for ergonomic design of light armoured vehicle employing digital and physical mock-ups. [Writing to be submitted].

1.14 Outlines of the thesis

A brief summary of the study divided into six chapters in the thesis is as follows:

Chapter 1 focuses on the present scenario of LAV and the need for studying LAVs in Ethiopia. It reviews the existing literature related to ergonomic design flaws of LAVs and summarizes the research gaps. It describes the need for design intervention for the Ethiopian army population's ergonomic and crew protective aspects of LAVs. The research questions, aim of the present research, objectives to achieve the aim, hypotheses, and framework of the thesis are also explored in this chapter.

Chapter 2 describes establishing an anthropometry database for Ethiopian army personnel and investigating the anthropometric variability with other countries to facilitate ergonomic design and development of various facilities (e.g., equipment/ devices and workspaces) for the Ethiopian army. The anthropometric data from 250 males and 60 females of Ethiopian army personnel (four different ethnic groups at various age levels) were collected. It also demonstrated how to reduce the numbers of variables using Principal Component Analysis (PCFA) to be measured in an anthropometry survey involving a large number of sample data. Total 12 key variables were identified from the 32 measured anthropometric variables.

Chapter 3 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 proposing design dimensions considering anthropometry and ROM of the target population to avoid possible incompatibility. 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. Twenty-two basic design dimensions that comply with ergonomics principles were proposed.

Chapter 4 presents the optimal design analysis of an obliqued hull structure to ensure comfortable occupancy of the crew at its minimum attainable weight and higher protection capability from the gunfire. Three geometric models (G1, G2, and G3) were investigated for the LAV hull's optimal design to identify the highest protection capability and comfortable occupancy for the targeted users without affecting the mobility of LAV.

Chapter 5 examines the compatibility of predicted workspace dimensions of LAV using digital human modeling (DHM) and physical evaluations. The purpose was to ensure the accuracy of the predicted design dimensions that comply with ergonomics principles early in the design of new LAVs.

Chapter 6 consists of discussions, limitations, conclusions, and conclusions. It discusses the novelties and contributions of this thesis. The fulfillment of objectives and testing of hypotheses were also depicted here. This chapter covers the recommendations and suggestions for the design interventions from the perspective of ergonomics and crew protections and presents limitations and the future scope of the study.

2

Anthropometric measurement of Ethiopian army personnel for ergonomic design and analysis of LAVs

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Abstract

The anthropometric characteristics of the users depend upon the topography, nutrition, age, ethnicity, gender, and living conditions and play a crucial role in the design of the equipment and the workspace to be used by them. This study aims to establish an anthropometry database for Ethiopian army personnel and investigate the anthropometric variability with other countries, to facilitate ergonomic design and development of various facilities (e.g., equipment/ devices, and vehicular workspaces) for the Ethiopian army. Following reliability assessment of physical measurement technique, the anthropometric data (32 anthropometric variables) from 310 (250 male and 60 female) Ethiopian army personnel (four different ethnic groups at various age levels) were collected and normality of the data set was tested for male army personnel. The anthropometric database of Ethiopian army personnel in terms of range, mean, standard deviation, percentile values (5th, 50th, and 95th) was documented. PCFA followed by regression analysis was applied to identify key anthropometric variables from the 32 for various applications. Hence, the 12 relevant anthropometric variables which account for those 32 measured variables were identified based on their component factor loadings, commonality values, and correlation coefficient of regression analysis. ANOVA and follow-up *posthoc* test (Tukey's HSD test) were also carried out to compare anthropometric differences of identified variables among different age

groups and ethnic variations. The mean anthropometric differences were compared with databases from other countries (India, Korea, and the USA) using a t-test. When the anthropometry was compared between age, ethnicity, and cross-nationals, significant variations were found. The findings indicate that variations in geographical factors could have a significant impact on the ergonomic design of equipment and vehicular workspaces of Ethiopian army personnel. The results of PCFA and regression analysis also depicted that there is a possibility to identify less number of key anthropometric variables that represent the overall anthropometric variability of the population for utilizing them in various applications.

Keywords: body dimension; physical measurement; ergonomic design; army workspace

2.1 Introduction

Anthropometry has been considered an essential factor for product design, hand tools, and the workplace to increase workers' comfort, efficiency, and safety (Sutalaksana and Widyanti, 2016). In the present era, user-centric design for specific users considering anthropometric and range of motion variability is highly desirable (Chatterjee et al., 2019). Many researchers (Brabec, 2005; Nowak, 1996; Vaidya et al., 2009) agreed that anthropometric measurements for the targeted user population play a vital role in designing ergonomic solutions.

In the present era, user-centric design for specific users considering anthropometric and range of motion (ROM) variability is highly desirable. Developing such an anthropometric database is relatively common in many other countries of the world (Jafry et al., 2000; Karmegam et al., 2011). Due to the diverse anthropometric characteristics, every country must build its anthropometric database. It helps resolve variations in body sizes that may occur due to different reasons such as topography, nutrition, ethnicity, gender, and living conditions (Da Silva et al., 2018).

Nowadays, most armies also produce their military clothes, weapons, and equipment according to the anthropometric characteristics of their soldiers (Tomkinson et al., 2010). Since the early 19th century, many anthropometric databases for the army population have been measured in different parts of the world. Countries like Sweden, the USA, and Latin-American countries have their updated anthropometric database for their army by diversifying the effects of factors like age, gender, ethnics, geographical differences (Brabec, 2005; Dobbins and Kindick, 1972; Gordon et al., 1989), etc. Similarly, the development of anthropometric data for specific users of facility design in Asian countries is not new for the implementation in arm forces[12-14]. These databases were used to design the ergonomic equipment, clothes, tools, and workspaces for the armed forces (Zachariah et al., 2001).

Based on the literature survey, it was found that extensive research on developing an anthropometric database and its applications for ergonomic designs of equipment/ products/ facilities for army personnel are general practices in developed countries. Still, the same has not got its due attention and importance in Ethiopia. The Ethiopian army employs more than 200,000 army personnel (Berhe, 2017); however, no anthropometric database is available to date. Miss-match between the size of the equipment and workspace to the Ethiopian army is merely common due to the unavailability of the anthropometric database. Unavailability of the anthropometric data for Ethiopian army personnel makes it impossible for ergonomic evaluation and, thereby, design modification of existing workspaces or equipment/ devices used by them. It is also true that the unavailability of anthropometric data of the Ethiopian army also hinders in conceptualizing and designing new workspace and devices of defense requirements. Therefore, there remains a need for developing an anthropometric database for the Ethiopian army population.

The effect of lifestyle, geographical factors, ethnicity, and social and economic environments may exhibit significant dissimilarity in body sizes (Yusof et al., 2019). The nutrition level/ living facilities provided to the soldiers of countries like America make their physique comparatively better than soldiers from other countries. Thus, generally, Westerns and Russian people have larger body sizes (Max et al., 2020; Skogberg et al.2018), whereas Asian people (including the army population) have a smaller body size (particularly in limb measurement) in comparison to Westerns due to geographical diversity (Yusof et al., 2019). Thus, it is essential to understand the difference in anthropometric data of Ethiopian army personnel with other national databases so that the design of products and workplaces used by soldiers can be improved.

The collected anthropometric data of Ethiopian army personnel can be predominantly used for the ergonomic design of workspaces and equipment of defense requirements of Ethiopia (Blanchonette and Alistair, 2012; Oudenhuijzen et al., 2008). The respective anthropometric measurements acquired from this study may help in designing the army vehicular workspace such as the crew seat (Halder et al., 2017), gunners, and commander workspaces (Tank archive, 2017) and driver workspace (Guan et al., 2012).

Designing any facility for the targeted user population requires many anthropometric variables (Sutalaksana and Widyanti, 2016). For developing the anthropometric database, data collection of many anthropometric dimensions becomes quite tedious, time-consuming, costly, and needs special support. Also, considering the large sample size while data collection is constrained by a lack of resources, manpower, and financial support. PCA is one of the widely used methods for the dimensional reduction process (Lu et al., 2007). In statistics, variable selection is the method of selecting a subset of predictors for dimensional reduction for straightforward interpretation and ease of researching by the researchers (James et al., 2013). Predictors from each component factor can represent/ predict the measurement of respective inter-correlated variables without conducting all measurements.

This study aims to develop an anthropometry database for Ethiopian army personnel intended to be predominantly used for army vehicular workspace design. We investigated the anthropometric variability across ethnicity, age, and other countries. It is envisaged that the developed database would help design and develop equipment, devices, vehicles, and any other facilities for the Ethiopian army. Moreover, designers/ engineers may refer to this anthropometric database for addressing the region-specific sizing of the equipment and workspaces. The anthropometric survey of Ethiopian army populations helps to address the research questions (RQ-1 and RQ-2).

RQ-1: Does anthropometry of the Ethiopian soldiers is significantly different from anthropometry of some other countries ($p < 0.05$)?

RQ-2: What key anthropometric variables represent the other required variables to simplify design and analysis research?

2.2 Methodology

This section consists of sample size calculation, anthropometric measurement procedures, required body variables, and data analysis techniques.

2.2.1 Participants and sample size determination

The target population for this study was the Ethiopian male army personnel. The participants were randomly selected from the ground forces and, distributions of their age and ethnicity were documented. A total of 250 male armed personnel participated in this study. The participants, aged between 18 and 52 years (mean = 30.86; SD = 6.7) were included. During the recruitment of soldiers to join the army, stature and mass were considered as the main selection criteria (minimum: 160cm and 50kg and maximum: 185 cm and 75 kg). Therefore, the collected anthropometric data of army personnel could not represent the general population, even though the soldiers were selected from the civilian population. Based on the proportion of army population distribution, the participants were selected to measure each ethnic and age group. Therefore, the samples were further divided into these four subgroups to investigate the variability of the anthropometric data among the ethnic groups. The majority of participants belong to Amhara (n=65), Tigray (n=63), Oromia (n=62), and South Region (n=60) of Ethiopia. The rest ethnic regions were not considered in the study due to less number of army populations representing their ethnicity during data collection. Apart from ethnicity, the participants were divided into three groups according to the categories of age (<30, 30–40, and >40 yrs) from the questionnaire. The numbers of participants belonging to age categories <30, 30–40, and >40 yrs were 108, 82, and 60.

The minimum sample required for a 95% confidence interval for the 5th and 95th percentile was estimated based on ISO 15535:2003 as discussed in Haitao et al. (2007), Rahman et al. (2018), and Shahida et al. (2015). The minimum required sample size was found to be 56, which is less than the sample size of individual age group or ethnicity. Furthermore, Freud and Perles (1999) and Hogg and Tanis (2001) have stated that the sample size of the mean larger than 30 can be assumed as normally distributed. This sample size has been calculated based on the following formula:

$$N \geq \frac{(3.006 * CV)^2}{\alpha^2}$$

Where,

N = sample size required; CV is the coefficient of variation (CV= 25); α is the percentage of relative accuracy desired (α = 10%) for a 95% confidence interval for the 5th and 95th percentiles.

2.2.2 Equipment used and measurement procedure

The GPM, Switzerland, made standard anthropometric set used by Hsiao et al. (2005) was used in addition to other instruments for anthropometric measurements. The particular standard anthropometric instruments used in this study were a vertical stand anthropometer (expandable to 2100 mm), sliding calipers (measuring range 0-250 mm and 0-600mm), spreading caliper (measuring range 0 - 3000 mm), a weighing scale (maximum capacity: 136kg; Model: Equinox BR-9201; Make: Indian) and a steel measuring tape (3000 mm). Adjustable stool for measuring in sitting posture was also used for adjusting the height according to the subjects' preferences[26].

Anthropometric measurements followed the previously published ISO standards, books, and literature protocol (Chakrabarti et al., 1997; Chandna et al., 2010; Hsiao et al., 2005; ISO 7250-1: 2008; Pheasant and Haslegrave, 2005; Roebuck, 1975). The identification of landmarks on body segments was the prior task during measurement. The measurement was taken from the subject with barefooted and light clothing. Participants were told to stand and sit in proper posture, looking forward without body flection, extension, and twisting during the measurement. All body dimensions were measured to the nearest 0.1cm precision (weight was measured to the nearest 0.1kg).

2.2.3 Ranges of the measured variables

Though an adequate description of the human body measurement may require over 300 dimensions (Pheasant and Haslegrave, 2005), the scope of this study was limited to measurement of 32 static anthropometric dimensions (including mass) for army equipment and workspace design as shown in Figure 2.1 based on the design objective of LAVs and literature (Chaillet et al. 1966) as stated in section 1.2.1.4. These typical anthropometric variables were adopted from the recommendations for the book of “Body Space for Design of Work” (MoD Std 00-25-17, 2004) and Defence standard of “Using Anthropometry in Designing for Enhanced Crew Performance” (Pheasant and Haslegrave, 2005) as discussed by Ross (2011). The respective descriptions of different body parts are also defined by Pheasant Haslegrave (2005) in his book.

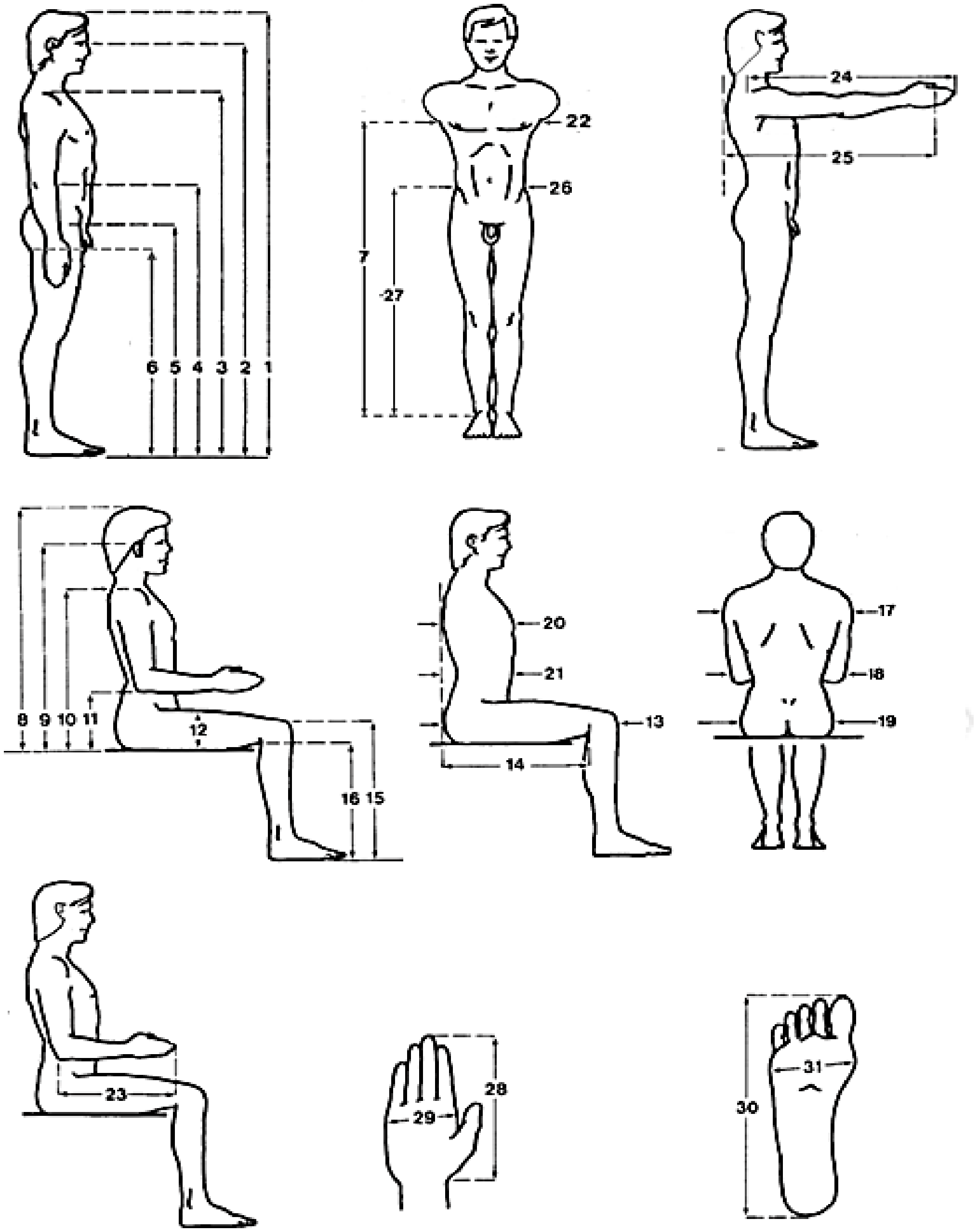

Figure 2. 1:|Anthropometric variables in standing and sitting posture *(Adapted from Pheasant, 2005)*

Note.

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

2.2.4 Reliability assessment

Before conducting the actual experiment, a pilot study was carried out in order to test the precision or reliability of the repeated anthropometric data collected by the inter-observers. Two different observers measured the same subjects from a sample of 20 volunteers (taking 13 body variable measurements from each volunteer). Using the Technical Error of Measurement (TEM), a reliability test was carried out. The coefficient of reliability (R) or precision was used to estimate the similarity of repeated measurements by two different observers to ensure the further collected data are supposed to be free from measurement error. The same approach was followed by Stomfai et al. (2011) to estimate the reliability of anthropometric measurements using these tools from 20 volunteers. Many researchers considered the value of $R > 95\%$ for error-free of their measurements (Ulijaszek and Kerr, 1999; WHO, 2006). In the present study, we have not included the data from the pilot experiment.

2.2.5 Statistical analysis

The anthropometric data (32 variables) representing Ethiopian army body dimensions were developed and statistically analyzed using IBM SPSS version 25 software with confidence levels set to 0.05 and 0.01. Following an anthropometric survey (32 variables) of Ethiopian army personnel (n =250 male), 12 key variables that account for the variability produced by the 32 original variables were identified using Principal Component Factor Analysis (PCFA) and followed by regression analysis (Jackson 1980; Lu et al. 2007). They were identified based on component factor loadings, commonality values, and correlation coefficient of regression analysis. Following clustering variables into closely related variables (higher-order category) using PCFA, the variable with the highest factor loading factor was identified as predictor/ most dominant variable in each component factor (Patel et al., 2016). Variables with less commonality and correlation coefficients (R) (less inter-correlation) were also included in a minimum data set with their respective predictors since they do not represented by any other variables. Principal components were categorized based on their eigenvalues greater than 1.0. The variables with a higher factor loading coefficient (> 60%) in each factor category along with commonality (>70%) were considered to be highly inter-correlated variables. Relevant body variables that had correlation coefficients (R) > 0.70 were also considered to be higher inter-correlated variables.

The linear regression models were constructed using the least square method. These models were used to predict the regression equation of relevant body variables that had correlation coefficients (R) > 0.70 (Patel et al., 2016). Based on the aforementioned percentage values, 06 most dominant variables, 02 variables with less commonality, 03 variables with less correlation coefficient from their respective predictors, and one targeted variable 'mass' (Lin et al., 2008) that account for the variability produced by the 32 original variables were identified and included in a minimum data set (Bermingham et al., 2015; Guyon and Elisseeff, 2003). Furthermore, the majority of dimensions that dominant variables could reliably represent were dropped from the list of key anthropometric dimensions.

Finally, the comparison of anthropometric difference among the different ages and ethnic groups were analyzed using ANOVA and follow-up *posthoc* tests (O'Connor et al., 2010). Considering all the 32 anthropometric dimensions (including less important physical dimensions) for analyzing and interpreting ANOVA posthoc multiple comparisons results is arduous and may be unnecessary. A comparison test of the present Ethiopian armed personnel anthropometry with other world countries was carried out using the two-sample t-test.

2.3 Results and discussion

This section mainly includes anthropometric data descriptive along with four investigation results, viz. reliability test of the measurement, and normality of anthropometric data descriptive, and lastly, the comparison of anthropometric data in variations of age, ethnics, and the country-wise population.

2.3.1 Reliability measurement

TEM, %TEM and R-values of the inter-observers for a pilot study of 20 volunteers (taking 13 body variable measurements from each volunteer) were presented in Table 2.1.

Table 2. 1: Reliability test for inter–observers measurement (n = 20).

	Inter-observers		
Body dimensions (cm)	**TEM (cm)***	**%TEM***	**R***
Bideltoid breadth	0.02	0.05	1.000
Elbow Rest Height	0.18	0.76	0.994
Forearm Length	0.48	1.01	0.976
Hand Length	0.27	1.34	0.951

Hand width	0.08	0.95	0.988
Popliteal Height	0.33	0.73	0.954
Popliteal Length	0.63	1.26	0.969
Buttock to Knee Length	0.49	0.80	0.973
Foot length	0.23	0.92	0.976
Sitting Hip Breadth	0.13	0.33	0.997
Thigh Thickness	0.10	0.59	0.995
Waist Breadth	0.49	1.59	0.960
Waist Depth	0.44	1.58	0.972

TEM is technical error of measurement; %TEM = relative technical error of measurement;
R = coefficient of reliability.
*Ulijaszek & Kerr (1999)

As evident from Table 2.1, TEM, %TEM and R values for inter observers' measurements ranged from 0.02–0.63, 0.05–1.59, and 0.951–1.000, respectively. All the anthropometric measurements are higher than 0.95 in reliability value or 95% error-free or accurate. Many researchers (Ulijaszek & Kerr, 1999; Nugent et al., 1991) agreed that the 0.95 of reliability is an adequate value to accept though there is no restriction to this value for acceptance or rejection. Since the reliability of our pilot study was greater than 95%, the physical measurement for the main survey (including more participants) would be expected trustworthy and accurate.

2.3.2 Anthropometric data and normality test

Table 2.2 shows the descriptive statistics of anthropometric measurements for Ethiopian soldiers. The measurements of anthropometric data collection were presented for both genders. The anthropometric database of Ethiopian soldiers for military workspace design was developed in terms of range, mean, standard deviation, percentile values (5th, 50th, and 95th). The body mass index (BMI) was also calculated and reported in Table 2.2. The mean BMI was also found to be 21.95 kg/ m^2 and is within the normal range of 18.5–24.9 (Brolin et al., 2012). The normality of the data distributions was tested using skewness and kurtosis tests for validating the nature of data distributions representing the army population (O'Connor et al., 2010) though only male data were used for normality test due to a smaller sample size of female participants, as shown in Table 2.2. If the ratio of skewness and kurtosis to their standard error (Z-scores) lie between -2 and 2, then the respective distribution could be considered normal (Kroemer et al., 2010; Singh and Kumar, 2019; Taifa and Desai, 2017).

Table 2. 2: Measurements of anthropometry for Ethiopian soldier population (Male (n) = 250; Female (n) = 60) along with normality test for male participants.

	Anthropometric Variables	Male				Female			
		Mean (SD)	5th	50th	95th	Mean (SD)	5th	50th	95th
Standing Posture									
1	Stature	170.34 (6.40)*	161.00	169.50	179.90	158.46 (5.31)	150.80	158.00	169.20
2	Eye height	159.83 (6.40)*	150.60	159.00	168.90	143.97 (5.57)	142.30	147.50	156.86
3	Acromial height	140.86 (5.60)*	132.50	140.00	149.00	123.7 (4.66)	120.80	131.81	139.68
4	Chest height	131.22 (4.90)*	117.50	125.00	134.50	116.95 (3.86)	110.26	117.30	124.98
5	Elbow height	108.22 (4.90)*	101.00	108.00	116.00	101.11 (3.10)	96.07	101.00	107.51
6	Waist height	96.96 (5.60)*	87.10	96.00	105.00	89.64 (4.94)	80.00	90.00	99.40
7	Hip height	84.41 (5.10)*	75.50	84.00	91.00	80.57 (4.60)	73.81	81.20	89.50
8	Arm length	75.93 (3.70)*	70.00	75.50	81.90	72.79 (3.79)	60.00	69.75	73.38
9	Grip arm length	69.89 (3.45)*	64.20	69.50	75.50	66.23 (3.21)	59.60	64.20	67.80
Sitting Posture									
10	Sitting height	85.01 (3.6)*	79.77	84.60	90.86	79.05 (2.77)	75.48	78.26	83.82
11	Eye height	73.80 (4.0)*	67.48	73.35	80.20	67.13 (2.76)	63.44	67.08	72.48
12	Acromial height	58.69 (3.4)*	52.71	58.18	64.15	53.51 (2.19)	49.54	51.42	58.52
13	Elbow rest height	21.74 (2.9)*	17.20	21.75	26.31	17.12 (2.37)	13.76	17.20	22.10
14	Thigh thickness	15.89 (1.1)*	14.33	15.74	17.68	14.68 (1.55)	12.34	14.77	17.72
15	Bideltoid breadth	45.31 (1.9)*	42.34	45.00	48.58	39.70 (2.01)	36.50	39.50	43.68
16	Elbow to elbow breadth	50.19 (2.6)*	46.21	49.77	54.55	42.68 (2.68)	38.40	42.41	48.00
17	Chest breadth	29.41 (1.7)*	29.00	31.00	34.00	27.12 (1.37)	24.60	27.00	29.90
18	Chest depth	23.27 (2.6)*	23.38	26.03	30.02	20.92 (1.80)	17.60	20.77	24.60
19	Waist breadth	29.41 (1.7)	27.10	29.00	32.90	27.88 (1.65)	25.02	27.60	31.30
20	Abdominal depth	23.27 (2.6)	19.53	22.60	28.44	20.84 (2.50)	16.49	20.41	26.04
21	Hip breadth	37.03 (2.28)	34.50	36.50	40.90	36.32 (2.28)	32.43	35.96	41.67
22	knee height	54.13 (2.9)*	50.83	54.16	57.16	51.88 (1.19)	49.55	52.70	54.83
23	Popliteal height	43.56 (2.5)	40.35	42.58	47.81	39.37 (1.82)	37.30	39.09	42.61
24	Buttock to popliteal length	48.54 (2.1)*	44.99	48.90	50.86	46.72 (1.86)	42.83	47.05	49.84
25	Buttock to knee length	61.18 (2.4)*	57.35	60.71	64.25	57.73 (1.98)	53.64	58.28	60.51
26	Forearm length	45.83 (3.3)*	41.10	45.50	50.40	44.96 (0.86)	40.41	45.00	46.37
27	Forward thumb tip reach	81.25 (3.9)*	75.33	80.82	87.27	74.08 (3.55)	64.74	74.91	78.70
Standing/ Sitting Posture									
28	Hand length	18.45 (1.4)*	16.52	18.29	20.70	17.95 (0.53)	16.88	18.09	18.68
29	Handbreadth	8.40 (0.70)	7.41	8.33	9.50	8.01 (0.49)	6.74	8.33	8.51
30	Foot length	25.21 (0.90)*	23.50	25.00	26.50	22.82 (0.54)	21.84	22.75	24.12

31	Foot-breadth	9.55 (0.40)	8.77	9.50	10.00	8.16 (0.40)	7.37	8.12	9.04
32	Mass (kg)	66.75 (9.4)	55.00	65.00	84.00	52.50 (5.47)	45.00	53.00	63.80
	BMI (kg/m^2)	23.00 (2.61)*	21.2	22.6	25.4	20.90 (2.21)	19.8	21.2	22.3

All measurements are in cm unless specified; SD = standard deviation; BMI = body mass index.
** The data is normal distribution.*

As evident from Table 2.2, the majority (>80%) of the body variables could be considered normal in both skewness and kurtosis values. Brolin et al (2012) and Taifa and Desai (2017) pointed out that stature and other limb measurements are often normal, irrespective of small sample size. In related literature (Bhattacharya and McGlothlin, 2012; Samuel et al, 2015), it has been documented that most of the anthropometric variables are normally distributed, even for smaller sample size; however, body weight and muscular strength often show a positively skewed distribution. Our study also reports similar inferences about the distributional patterns.

2.3.3 Principal component factor analysis (PCFA) followed by regression analysis

To tackle the difficulty of analyzing and interpreting large numbers of variables and levels in a data set, various variable reduction techniques such as decision tree and PCA can be used for clustering and identifying the most important factors/variables (Lin et al., 2008; Mohamady et al., 2019). For this particular study, PCA concepts have been utilized before further analyses. The highly inter-correlated anthropometric variables were grouped into six factors during this study, as shown in Table 2.3. Estimated factor loadings and communality results could be used to define each factor. These six factors were constructed to achieve minimum effective data values that will account for the maximum variances in the data for the particular multivariate analysis.

Table 2. 3: Factor loadings and communality results for the anthropometric dimensions (satisfying the eigenvalue ≥1 criterion)

Anthropometric Variables	Component factors						Commonality
	Fac01	Fac02	Fac03	Fac04	Fac05	Fac06	
Stature	**.949***	.540	.751	.474	.588	.575	.927$^{\#}$
Acromial height	**.944***	.600	.703	.491	.543	.517	.923$^{\#}$
Standing eye height	**.939***	.572	.728	.512	.610	.558	.919$^{\#}$
Hip height	**.908***	.349	.535	.366	.421	.422	.881$^{\#}$
Chest height	**.902***	.581	.641	.492	.516	.518	.852$^{\#}$
Standing elbow height	**.896***	.590	.677	.488	.452	.549	.878$^{\#}$
Waist height	**.893***	.374	.606	.333	.489	.499	.816$^{\#}$
Knee height	**.835***	.428	.607	.248	.401	.375	.714$^{\#}$
Popliteal height	.805	.284	.565	.229	.293	.324	.690
Buttock to knee length	**.760***	.592	.673	.074	.525	.487	.756$^{\#}$
Popliteal length	.727	.503	.620	.021	.462	.474	.686
Sitting hip breadth	.465	**.964***	.349	.347	.634	.316	.938$^{\#}$
Abdominal depth	.481	**.963***	.354	.362	.625	.341	.932$^{\#}$
Waist breadth	.435	**.958***	.343	.311	.646	.315	.931$^{\#}$
Thigh Thickness	.483	**.946***	.347	.308	.611	.362	.895$^{\#}$
Mass	.520	**.824***	.327	.516	.772	.490	.824$^{\#}$
Arm length	.608	.294	**.963***	.180	.300	.317	.952$^{\#}$
Grip arm length	.603	.288	**.958***	.175	.286	312	.948#
Forearm length	.591	.283	**.956***	.171	.280	.308	.945$^{\#}$
Sitting thumb tip reach	.678	.372	**.895***	.170	.429	.251	.901$^{\#}$
Sitting height	.572	.465	.375	**.892***	.568	.403	.866$^{\#}$
Sitting eye height	.589	.403	.452	**.877***	.576	.437	.867$^{\#}$
Sitting acromial height	.535	.297	.392	**.866***	.517	.419	.828$^{\#}$
Elbow rest height	.028	.182	-.112	**.802***	.039	.093	.823$^{\#}$
Bideltoid breadth	.472	.710	.347	.283	**.899***	.354	.864$^{\#}$
Elbow to elbow breadth	.471	.702	.346	.283	**.897***	.353	.862$^{\#}$
Chest depth	.342	.702	.395	.392	**.878***	.479	.837$^{\#}$
Chest breadth	.334	.609	.252	.372	**.867***	.479	.835$^{\#}$
Foot breadth	.428	.597	.196	.210	**.825***	.300	.863$^{\#}$
Hand breadth	.257	.560	.192	.140	**.807***	.269	.882$^{\#}$

Foot length	.456	.322	.328	.314	.484	**.931***	.951$^{\#}$
Hand length	.444	.280	.285	.304	.445	**.834***	.938$^{\#}$
Eigenvalue	**16.56**	**4.641**	**2.61**	**1.86**	**1.65**	**1.06**	---
Total Variance (%)	**50.17**	**14.06**	**7.900**	**5.63**	**5.00**	**3.20**	---
CV (%)	**50.17**	**64.23**	**72.13**	**77.76**	**82.75**	**85.95**	---

CV = Cumulative of Variance

$^{\#}$*Communalities ≥ 0.70*

**Factor loading ≥0.60*

Table 2.3 shows the criteria for the selection of variables under the component loading factors. Variables with loading factor coefficient and commonality greater than 0.60 and 0.70 respectively were clustered in each factor. The most considerable portion of variation (50.2%) was accounted by the first factor, and nearly 35.8% of the total variance was distributed in the remaining ones. The anthropometric variable having maximum factor loading value and commonality gets the preference for grouping under the respective component factor. For example, although the factor loading coefficient of stature was higher than 0.60 for factors 1 and 3, it was considered factor 1 (Fac01).

One dominant variable called predictor (which represents other variables) within the group was taken from each component factor category (Lin et al., 2008). These predictors were identified based on their higher factor loading coefficient and commonality. Within each component factor, they would be considered the essential dimensions for anthropometric characteristics of the Ethiopian soldiers in different applications and analysis of variances under a certain limit of errors. The highest dominant variables in each component factor were foot length, arm length, sitting height, hip breadth, bideltoid breadth, and stature. These dimensions would be considered the most essential/ dominant dimensions in terms of physical characteristics of the Ethiopian army. These six variables are expected to have nearly similar characteristics of variances in each component factors (Charles, 2019) and account for a considerable portion of the total variance. Earlier studies have also shown that the dominant variable can represent other variables within the group (Patel et al., 2016). It is worth noting to consider variables that are not represented by other variables or not a part of any component factor category. Apart from the six predictors, we have also considered popliteal height and popliteal length, with lower recommended communality values (< 0.70) yet high factor loading coefficients. Mass also considered as a targeted variable, and added in to a minimum data set even though it is inter-correlated with the hip breadth family (Lin et al., 2008).

Apart from reducing redundant variables for simplifying the analysis of variability test, this longitudinal study aims at demonstrating how to reduce the numbers of variables to be measured in an anthropometry survey that involves sample data of a large number of variables with the combination of both PCFA and regression analysis. In addition to PCA, the linear regression models were also constructed using the least square method to predict the regression equation of relevant body variables that had correlation coefficients (R) > 0.70 (Patel et al., 2016). Variables having the lesser factors loading coefficient (<60%), commonality, and correlation coefficients (<70%) were counted as independent variables and included in a minimum data set for measurement.

The six highly dominant anthropometric variables are listed in the factor-wise category in Table 2.4 based on inferences drawn from Table 2.3. Therefore, we proceeded to compute linear regression models with these six dominant independent variables to verify the dependency of other relatively less dominant variables on them. The variables which are grouped in the same component factors were used to formulate the linear regression equation of the anthropometric variables, which were under the respective component factor.

Table 2. 4: List of factor-wise independent variables

Component Factors	Dimension
Fac01	Stature*, acromial height, standing eye height, hip height, chest height, standing elbow height, waist height, knee height, buttock to knee length,
Fac02	Bideltoid breadth*, elbow to elbow breadth, chest depth, chest breadth, foot breadth, handbreadth
Fac03	Sitting hip breadth*, abdominal depth, waist breadth, thigh thickness, mass,
Fac04	Sitting height*, elbow rest height, sitting eye height, sitting acromial height
Fac05	Arm length*, grip arm length, sitting thumb tip reach, forearm length
Fac06	Foot length*, hand length
V	Popliteal height, popliteal length

*The highest factor loading variables within component factor.

V = variables having less commonality values (<70%)

The regression equations predict dependent variables from the predictors if the dependent variable and predictors (independent variables) have higher factor loading and commonality coefficient in the same factor loading category. Based on these criteria, regression equations for the most relevant dependent variables were predicted from the six dominant independent variables viz. stature, bideltoid breadth, hip breadth, sitting height, arm length, and foot length (Table 2.3). These six independent variables do not limit the regression analysis, but there are multiple chances to formulate several simple regression equations from these six good predictors. Table 2.5 reports the list of equations derived to estimate the value of one variable from the given value of another anthropometric variable. These equations were formulated based on the categories of highly correlated dominant variables, as it was referred from Table 2.4. The regression model for equation #12, #13, and #19 in Table 2.5 were rejected since the dependent variable cannot be predicted from the independent variable with a lower value of the coefficient of determination (denoted by R^2). Therefore, 12 anthropometric measurements from the six measured values of dominant variables using the developed equations shall be applicable for data collection.

Table 2. 5: Linear regression equations for the estimation of body variables from their predictors

No.	**Regression Equation**	**F-ratio**	**SEE**	**R**	**R^2**
1	Standing acromial height = 0.844 × (Stature) – 2.93	1430*	1.92	0.94	0.88
2	Standing eye height = 0.974 × (Stature) – 6.10	4836*	1.20	0.98	0.96
3	Hip height = 0.627 × (Stature) – 22.38	339*	3.05	0.82	0.67
4	Chest height = 0.795 × (Stature) – 10.00	955.5*	2.22	0.91	0.83
5	Standing elbow height = 0.6802 × (Stature) – 7.65	690*	2.29	0.88	0.78
6	Waist height = 0.713 × (Stature) – 24.53	393*	3.22	0.82	0.67.
7	Knee height = 0.3395 × (Stature) – 10.12	231*	1.89	0.74	0.55
8	Buttock to knee length = 0.2782 × (Stature) +13.8	261*	1.52	0.76	0.58
9	Elbow to elbow breadth = 1.34 × (Bideltoid breadth) –10.4	2429*	0.72	0.97	0.83
10	Chest depth = 0.843 × (Bideltoid breadth) –11.69	227*	1.45	0.76	0.58
11	Chest breadth = 0.644 × (Bideltoid breadth) + 2.16	135*	1.06	0.74	0.55
12	~~Foot breadth = 0.072 × (Bideltoid breadth) + 6.27~~	234*	0.54	0.51	0.26
13	~~Hand breadth = 0.0727 × (Bideltoid breadth) + 5.09~~	219*	0.35	0.47	0.22
14	Waist breadth = 0.759 × (Hip breadth) – 1.31	1517*	0.55	0.94	0.88
15	Thigh Thickness = 0.486 × (Hip breadth) – 2.10	1534*	0.35	0.93	0.86
16	Abdominal depth = 0.697 × (Hip breadth) + 15.2	1804*	0.80	0.95	0.90
17	Sitting eye height = 0.977 × (Sitting height) – 9.21	1318*	1.37	0.94	0.88
18	Sitting acromial height = 0.701 × (Sitting height) – 0.90	321*	2.01	0.78	0.61
19	~~Elbow rest height = 0.375 × (Sitting height) – 10.172~~	132*	2.44	0.50	0.25
20	Grip arm length = 0.790 × (Arm length) + 10.480	321*	2.22	0.79	0.63
21	Forearm length = 0.696 × (Arm length) – 7.07	601*	1.47	0.87	0.76
22	Thumb tip reach length = 1.026 × (Arm length) +3.32	3947*	0.84	0.87	0.76
23	Hand length = 1.44 × (foot length) -17.25	507*	0.66	0.85	0.72

All dimensions are in cm; SEE = standard error of the estimate; R= correlation coefficient
The ~~strikethrough~~ line signifies the excluded equation and its dependent variable having a low coefficient of determination ($R^2 < 50\%$)
*$p < 0.05$

Henseler et al. (209) proposed a rule of thumb for acceptable R^2 values of 0.75, 0.50, and 0.25, are perceived as substantial, moderate, and weak, respectively. On the contrary, Hair et al. (2011) opined that a thumb rule could not be applicable to all disciplines. R^2 acceptability is reliant upon the model complexity and the research discipline. Kroemer et al. (2010), in their study, also pointed out that the independent variable has a higher correlation coefficient (>0.70) that predicts the dependent variables. The variables having higher factor loadings, commonality, and correlation coefficients could provide a good prediction of regression equations (Patel et al., 2016). Altogether from Table 2.5, as the correlation and regression coefficients range from 0.71 to 0.98 and 0.50 to 0.96 in all the cases (moderate to substantial), it may be concluded that the mathematical model has good fitness for predicting analysis. However, due to the lower correlation coefficient (R<70%) of elbow rest height and breadth with their respective predictors, the mathematical model is not good for predicting analysis.

The correlation and regression coefficients from Table 2.5 revealed that most of the variables amongst the same component factor were highly correlated. For example, the dependent variables viz. sitting acromial height and sitting eye height were found predictable from their most dominant variable, i.e., sitting height (independent variable) in principle component factor 4 (Fac04). Therefore, it can be concluded that the six predictors nearly account for the characteristics of 20 original variables other than popliteal height, popliteal length, elbow rest length, foot breadth, handbreadth, and mass. Total 20 regression equations of dependent variables were constructed from the six predictors by rejecting variables with less correlation coefficient. Those rejected variables are included in the minimum data set, including the mass of 32 variables.

Therefore, it is essential to consider independent variables not represented by other anthropometric variables in the component factor category. Variables have high factor loading coefficients but lower recommended commonality values (< 0.70) like popliteal height and popliteal length, and variables with lower correlation coefficients like elbow rest length, foot breadth, and a handbreadth were considered for the representations of those 32 original variables. We have also included mass as one targeted variable (Lin et al., 2008). Therefore, the six dominant variables, the two variables having less commonality, the three variables having less correlation coefficient, and the one targeted variable called mass can also be counted as the independent variable for representing itself in anthropometric data survey of those the 32 variables when large sizes are involved.

Hence, the variable reduction technique can be helpful for simplifying the anthropometric data collection process in measurement surveys of large sample sizes while using fewer variables that can be an accurate representation of larger numbers of variables in a data set. The method of reducing variables in the present study can be utilized for any anthropometry survey with a sample size larger than 250 subjects.

2.3.4 Anthropometric data variations on age and ethnicity

Among 32 anthropometric variables, the 12 key variables were analyzed using ANOVA for a dimensional reduction in the analysis report.

Table 2.6 compares different age groups (<30, 30-40, and >40 years) with a sample size of 108, 82, and 60. The AG1 age group (< 30 years) was taken as a reference to the other age groups (AG2 = 30-40 years and AG3 = >40 years) for the group comparison.

Table 2. 6: ANOVA statistics for comparison among the three age groups (<30, 30-40, and >40) of army personnel.

Anthropometric Variables	**Mean(SD)**			**Mean Square**	**F value**	***p* value**
	AG1	**AG2**	**AG3**			
Mass (kg)	62.2 (6.6)	67.4 (8.5)	74.6 (8.9)	1721	27.42	.000**
Stature	168.6 (5.0)	170.2 (5.8)	172.2 (6.2)	172	4.46	.013*
Sitting height	83.9 (3.4)	85.1 (3.5)	86.1 (3.5)	70	5.34	.006**
Arm length	74.7 (3.2)	76.4 (3.3)	76.5 (3.6)	59	4.52	.012*
Elbow rest height	21.74 (2.5)	20.5 (2.6)	21.1 (3.3)	51	3.52	.032*
Popliteal length	47.9 (1.8)	48.5 (2.0)	49.1 (1.7)	20	4.84	.009**
Popliteal height	43.3 (2.27)	43.3 (2.2)	44.1 (1.8)	8	1.37	.256
Bideltoid breadth	44.6(1.7)	44.8(1.5)	45.9(1.9)	73	23.44	.000**
Hip breadth	36.1 (1.4)	36.9 (1.8)	38.8 (1.9)	84	28.45	.000**
Hand breadth	8.40 (0.8)	8.90 (1.0)	9.4(1.1)	7	8.60	.000**
Foot breadth	9.55 (0.5)	9.76 (0.7)	9.8 (0.8)	69	33.83	.000**
Foot length	25.0 (0.6)	25.2 (0.9)	25.6 (0.9)	5	6.00	.003**

All measurements are in cm unless specified
***(p<0.01)*
**(p<0.05)*
AG1=Age group 1 (<30)
AG2=Age group 1 (30-40)
AG3=Age group 1 (>40)

Table 2.6 depicts that there was a significant change in all the anthropometric measurements among the three age categories at a significant level of 0.05 except popliteal height. McDowell et al (2008) categorized the age levels and opined that the mass increases significantly up to the age of 60 years and then tends to decrease. Unlike mass, the stature measurements have no specific trend and may either decrease or increase in each age group. Our results showed that there was a high variation in variables other than limb measurements among the age groups. Therefore, the anthropometric data of the army personnel shall be developed for each age group as long as significant variation exists among them.

Following the ANOVA analysis, Tukey's HSD *post-hoc* comparisons were conducted to investigate the pairwise significance among the three age groups, as shown in Table 2.7. As apparent, the majority of the selected anthropometric variables have significant mean differences among the age groups. It was evident that with growing age, the anthropometric variables like mass and breadth measurements were also increasing. However, no effect of age was observed on the limb measurements.

Table 2. 7: ANOVA *post hoc* multiple comparisons (Tukey's HSD test) pairwise comparisons among the three age groups.

		Mean difference		
S/No.	**Anthropometric variables**	**AG1-AG2**	**AG1-AG3**	**AG2-AG3**
1	Mass (kg)	-5.01*	-12.20*	-7.19*
2	Stature	-1.74	-3.75*	-2.01
3	Sitting height	-1.23	-2.32*	-1.10
4	Arm length	-1.56	-1.61	-0.06
5	Elbow rest height	-1.32	-1.73	-0.41
6	Popliteal length	-0.58	-1.29*	-0.71
7	Popliteal height	-0.03	0.79	-0.75
8	Bideltoid breadth	0.5	2.4*	-1.9*
9	Sitting hip breadth	-0.86*	-2.71*	-1.85*
10	Hand breadth	-0.60*	-0.56*	-0.33
11	Foot breadth	-0.3	-0.55*	-0.4
12	Foot length	-0.20	-0.64*	-0.43

All measurements are in cm unless specified
** The mean difference is significant at 0.05 levels.*

Samuel et al (2015) studied the effect of age on anthropometric measurements among 120 Gari frying workers in Southwest Nigeria. They pointed out that the mass, BMI, and the majority of girth measurements significantly increase as the age increases up to 55 years. Our study reports similar implications about the effect of age on anthropometric measurements among the Ethiopian armed personnel. Hence, designers need to use appropriate anthropometric data according to the target age group. Practicing the wrong anthropometry in designing the work system may result in an unsafe workplace, affecting user comfort and efficiency.

While comparing anthropometry w.r.t ethnicity, the Amhara region was taken as a reference for the group comparison. The sample sizes in regions of Amhara, Tigray, Oromia and South Regions were 65, 63, 62, and 60, respectively. Table 2.8 and 2.9 show the ANOVA and its follow-up posthoc comparisons to test the ethnic difference among the anthropometric variables of soldiers from these ethnic regions.

Table 2. 8: ANOVA statistics for comparison among the four ethnic groups (Tigray, Amhara, Oromia, South Region, and Other ethnic regions) of army personnel

Anthropometric Variables	**Mean(SD)**				**Mean Square**	**F value**	***p* value**
	Amhara	**Tigray**	**Oromia**	**South Region**			
Mass	63.1(7.6)	62.8(6.7)	71.3(10.1)	70.2(8.6)	704.59	10.56	.000**
Stature	168.4(4. 9)	169.5(5.5)	171.4(6.0)	170.0(6.1)	93.72	2.42	.050
Sitting height	83.7(3.0)	84.6(3.3)	85.9(3.4)	84.9(4)	45.59	3.52	.008**
Sitting eye height	72.4(3.6)	73.3(3.4)	74.8(3.5)	73.6(4.2)	55.99	4.06	.003**
Arm length	75.3(3.6)	75.0(3.4)	76.4(3.2)	76.3(3.2)	25.00	1.88	.116
Elbow rest height	20.7 (1.5)	20.5 (1.6)	21.9 (1.8)	21.8 (2.3)	31	2.56	.032*
Popliteal length	47.9(1.9)	48.0(1.9)	49.2(1.9)	48.3(1.9)	14.57	3.52	.008**
Popliteal height	43.3(2.1)	43.4(2.5)	43.4(2.2)	43.6(2.7)	1.35	.23	.920
Bideltoid breadth	44.7(1.7)	44.6(1.5)	46.2(2.0)	45.9(1.9)	25.65	7.92	.000**
Hand breadth	8.40 (0.8)	8.20 (1.0)	9.1(1.1)	8.7(1.1)	2.6	2.60	.042*
Foot breadth	9.55 (0.5)	9.52 (0.7)	9.8 (0.8)	8.9 (0.8)	3.4	3.83	.044*
Foot length	25.1(0.9)	25.2 (0.8)	25.2(1.0)	25.1(0.9)	.14	.18	.950

All measurements are in cm unless specified

***(p<0.01)*

**(p<0.05)*

Table 2.8 shows the ethnic variation has a significant change on the majority of the presented anthropometric measurements at a significant level of 0.05. Stature, arm length, and foot length were the non-significant variables among the selected body variables. However, the other four crucial variables (mass, sitting height, bideltoid breadth, hip breadth) showed significant variation among the groups. It indicates that the anthropometric data of the army personnel shall be developed for each ethnic group as long as significant variation exists among them.

Following ANOVA, the significance of the mean differences within pairwise ethnic groups was reported in Table 2.9 to investigate the difference among groups.

Table 2. 9: ANOVA *post hoc* multiple comparison (Tukey's HSD test) pairwise comparisons among the four ethnic groups

Anthropometric variables	**Ethnic groups**	**Mean difference**			
		Amhara	**Tigray**	**Oromia**	**South Region**
Mass	Amhara	0.00	0.35	-8.50*	-6.97*
	Tigray	-0.35	0.00	-8.85*	-7.31*
	Oromia	8.50*	8.85*	0.00	1.54
Stature	Amhara	0.00	-0.78	-3.52	-2.41
	Tigray	0.78	0.00	-2.74	-1.63
	Oromia	3.52	2.74	0.00	1.11
Sitting height	Amhara	0.00	-0.91	-2.46*	-1.63
	Tigray	0.91	0.00	-1.55	-0.72
	Oromia	2.46*	1.55	0.00	0.84
Arm length	Amhara	0.00	0.48	-2.10	-1.27
	Tigray	-0.48	0.00	-1.68	-1.75
	Oromia	1.19	1.68	0.00	-0.07
Elbow rest height	Amhara	0.00	0.36	-0.29	-0.43
	Tigray	-0.06	0.00	-0.65	-0.79
	Oromia	0.29	0.65	0.00	-0.04
Popliteal length	Amhara	0.00	0.09	-1.32*	-0.56
	Tigray	-0.09	0.00	-1.41	-0.66
	Oromia	1.32*	1.41*	0.00	0.75
Popliteal height	Amhara	0.00	0.00	-0.20	-0.44
	Tigray	0.00	0.00	-0.21	-0.44
	Oromia	0.20	0.21	0.00	-0.24
Waist breadth	Amhara	0.00	0.21	-2.18*	-1.75*
	Tigray	-0.26	0.00	-2.60*	-2.10*
	Oromia	2.23	2.60*	0.00	0.47
Sitting hip breadth	Amhara	0.00	0.20	-1.59*	-1.10
	Tigray	-0.20	0.00	-1.78*	-1.30*
	Oromia	1.59*	1.78*	0.00	0.48
Hand length	Amhara	0.00	-0.07	-0.16	-0.09
	Tigray	0.06	0.00	-0.10	-0.04
	Oromia	0.15	0.11	0.00	0.07
Foot breadth	Amhara	0.00	-0.09	-0.12	-0.12
	Tigray	0.06	0.00	-0.16	-0.13

	Oromia	0.14	0.15	0.00	0.07
Foot length	Amhara	0.00	-0.05	-0.13	-0.08
	Tigray	0.05	0.00	-0.08	-0.03
	Oromia	0.13	0.08	0.00	0.05

All measurements are in cm unless specified

** The mean difference is significant at 0.05 levels.*

The result from Table 2.9 depicts that the Oromia was significantly different in mass and breadth and sitting height measurements compared with Amhara. Moreover, South Region measurements were significant for mass and bideltoid breadth compared with Amhara. However, no statistical difference was evident between Amhara and Tigray in any of the anthropometric measurements. Oromia has the largest anthropometric measurements among the four ethnic groups. Furthermore, the Oromia ethnic group was recorded as the highest anthropometric measurement compared to all other groups, whereas Tigray and Amhara ethnic groups were recorded as the least. Notably, the major anthropometric differences between Oromia and South Region were depicted in mass and breadth. Therefore, it concluded that breadth and mass are the major variables that are affected by these ethnic group variations.

2.3.5 Comparison of present anthropometric data with International databases

Anthropometric mean values of the Ethiopian army were compared with other countries like Korea (Hart et al., 1967), India (Zachariah et al., 2001), and the USA (Gordon et al., 2014). Those countries were chosen for comparison tests based on the availability of the army anthropometric data and the diversity of the population among the Western and Eastern worlds (Yusof et al., 2019; Max Roser et al., 2020). The comparison of Ethiopian anthropometric mean values and their significance with the mentioned countries is shown in Figure. 2.2 and Table 2.10.

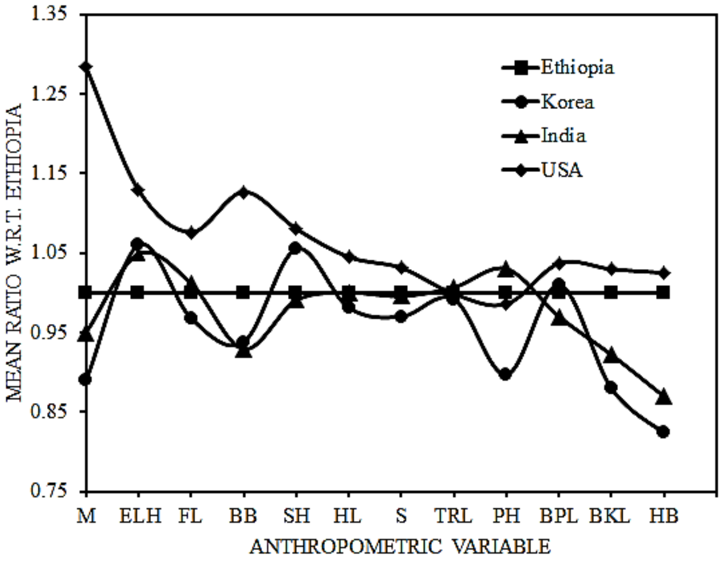

Figure 2. 2: Comparison of the Ethiopian anthropometric mean with three different countries

Note. M-mass; ELH-elbow rest height; FL-foot length; BB-bideltoid breadth; HL-hand length; S-stature; SH-sitting height; TRL-thumb tip reach length; PH-popliteal height; HB-hip breadth; BKL- buttock to knee length; BPL-Buttock to popliteal length.

Table 2. 10: Significant t-test for anthropometric data of Ethiopian male soldiers comparing with other countries

Anthropometric Variables	**Ethiopia[#] (n=250) Mean (SD)**	**USA[1] (n=4082) Mean (SD)**	**India[2] (n=11,458) Mean (SD)**	**Republic of Korea[3] (n=3,747) Mean (SD)**
Mass (kg)	66.8 (9.4)	85.52 (14.22)*	63.4 (7.42)*	59.4 (4.9)*
Stature	170.3 (6.4)	175.62 (6.86)*	169.6 (5.43)	165.2 (4.9)*
Eye height	159.8 (6.4)	NA	158.3 (5.4)*	NA
Acromial height	140.9 (5.8)	144.07 (6.33)*	141.8 (7.3)*	134.1 (4.7)
Sitting height	85.0 (3.6)	91.83 (3.57)*	84.2 (4.6)*	89.7 (2.7)*
Sitting eye height	73.8 (4)	80.45 (3.32)*	NA	78.2 (3.1)*
Sitting acromial height	58.7 (3.4)	NA	60.7 (3.4)*	58.3 (3.1)*
Sitting elbow height	21.7 (2.9)	24.50 (2.87)*	22.8 (2.6)*	24.8 (1.2)*
Popliteal height	43.6 (2.5)	42.98 (2.48)*	44.9 (2)*	39.1 (2.4)*
Thigh thickness	15.9 (1.1)	18.05 (1.56)*	NA	NA
Buttock to knee length	60.2 (2.4)	61.80 (3.06)*	56.4 (2.6)*	53.8 (2.7)*
Buttock to popliteal length	48.5 (2.1)	50.29 (2.74)*	47.0 (2.6)*	43.0 (2.6)*
Acromial to elbow length	45.8 (3.3)	36.37 (1.82)*	36.3 (1.9)	33.5 (1.9)*
Lower arm length	36.5 (3.1)	48.02 (2.33)*	47.2 (2.2)*	44.0 (2.0)*
Thumb tip reach length	81.3 (3.9)	81.19 (4.37)	81.8 (4.5)	80.6 (4.2)
Bideltoid breadth	45.3 (1.9)	51.04 (3.25)*	42.1 (2.2)*	42.5 (1.9)*

Abdominal depth	23.3 (2.6)	25.47 (3.73)*	NA	NA
Hip breadth	37.0 (2)	36.93 (3.02)	32.2 (1.9)*	30.5 (1.6)*
Hand length	18.5(1.4)	19.33 (0.99)*	NA	18.1 (0.7)*
Hand breadth	8.4 (0.7)	8.83 (0.44)*	8.4 (0.42)	8.5 (0.5)
Foot length	25.2 (0.9)	27.12 (1.31)*	25.5 (1.2)*	24.4 (1.3)*
Foot breadth	9.6 (0.4)	10.19 (0.52)*	9.6 (0.6)	9.6 (0.4)

All measurements are in cm otherwise specific; NA = Not applicable (no information available)

** The mean difference is significant at the 0.05 level (2-tailed).*

two-sample t-tests treating this group as a control, and comparing all other groups against it.

[1] *Gordon et al., 2014*

[2] *Zachariah et al., 2001*

[3] *Hart et al., 1967*

The result shown in Table 2.10 depicts the mean anthropometric differences of Ethiopian soldiers compared with other countries' army populations like the USA, Korea, and India. The majority of body measurements were statistically significant at 0.05 levels (2-tailed). Generally, the Asian countries have the least body size, and all the body dimensions of the USA army are larger than the Ethiopian army (Figure 2.2) except the thumb tip reaches length. In general, these comparative results indicate that the majority of Ethiopian army body sizes are not compatible with those of other countries.

As long as the size of the body varies significantly, the variability has an ergonomic impact on the design of tools, equipment, and workspaces for army users. In ergonomics design, attention should always be given to the variability of body dimensions (Parcells et al., 1999; Nadadur et al., 2016). For instance, the hip breadth of the Ethiopian army was larger than all the countries reported in this paper. Thus, the wide range of user compatibility products from other countries might not be compatible with the Ethiopian armed personnel.

Except for the study of the anthropometric characteristics done by Odhuno-Otieno (2016) among the students from Bahir Dar University (from age 18 to 24 years), there is no other reported study about the establishment of an anthropometric database for the Ethiopian civil and army population. Therefore, the current research towards developing the anthropometric database of the Ethiopian Army population is the first of its kind.

It is expected that baseline information suggested in the present study would be helpful towards for ergonomists and designers designing army equipment and workplaces based on ergonomic considerations. Moreover, it would be helpful in curtailing the between miss-match body size and product/ workspace dimensions. The effective design of the army equipment and workspaces considers the human body dimensions for the design compatibility of equipment/ workspace (Hsiao, 2013). Since the shape and size of the human body can vary significantly due to those factors, the variability has an ergonomic impact on the design of tools, equipment, and workspaces for the user (Ayodeji et al., 2008). In some studies (Laubach et al., 1981; Reed et al., 2000), investigators have proposed that engineering anthropometry aims to provide accurate body dimensions for obtaining a good fit of a product to the user.

Moreover, the fitness of the Ethiopian army user anthropometry to the product dimension should be considered whenever the defense sector imports the army goods from partners of world countries (Beshah et al., 2014). Unless the specifications are provided, the equipment manufacturers or suppliers may consider developing the product as per the anthropometric dimension within their respective country (Vaidya et al., 2009). At present, the variability of the body sizes between Ethiopia and its partner countries affects the ergonomic compatibility of the products for the intended users in Ethiopia. However, we anticipate that establishing an anthropometric database for the Ethiopian army will undoubtedly reduce the variability of the product dimensions and anthropometric characteristics. This anthropometric data development might also be used as the primary input for the main anthropometric data of Ethiopia that will be developed in the future at diverse and extensive levels.

The findings of this anthropometry survey are not without limitation. It must be noted that this study shall not be restricted, conducted only on a small group of army personnel. One should be cautious about using the survey data before further studies. Being the first of its kind, the data can be used as a foundation for future studies. The developed anthropometric data may not be sufficient for designing of ergonomic fit uniforms/clothing due to the lack of some required girth/ circumference measurements (Dobbins et al., 1972). Future directions include extending the sample size to achieve a more reliable anthropometric database and conclude the variation effects. The normality test of the data distribution we attempted to assess indicates that the majority of the data are normal. Although the data seems normal, it needs an adequate anthropometric data collection survey to represent the army population purely. Experimenting with a large sample size is highly time-consuming, costly, and difficult[33] unless the apprehensive sectors give special support. Moreover, incorporating anthropometric data of female army personnel is also important as female participation in defense services is also increasing with time. Although no attempt was made in current research, it will be interesting to investigate the biomechanical characteristics, body range of motion, and strength capabilities among the army personnel in future studies.

2.4 Conclusion

In this work, an attempt was made to develop the anthropometric database for the Ethiopian army population in advance for further investigation of anthropometric variation based on different age levels, ethnic groups, and country-wise comparisons. Following data collection, detailed data analysis was done to ensure reliability and appropriateness of data distribution, the significance of observed differences, and interpretations. The results revealed a significant variation of anthropometric measurements among ages and ethnicity. This study proposes the need for further anthropometric development studies on larger scales. The comparison results showed that the anthropometry of the Ethiopian army varied significantly concerning other countries. Therefore, this developed anthropometric measurement is highly needed for the ergonomic design of military facilities in Ethiopia to advance user-compatible products and workspaces for specific users.

As a result of this research, the first of its kind anthropometric study and thereby the development of the anthropometric database for the male Ethiopian army personnel has been initiated. Based on the principles of the adequate sample size estimation, it is recommended to include more army personnel in the near future for a more reliable database. Until additional studies, the present anthropometric database may be considered for designing military equipment and workspaces.

Identifying less number of key anthropometric variables that are representative of the overall anthropometric variability of the population (by using PCFA and regression analysis) is helpful for the reduction of a large number of variables while data collection is constrained by a lack of resources, manpower, and financial support. A minimal number of volunteers for user trials of PMUs can also be identified by using the extreme anthropometric values (5th or/and 95th p values) of the identified key variables.

3

Associations of anthropometric diversity with workspace dimensions in ergonomic design of light armored vehicle

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Abstract

To ensure effective carrying, scouting, patrolling, and large-scale combat operations, the workspace design of 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 the 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. The assessment was conducted on three existing Ethiopian LAVs, and mathematical equations were framed to predict the vehicular design dimensions. Anthropometric data of Ethiopian soldiers (n = 310) and global standard ROMs from an earlier reported survey 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. 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. 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 Ethiopian soldiers' anthropometry and ROM dimensions.

Keywords: Ergonomic evaluation; predictive equations; army vehicle; workspace design; anthropometric measurement.

3.1 Introduction

As protection capabilities in heavily armored vehicles (HAVs) and LAVs are generally prioritized, 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. 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 working positions' dynamic or functional anthropometry (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 mainly depend on static anthropometry and ROMs for 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.

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 and 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), and is susceptible to biased results due to the influence of personal preferences (Annett, 2002; Singh et al., 2019). Therefore, an objective evaluation was conducted in this study. Several researchers have employed different objective evaluation methods 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.
- 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. The comparison test of existing workspace dimensions with predicted dimensions will help to address the research question (RQ-3).

RQ-3: Does Ethiopian army personnel body dimension has a significant effect on ergonomic design of the Ethiopian army vehicle (accommodation capacity < 75%)?

3.2 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 study (**chapter 2**) were used in this study. 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 3.1 shows the schematic representation of the proposed study design for evaluating the army vehicular workspace.

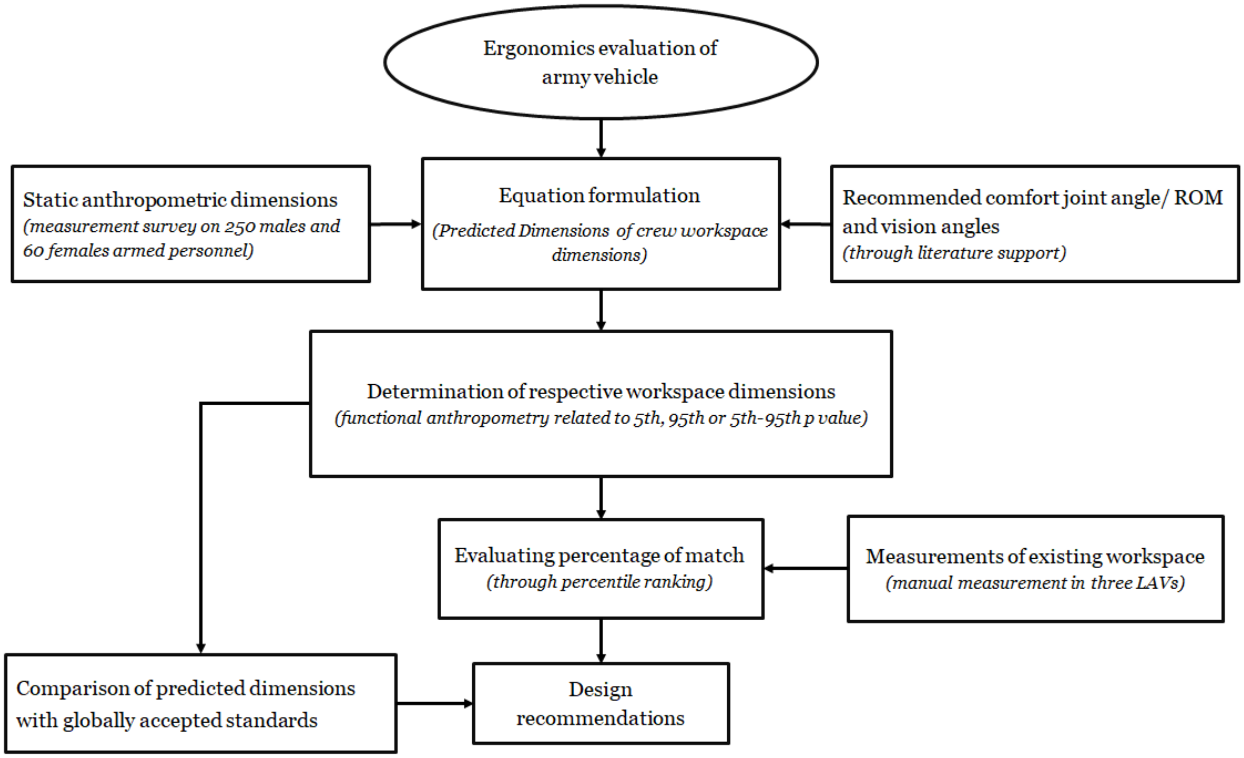
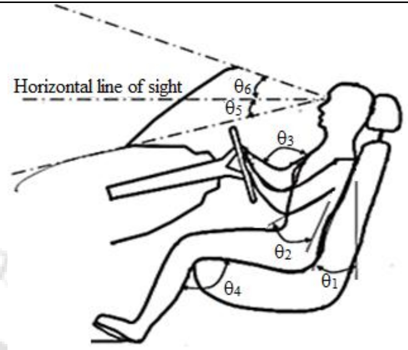


Figure 3. 1: Dimensional compatibility evaluation strategy adopted in the present study

3.2.1 Anthropometric data

We used the anthropometric dimensions (see Figure 2.1 and Table 2.2 in **chapter 2**) of Ethiopian armed personnel (250 males and 60 females) developed (**chapter 2**) 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 2.2) and recommended ROM and vision angles (Table 3.1) were used to compute the suitable design dimensions discussed later in the text.

Table 3. 1: 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 (2015)*	
θ_2: shoulder joint	22°		
θ_3: elbow joint	127°		
θ_4: knee joint	119°		
θ_5: down vision angle	15°	*Van Cott (1972)*	
θ_6: up vision angle	15°		

3.2.2 Existing vehicular workspace dimensions and measuring techniques

Three different models of locally fabricated or assembled LAVs (Figure 1.1) 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 3.2). 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 3.3a, b, c, and d, respectively. The measured D_W with its corresponding descriptions is presented in **Appendix 1**.

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 to identify 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 2.2 in **chapter 2**). 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 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 and Whyte, 2012).

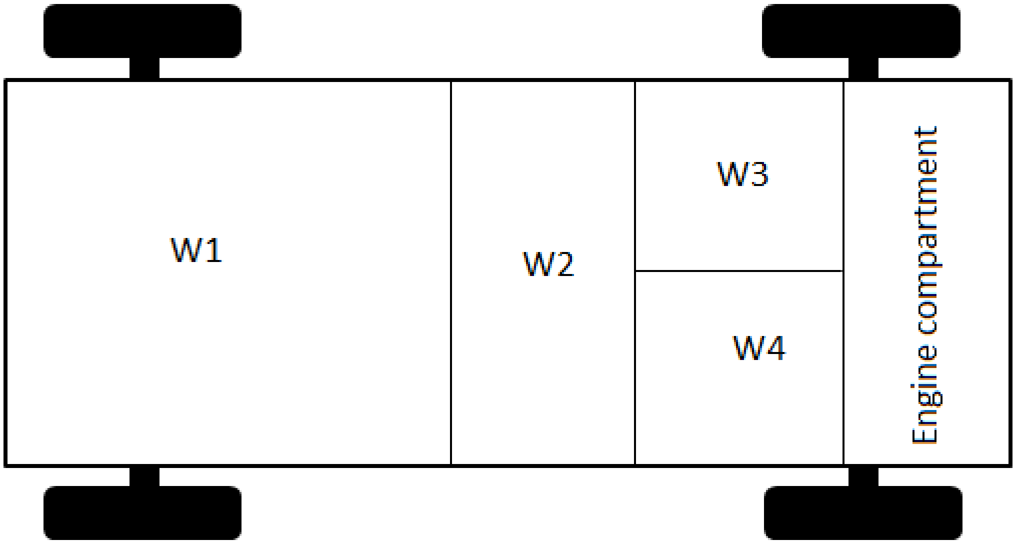


Figure 3. 2: Workspaces layout with actual workspace arrangements of LAV *(adapted from Gillingham & Patel, 2013) Note.*

4.3.1 *W1= infantry troop workspace; W2= gunner workspace; W3= driver workspace; W4= commander workspace*

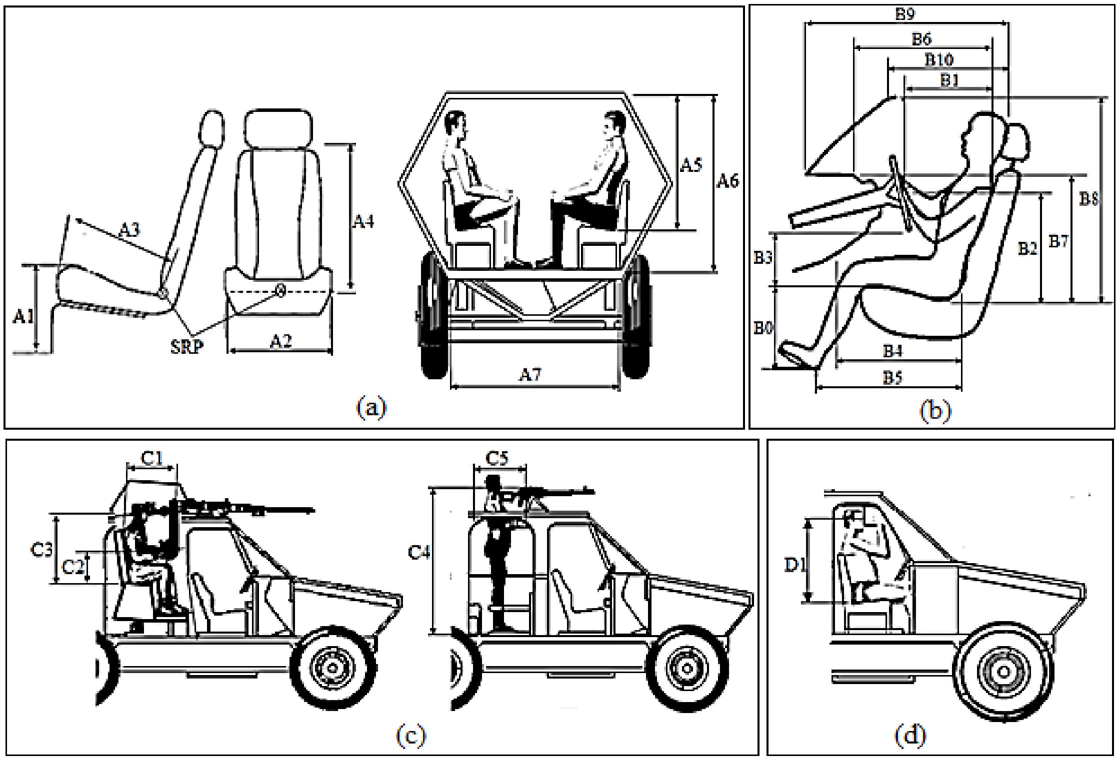


Figure 3. 3: Basic workspace dimensions of army vehicles (a) crew seat; (b) driver workspace; (c) gunner workspace in sitting posture and standing posture; (d) commander workspace.

Adapted and compiled from Reed (2000); Halder et al. (2017); Tank archive, (2013).

4.3.2 Note. 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.

3.2.3 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 and 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.

Four occupant spaces–infantry troop seat, commander, driver, gunner (standing and sitting), and workspaces were considered (Figure 3.4; 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's interior ergonomic characteristics.

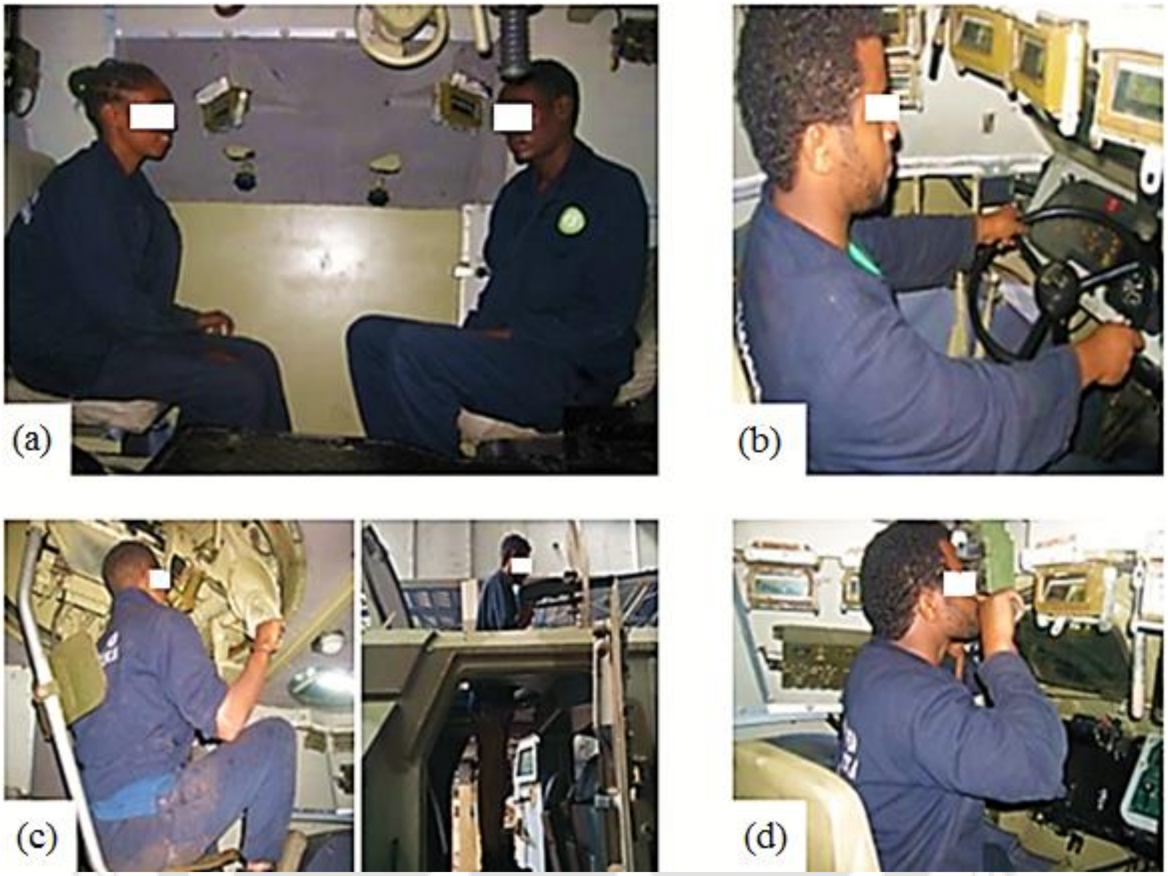


Figure 3. 4: Postures adopted during (a) normal crew sitting; (b) driving; (c) gunner firing in siting and standing posture; (d) commander sighting operation *(Photos taken from Bishoftu Motorization Engineering Complex, Ethiopia).*

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 (Ismaila et al., 2010; Evans et al., 1988). Table 3.2 presents the workspace dimensions and justification regarding design approaches (designing for percentile values).

Table 3. 2: 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)	A smaller crew member can easily rest their foot.
	Seat depth (A3)	A smaller crew member can support their back on the back rest.
	Backrest height (A4)	A smaller crew member can get a backrest at scapula portion and for full mobility to the arm and shoulder without being blocked.
	Driver seat height (B0)	The 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 gunners can easily reach to control dashboard.
	Cowl point height (B7)	Visual needs into the road for smaller drivers.
	Turret handle distance (C1)	Smaller gunners can easily reach into the turret handle horizontally.
	Turret handle height (C2)	Smaller gunners can easily reach into the turret handle vertically.
Designing for 95th percentile male value	*Seat width (A2)	Adequate size for a larger crew member.
	Head room height (A5)	Adequate clearance for the larger user.
	Steering wheel clearance (B3)	
	Roof height (A6)	
	Base width (A7)	
	Control dashboard clearance (B4)	Knee clearance for the 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 a horizontally adjustable seat (B1)	To accommodate and fulfill adjustability requirements in wide ranges of army population
	Foot pedal distance in the 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).	

** The seat width designed for 95th percentile female*

3.2.4 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 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 and Nussbaum, 2009; Porter and Gyi, 1998; Mircheski et al., 2014). Table 3.3 shows the mathematical relationship to predict design dimensions with respect to anthropometric measurements and ROM. The most relevant 22 dimensions (see Table 3.2) of the four workspaces were considered mathematical formulation and dimensional compatibility evaluation. These dimensions with the corresponding descriptions are indicated in **Appendix 1**.

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 values 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 (da Silva et al., 2020; Roebuck et al., 1975).

The following assumptions were made while formulating the predictive equations:

- 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 to the key dimensions' predictive equations.
- 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, 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 eye point.

Table 3. 3: 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**
$A1 = PH + 2cm$	(3.1)	2cm added to 5th p female value of the upright positioned popliteal height (PH) for shoe allowance (Gouvali and Boudolos 2006).
$A2 = 1.1HB \ or \ HB + 5cm$	(3.2)	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 5cm clearance (Mehta et al. 2008).
$A3 = BpL - 5cm$	(3.3)	Seat depth should be 5cm shorter than 5th p female value of female buttock-popliteal length (BPL) (Poulakakis & Marmaras 1998).
$A4 = 0.8AH$	(3.4)	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).
$A5 = SH + 5cm$	(3.5)	The minimum head room height should be 5cm greater than 95th p male value of male sitting height (SH) (Dreyfuss 1967).
$A6 = (SH + 5cm) + (PH \ + \ 2cm)$	(3.6)	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).
$A7 = \ 2(BPL + FL \ + \ 6cm)$	(3.7)	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 (3.5cm and 2.5cm) were added.
$B0 = (PH + 2cm)sin\theta_4$	(3.8)	Pedaling operation at θ_4* = 119^0 is comfortable for driver so that driver seat height is less than the normal seat height (Mircheski et al. 2014).
$B1_{max} \leq X1 + X2 - X3 \leq\ B1_{min}$ Where, $X1 = TRL - GAL$ $X2 = UAL\,\sin(\theta_1 + \theta_2)$ $X3 = (GFAL)\,\sin(\theta_1 + \theta_2 - \theta_3)$	(3.9)	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 (θ_1* = 20^0), shoulder joint angle (θ_2* = 22^0) and elbow joint angle (θ_3* = 127^0) shall be used (Mircheski et al., 2014; Ruiz, 2015). Refer **Appendix 2** for X1, X2 and X3.
$B2 = Y1 + Y2 + Y3$ Where, $Y1 = ELH$ $Y2 = UAL(1 - \cos(\theta_1 + \theta_2))$ $Y2 = (GFAL)\cos(\theta_1 + \theta_2 - \theta_3)$	(3.10)	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= AH-ELH), grip forearm length (GFAL), torso orientation (θ_1* = 20^0), shoulder joint angle (θ_2* = 22^0) and elbow joint angle (θ_3* = 127^0) shall be used (Mircheski et al. 2014; Ruiz, 2015). Refer **Appendix 2** for Y_1, Y_2 and Y_3.
$B3 = TT + 2cm$	(3.11)	Steering wheel clearance should ideally be 2 cm larger than 95th p male value of thigh thickness (TT) (Halder et al.2017).
$B4 = BKL + 5cm$	(3.12)	The knee clearance shall be 5cm larger than 95th p value of buttock to popliteal length (BPL) (Poulakakis & Marmaras 1998).
$B5_{max} \leq BPL - (PH + 2cm)cos\theta_4 \leq B5_{min}$	(3.13)	Ranges of 5th p female to 95th p male values of buttock to popliteal length (BPL), popliteal height (PH) and knee joint angle (θ_4* = 119^0) shall be used (Mircheski et al. 2014). The driver seat surface was assumed to be in the horizontal plane.
$B6 = TRL$	(3.14)	5th p female value of thumb tip reach length (TRL) shall be used (Bullock 1974).
$B7 = SEH - (B9 - HL)tan\theta_5$	(3.15)	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 (θ_5* = 15^0) (Peacock & Karwowski 1993; Fostervold et al. 2006) shall be used. The cowl point distance (B9) may not be restrictedly dependent on anthropometric variable.
		95th p male value of eye height (SEH), head length

$B8 = SEH + (B10 - HL)tan\theta_6$	(3.16)	(HL), horizontal distance of daylight opening point from design eye reference point (B10 – HL) and up vision angle (θ_6* = 15^0) **(**Peacock & Karwowski 1993; Fostervold et al. 2006) shall be used. The daylight opening distance (B10) may not be restrictedly dependent on anthropometric variable.
$C1 = TRL - GAL + UAL\sin(\theta_1 + \theta_2) + GFAL$	(3.17)	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 θ_1* = 10^0 (Mehta et al. 2008) unlike to the driver's seat backrest angle and shoulder joint angle at θ_2* = 22^0 shall be used (Mircheski et al. 2014) and forearm position is assumed to be horizontal.
$C2 = ELH - UAL(1 - \cos(\theta_1 + \theta_2))$	(3.18)	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, 2015) and forearm position is assumed to be horizontal.
$C3_{max} \leq SEH \leq C3_{min}$	(3.19)	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).
$C4_{max} \leq H + 2cm \leq C4_{min}$	(3.20)	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 2cm is added for shoe allowance.
$C5 = EEB + 25cm$	(3.21)	It shall be determined by 95th p male values of elbow to elbow breadth (EEB) with 25 cm side clearance (Woodson et al. 1992).
$D1_{max} \leq SEH \leq D1_{min}$	(3.22)	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).

Subscript 'max' denotes maximum value of D_W *usually limited by* 5^{th} *percentile of female value; 'min' denotes minimum value limited by* 95^{th} *percentile of male value (except the hip breadth of female).*

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

Note. 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.

3.2.5 Match/mismatch criteria

Table 3.4 describes the match/mismatch decision rule while comparing existing DWs 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).

Table 3. 4: Match/mismatch decision rule of workspace dimensions compared to 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

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.

3.2.6 Match/mismatch analysis

Match/mismatch and accommodation capacity of existing DWs for the Ethiopian army population were thoroughly analyzed. The 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 3.4). 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, Seattle, WA, USA, 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, Wellesley Hills, MA, USA, version 8).

3.3 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 3.5 presents the predicted and existing workspace measurements of Veh-1, Veh-2, and Veh-3.

Table 3. 5**:** The descriptive of existing vehicular workspace measurements and corresponding predicted design dimensions (D_P) at extreme limit levels.

Workspace type	**Predicted design dimensions**		**Existing workspace measurements**		
	Analytical Relationship	**Predicted design values**	**Veh-1**	**Veh-2**	**Veh-3**
Infantry troop seat	A1= PH+2cm	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 +5cm	96	99	92	96.5
	A6= PH+ SH +7cm	136	150	130	135
	A7= 2(BPL+ FL + 6cm)	165	220	195	215
Driver workspace	B0= (PH+2cm) 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 +5cm	96	108	91	96.5
	A6= PH + SH +7cm	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+2cm	19.68	21.5	20.5	20.5
	B4=BKL+5cm	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 + 2cm	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 + 5cm	96	99	92	96
	A6= PH + SH +7cm	136	150	130	135
	C1=TRL - GAL + UALsin32^0 + FAL – AL + GAL	61	NA	64.5	63
	C2= ELH+UAL(1 - cos32^0)	20-36	NA	31	29
	C3= SHE	63.5-80	NA	68	74.5
	C4 = EH	141-171	154	NA	NA
	C5 = EEB+25cm	79.5	81	NA	NA
Commander workspace	A1= PH + 2cm	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 +5cm	96	108	92	96
	A6= PH + SH +7cm	136	150	125	135
	D1 = SHE	63.5-80.2	NA	72	74

All measurements are in cm unless specified.

NA – not applicable.

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 (Figure 3.5, 3.6, and 3.7). 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.

a) Comparison of dimensions for reach and control units with 5th p predicted value:

According to the body extensions, reaching distance, controlling movements, and field of view (FOV) are restricted (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 3.5. The coordinate points drawn below the 5th p predicted values are considered acceptable measurements; the remaining points need modifications.

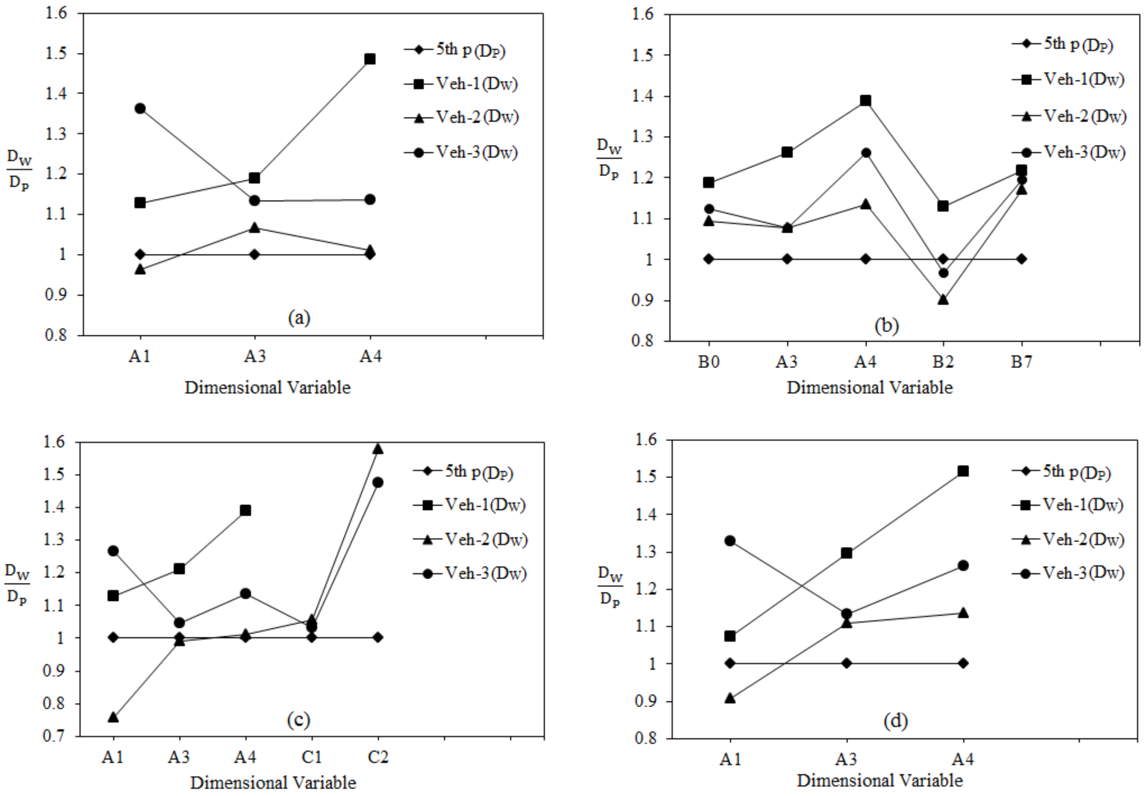


Figure 3. 5: Comparison between the predicted vehicular workspace dimensions associated with the 5th percentile female anthropometry and dimensions of existing (a) crew seat (b) driver workspace (c) gunner workspace (d) commander workspace.

Note. 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 the 5th percentile comparison.

Figure 3.5 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 mismatch of dimensions in Veh-1 was higher than that in Veh-2 and 3. Fewer vehicular dimensions were less than the 5th p values, viz., and infantry troop and gunner seat dimensions (A1, A3, and A4) of Veh-2 and steering wheel height (B2 of Veh-2 and Veh-3). In contrast, the existing reachability, control units, and FOV controlling needs (DW) of Veh-1 and Veh-3 do not accommodate the recommended body sizes.

b) 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 3.6) were considered acceptable; otherwise, modifications were required.

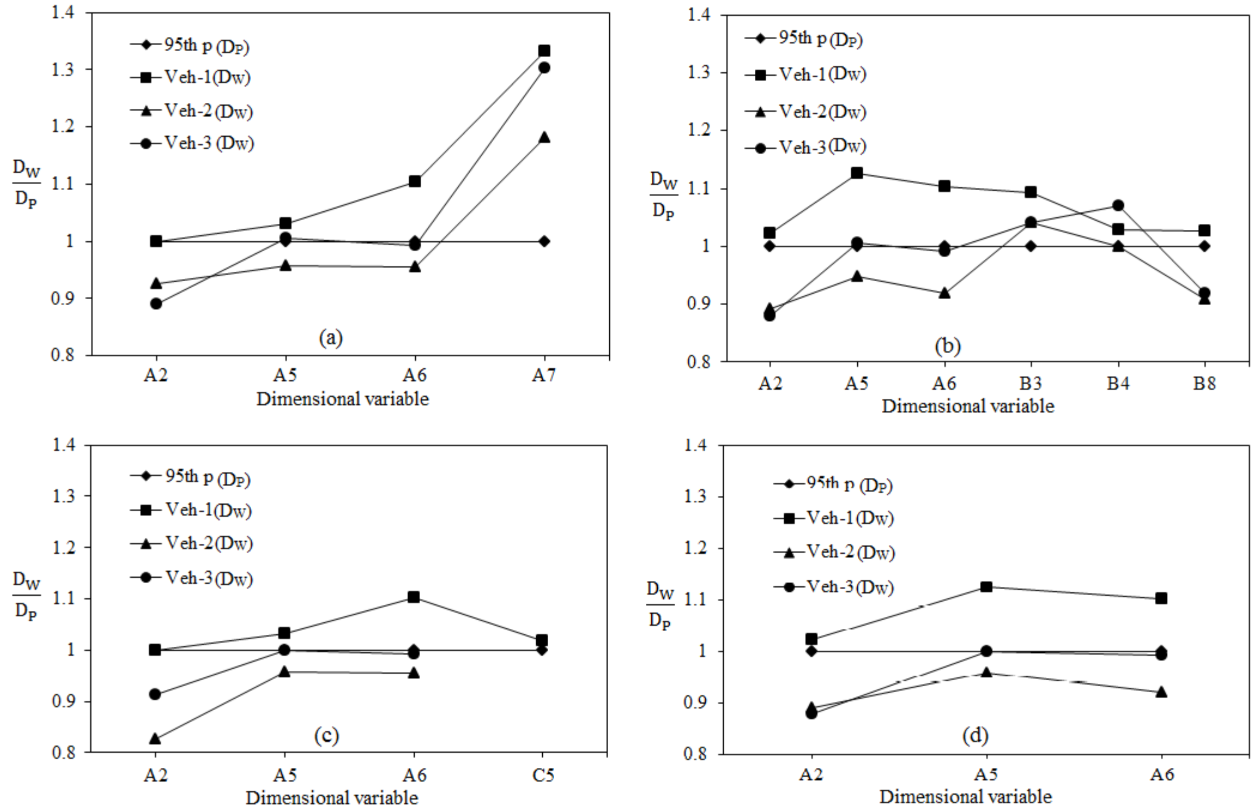


Figure 3. 6: Comparison of the workspace clearance dimensions associated with 95thp values of the anthropometry for (a) crew seat (b) driver workspace (c) gunner workspace (d) commander workspace.

Note. *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 *dimension in the 95th percentile comparison*.

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 3.6, 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 a roof height (A6) of Veh-2 are not adequate for sitting in a normal straight posture. The daylight opening height is also less than the 95th p values in Veh-2 and 3, and therefore, not compatible for army personnel with larger anthropometry.

c) 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 populations, an adjustable unit's maximum limit 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 condition is violated, the workspace measurements could not be accepted and need modification (Figure 3.7).

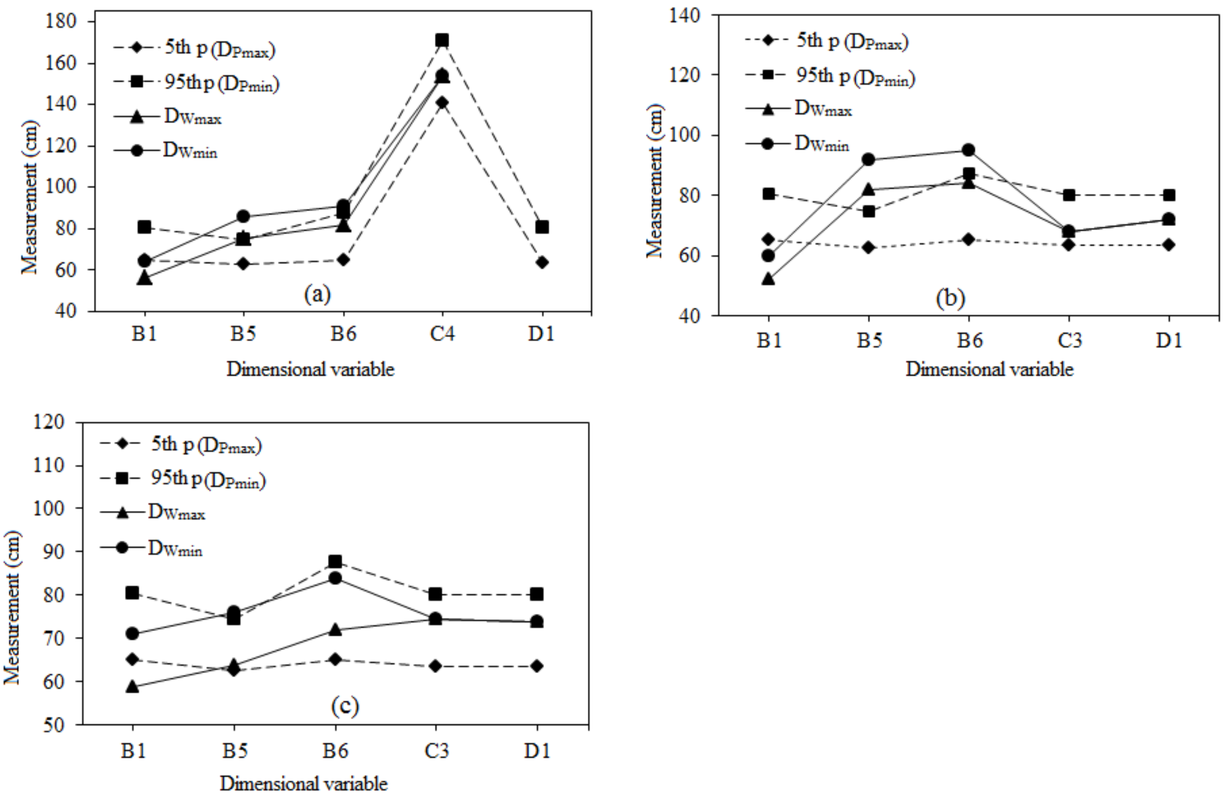


Figure 3. 7: Comparison of the adjustment vehicular workspace dimensions associated with 5thp and 95thp values of anthropometric measurements in (a) Veh-1 (b) Veh-2 (c) Veh-3.

Note. 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 assumes firing in standing posture.
None of the existing vehicles have the provision of adjustability for dimensions C3, C4, and D1.

None of the existing vehicle workspace dimensions satisfied the condition of adjustment over the range 5th to 95thp (Figure 3.7). 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.

3.3.2 Match percentage

Along with an investigation of 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 3.6. Our study emphasizes the boundary values (5th and 95th p) for predicting design dimensions to accommodate at least 90% of the army population.

Table 3. 6: Percentage of match estimation for the individual dimensions of existing vehicular workspace measurements compared to predicted dimensions.

Workspace type	Workspace Dimensions	D_P	Percentage of match					
			Existing vehicular dimension					
			Veh-1		Veh-2		Veh-3	
			Female	Male	Female	Male	Female	Male
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%	100%	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%	0%	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
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%

NA – not applicable

Note. The accommodation capacity of individual dimensions for adjustable and non-adjustable units was considered to be 90% and 95%, respectively regardless of anthropometric diversity considerations.

As shown in Table 3.6, 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 inappropriate for almost all army populations, 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. Tables 3.5 and 3.6 show that 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 compared with the predicted dimensions and those of Veh-2 and Veh-3.

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 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 3.8.

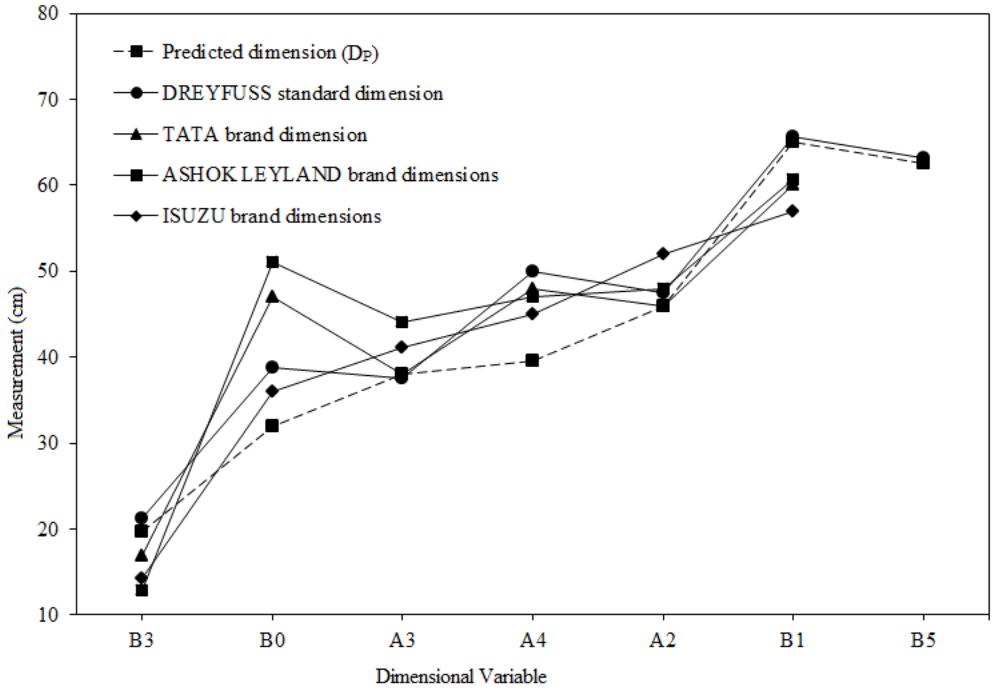


Figure 3. 8: Comparison of the predicted driver workspace design dimensions with other various brands.

Note. *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.*

In Figure 3.8, 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, 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.

3.4 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 (Punchihewa & Gyi 2016; Belmont et al., 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 reaching controls and obstructing 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. (2006) 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 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., 2006).

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 essential (Bhattacharjya and 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 vital for the sighting and control units (Vogt et al., 2005; Hogberg, 2009). Overall, the sighting system and controlling units should be compatible with the anthropometric range of specified users (5th to 95th p) (Mechulam et al., 1976).

The percentage matches for most workspace dimensions are below 75% (Table 3.6). 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 accommodate 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 compared with the male army population (Table 7). Because females' biological and anthropometric characteristics are quite distinct from 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 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 (joint comfort 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 more extensive 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) of 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 and Yadav et al., 2017), there has been no to the best of our literature search other reported research for predicting design dimensions in LAVs. Therefore, the proposed baseline predictive models and design methods are the first of their kind to help ergonomists and designers 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). Apart from anthropometric measurements of Ethiopian soldiers, ROMs should be measured and utilized instead of global standard ROMs. 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, as it was reported in **chapter 2**, 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.

3.5 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 match/mismatch evaluation findings 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.

4

Intervention of ergonomic issue and crew protective aspects in an optimal design of Light Armoured Vehicle

Abstract

Apart from achieving comfortable occupancy for the crew, strengthening crew protective capability from gunfire using the hull obliquity in a LAV is desirable. Thus, it requires a critical design analysis for the obliqued hull. The study aims to present the optimal design analysis of an obliqued hull structure to ensure comfortable occupancy of the crew at its minimum attainable weight and higher protection capability from the gunfire. Three geometric models (G1, G2, and G3) were investigated for the LAV hull's optimal design. The analytical approach was used to investigate the hull obliquity's effect, and the results were validated using experimental data reported by other researchers. The digital human modeling approach was adopted to validate the hull's space adequacy. It was observed that the hull's crew protection capabilities from the horizontal strike of AP rounds were improved almost by half and double for G2 and G3, respectively, when compared with G1. The analytical results also agree with globally accepted experimental data at reasonable variations. G3 can achieve the highest protection capability and comfortable occupancy for the targeted users without affecting the mobility of LAV.

Keywords: oblique angle; effective thickness; projectile deflection; penetration resistance-to-weight ratio; ergonomic design; DHM.

4.1 Introduction

Increasing the effectiveness of passive armour protection by inclining hull surfaces has been common while designing both LAV and HAV (Park, 2017; Wiśniewski and Żochowski, 2013). The lightweight armour design and analysis can be done experimentally or through numerical simulations (Fawaz et al., 2004; Meng et al., 2020). So far, the hull obliquity was extensively tested for crew protective capabilities (Dikshit, 2013; Jena et al., 2010; Khan et al., 2003; Saeimi-Sadigh et al., 2014), without considering much about ergonomics (occupant workspace) and weight factors (vehicle weight). Along with protective capability, the effect of hull obliquity on vehicular weight and occupant space is equally important (Eliyas & Vithal, 2014). The hull needs to be designed with minimum weight and maximum resistance to increase vehicle mobility and reduce material costs (Rahman et al., 2017).

Moreover, the effect of the geometric change on occupant space and vehicular weight is still contradictory, and there is a need to analyze their combined effects (Balos et al., 2010; Zaera and Sanchez, 1998). The desired oblique angle should be predetermined at the initial design stages, and it highly depends on the roof height and base width of the interior space. However, due to the paucity of literature on optimum oblique angle of hull, the random angle has been used by designers during the initial design process towards the enhancement protection capability (Park, 2017).

Armoured vehicles generally provide protection from armour piercing (AP) rounds/bullets (or blasts) by enhancing the hull's protective capability. Khan et al. (2003) noted that evaluating the phenomena of normal and oblique impacts on thin plates is of interest in many engineering applications, like the crashworthiness of vehicles and the design of lightweight body armour. The advancement in using different composite materials has also shown progressive improvement in the survivability of armoured vehicles (Vemuri and Bhat, 2011). To increase the passive protection, the diamond geometric shape of the hull (oblique armoured surface) is one of the commonly used armor types (Vemuri and Bhat, 2011). The shoulder-launched missiles or rounds/bullets are most likely to hit the hull's surface horizontally (Rahman et al., 2017). The obliqued armour plate has been proven to deflect away from the energy of projectiles/bullets that comes from horizontal direction and minimize surface penetration (Yap, 2012). Therefore, to increase armor protection effectiveness, the inclination of the hull surface is relatively common in LAVs (Wiśniewski and Żochowski, 2013).

Regarding ergonomic issues, the workspace's poor design affects crew’s operating performance during carrying and combating missions (Biebuyck et al., 1990). Therefore, human factors are considered to be the most important in military system design (Chatterjee et al., 2019; Liu and Boyle, 2009). While dealing with the ergonomic system design approach in vehicle design, it is necessary to consider a seated person's basic anthropometric dimensions to determine the space height and width (Gillingham and Patel, 2013). Therefore, armoured vehicles’ ergonomic considerations should be given equal importance as protection, mobility, and firing capabilities.

The present research aims to enhance crew protection capabilities of Ethiopian LAVs through-hull obliquity (and its geometries shape) with due considerations of occupant space and mobility of the vehicle. We hypothesize that the change in geometry of the hull will also change protection capability, adequacy of occupant space, and mobility/mass of the LAVs. We sought to test whether the optimum oblique angle increases the vehicular hull's energy absorption capacity when hit by bullets' horizontal projection without adversely affecting mobility and occupant space. The three optimal design constraints viz. occupant space, protection, and mobility of the vehicle were considered to achieve the goal. The occupant space is characterized by roof height and base width of the hull (Gillingham and Patel, 2013); the protection is characterized by energy absorption (Jena et al. 2010) and deflection angle, while the weight of the hull characterizes the mobility. The hull's penetration capability can be enhanced by increasing the hull structure's effective thickness and oblique angle. The optimal hull structure design for LAVs helps address the research questions (RQ-4 and RQ-5).

RQ-4: Does crew protection enhancement due to hull obliquity contradict the ergonomic aspects (space occupancy) and weight of the LCVs?

RQ-5: How is it possible making a design intervention to increase crew comfort and protection capability without variation of weight/mobility?

4.2 Methodology

The effect of the vehicle hull's oblique angles was analyzed on the occupant workspace, its weight, and energy required for penetration (energy absorption capability). The protective capability of the hull at different oblique angles was evaluated. It was tested considering occupant space as an important design constraint. The analytical results (from the present study) were then compared with the experimental results conducted by other researchers to verify the reliability of the study. The optimal solutions of the relevant parameters were computed by taking into account different design constraints and physiques. The agreement of analytical results with experimental data (reported by other researchers) was compared for verification purposes. Finally, the occupant space was evaluated using a virtual ergonomic evaluation technique called DHM to validate the space's adequacy for the targeted users.

4.2.1 Design object (LAV hull structure)

The LAV oblique hull structure (Figure 4.1) was the targeted object that needs to be evaluated and optimally designed for adequate interior workspace and protective capabilities. The shape and size of the hull affect the workspace as well as its protective capabilities (Ramamurthy et al., 2018). The hull's oblique angle and effective thickness were considered the two main factors influencing crew protection performance (Park, 2017). The horizontal projection of armour piercing projectile is considered as the most common direction (Park, 2017), and thus, due to the obliquity, the horizontal penetration distance (effective thickness, t_θ) of the oblique hull would be greater than the actual thickness (t) (Yap, 2012) as shown in Figure 1.4 (See **chapter 1**). The hull obliquity was also supposed to be advantageous in deflection the guided-projectile (Wiśniewski and Żochowski, 2013). Hence, the non-oblique and oblique hull's protective capability was evaluated in terms of the penetration resistance to weight ratio (R). The larger R (R >1) value indicates higher protective capabilities.

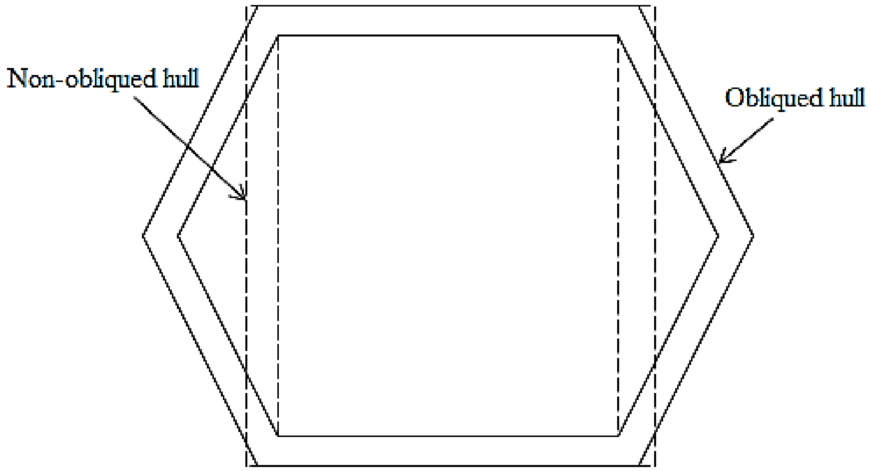


Figure 4. 1: LAV Hull Structure with non-oblique and oblique-angled

The following design assumptions were taken into consideration for designing the oblique hulls:

- Unlike the roof height and base/floor width, the length of occupant space was not considered as a relevant dimension since it has no effect on optimal design analysis of hull obliquity in this particular study.
- The ergonomic effect of hull obliquity was only tested among the infantry crew members seated back-to-back. The ergonomic evaluation does not cover workspaces for the gunner, commander, and driver since they are less likely affected by hull obliquity.
- Even though seat height is usually designed by the 5th percentile (p) value of popliteal height, the roof height from the footrest was considered to be the sum of the mean value of 50th p (male and female) of the popliteal height and 95th p (male) sitting height. The purpose is to accommodate larger users in case of using the seat having larger (other than recommended) seat height.
- The space for placements of the equipment and units such as drive train (including electrical power generation system), fuel storage, mission-essential payload, integral auxiliary equipment were not considered while evaluating occupant space dimensions.
- The study comprised only side hull obliquity (to protect from horizontal projectiles). The hull obliquity at the bottom (to protect against mine blast), front and back of LAV were not included in the study.

- The hull's thickness was considered insignificant in the study to determine hull size.
- The maximum hull width of LAV is assumed not to exceed 2.5 m (Trajkovski et al., 2018).
- This technical design emphasizes only on horizontal projection of AP rounds.

4.2.2 Interior space dimensions w.r.t. occupant/crew anthropometry

The seat height (A1), roof height (A6), and base width (A7) are considered to be the basic dimensions of the occupant space (Figure. 4.2). These dimensions need to accommodate a wide range of user populations adequately and are directly related to the basic anthropometry of seated occupants (Gillingham and Patel, 2013). The basic anthropometric dimensions of seated occupant considered for the interior workspace design were sitting height (SH), popliteal height (PH), buttock to popliteal length (BPL), and foot length (FL) depending on the adopted posture of the infantry troop and geometry of the hull (Figure 4.2a and b). The maximum hull width (B) is directly linked with A1, A6, A7, and oblique angle (θ).

The seated crew's anthropometric measurements and corresponding seat space dimensions are presented and described in Table 4.1 and Figure 4.2. The minimum and maximum interior space dimensions are often limited by 95th p male and 5th p female anthropometry. Similarly, the average dimensions are limited by the combined mean of 50th p female and male anthropometry. This study assumed that infantry troops would be seated at a nearly 90-degree knee angle to determine the minimum legroom (Figure 4.2a). Accordingly, the minimum leg room required for a person was limited by the buttock-popliteal length and foot length.

In a prior study, anthropometric dimensions of Ethiopian armed personnel (250 males and 60 females) were physically measured, as shown in Table 2.2 (**chapter 2**). Their later study (**chapter 3**) used those anthropometric dimensions to predict the relevant vehicular workspace. The same anthropometry dimensions of Ethiopian armed personnel were used in this study. The overall seated height from footrest called roof height (A6) could be approximated from the combination of sitting height (of 95th p male) and mean popliteal height (of 50th p male and female), altogether came out to be 136 cm as presented in **chapter 3** (Table 3.5). The half of A7 of interior space shall be approximated from the combination of the buttock to popliteal length and foot length (of 95th p male) and found to be 82.5 cm for a single person. Therefore, A7 = 165 cm can be considered effective space width to accommodate two crew sitting back to back in two rows. The height, A1 at a rectangular section of geometric design, G3 (Figure 4.2a), as defined by the seat height, which can be determined by the 5th p female popliteal height that came out to be 36.3 cm.

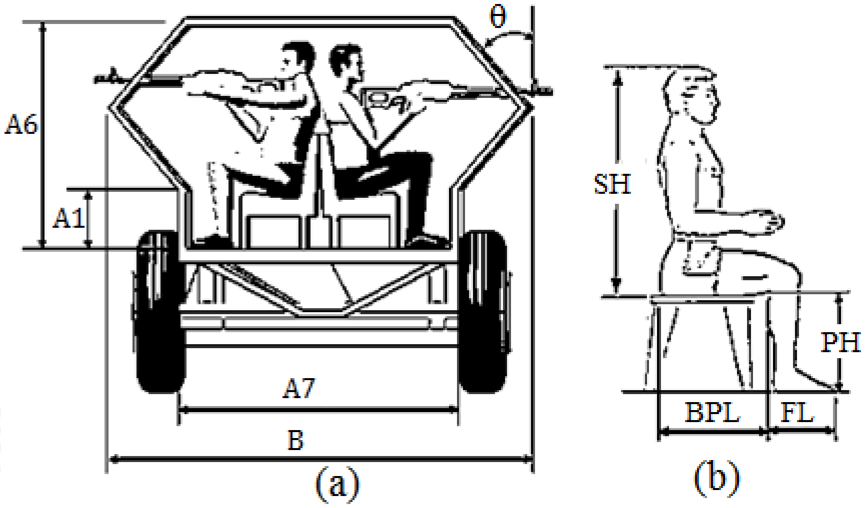


Figure 4. 2: Ergonomic design considerations of (a) infantry troop posture and interior space dimensions (b) relevant anthropometric dimensions.

4.2.3 Geometric models for conceptual design of the hull

Three geometries (one rectangular and two oblique geometries) of LAV hulls have been presented towards comparing different interventions for better ergonomics and protection aspects, as shown in Figure 4.3. The rectangular hull structure (G1) is an ordinary geometric design concept. It has been widely used in the existing vehicular body construction. From the two oblique hull design concepts, G2 and G3, the diamond-shaped hull structure (G2) is an advanced design concept. It has now been the widely used design concept for LAVs and HAVs (Park, 2017; Vemuri and Bhat, 2011). The third geometry (G3) is a new design concept. The current study presents a futuristic LAV design to achieve workspace ergonomic benefits by acquiring adequate legroom for the infantry troops. Since the injury in the leg portion (due to its dense/bone tissue) is not the most severe issue as compared to other soft tissue/organs (e,g. lever, brain, and abdomen), the protection improvement requirement of the hull for lower legs is ignored in the design concept of G3 (Balaji, 2016; Wilson, 1999).

4.2.4 Mathematical modeling for occupant space, penetration resistance, and mass of the hull

A comparative assessment between non-oblique (G1) and oblique (G2, G3) hulls were made to evaluate the effect of oblique hull angle on occupant space dimensions, protective capability, and weight/mobility. Mathematical relationships to formulate,

(a) Hull width (B_i)

(b) Effective thickness (t_θ)

(c) Mass of presented geometries (M_i)

(d) Mass ratio of oblique to non-oblique armor plate (R_{Mi})

(e) The energy required for penetration (E_i)

(f) Ratio of penetration resistance for the oblique to the non-oblique hull (R_{Ei}), and

(g) Penetration resistance to mass ratio (R_i) was established.

a) Hull Width

The width (B) of a non-oblique hull structure (G1) is the same as the base width (A7). However, the oblique hull structure's width (G2 and G3) width depends on the roof height (A6), base width, and oblique hull angle. Additionally, G3 depends on seat height (A1), as shown in Figure 4.3.

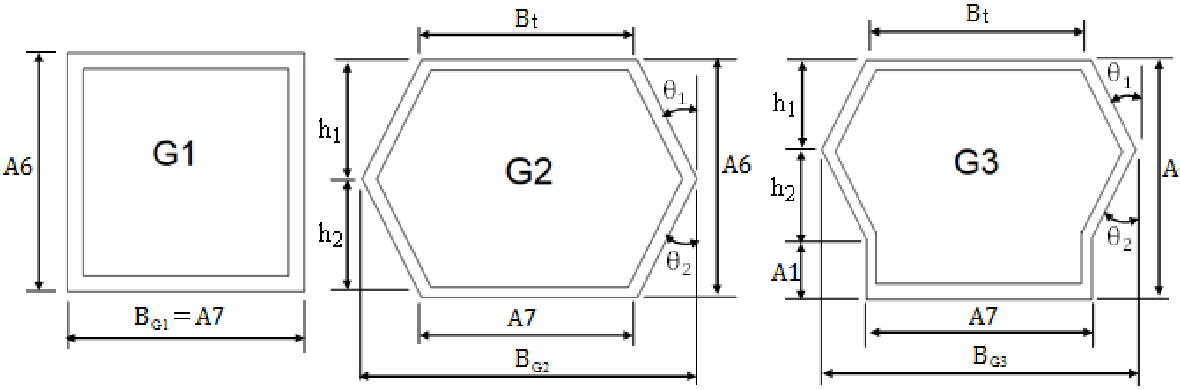


Figure 4. 3: Cross-sectional views and primary design variables for rectangular geometry hull (G1), diamond geometry hull (G2), and combination of diamond and rectangular geometry hull (G3).

The relationships of these parameters for the three geometries were formulated (eqn. 4.1a, 4.1b and 4.1c). For simplifying the models, the following assumptions are made:

$\theta_1 = \theta_2 = \theta$; $2h_1 = 2h_2 = A6$; $B_t = A7$.

For non-oblique hull (G1):

$$B_{G1} = A7 \tag{4.1a}$$

For the oblique hull geometry (G2) at A1 = 0, the width of hull (B_{G2}) can be evaluated as:

$$B_{G2} = A7 + (A6)\tan\theta \tag{4.1b}$$

For the oblique hull geometry (G3) in a certain value of A1, the hull width (B_{G3}) can be evaluated as:

$$B_{G3} = A7 + \left(A6 - A1\right)\tan\theta \tag{4.1c}$$

Where θ is the armour plate oblique angle measured from vertical direction; A7= base width of the hull; A6= roof height of the hull; A1 = seat height targeted to 5th p female.

b) Effective Thickness

As it was mentioned earlier, the projection of guided projectiles mostly comes from horizontal directions (Yap, 2012; Hetherington and Lemieux, 1994). Thus, the horizontal penetration distance (effective thickness, t_θ) will always be greater than the actual thickness, t (non-oblique hull) for the oblique hull. As effective thickness will always vary with oblique angle (See Figure 1.4 in **chapter 1**), the effective thickness can be determined as follows:

$$t_\theta = \frac{t}{\cos\theta} \tag{4.2}$$

Where θ is the armour plate oblique angle measured from vertical direction; t= actual wall thickness of hull; t_θ = effective wall thickness of the hull

c) Mass of Presented Geometries

Mass of non-oblique hull (M_{G1}), the oblique hull (M_{G2}) and (M_{G3}) were formulated (Eqn. 4.3a, b, and c) from the three geometries (see Figure 4.3), respectively.

$$M_{G1} = 2\rho\ell t(A6 + A7) \qquad (4.3a)$$

$$M_{G2} = 2\rho\ell t\left(\frac{A6}{\cos\theta} + A7\right) \qquad (4.3b)$$

And,

$$M_{G3} = 2\rho\ell t\left(\frac{A6 - A1}{\cos\theta} + A1 + A7\right) \qquad (4.3c)$$

Where, θ is the armour plate oblique angle measured from vertical direction; M_{G1} = mass of G_1; M_{G2} = mass of G2; M_{G3} = mass of G3; ρ = material density; t = hull thickness; ℓ = length of the hull having constant cross-section; A1 = seat height (targeted as 5^{th} p female); A6 = roof height of the hull; A7= base width of the hull.

d) Mass Ratio of Oblique to Non-oblique Armor Plate

For evaluating the relative change in mass for oblique hull w.r.t. non-oblique hull, the mass ratio of the oblique hull (M_{G2}) w.r.t. non-oblique hull (M_{G1}) was formulated by substituting eqn. 4.3a and 3 4.b as:

$$R_{M(G2)} = \frac{A6 + (A7)\cos\theta}{(A6 + A7)\cos\theta} \qquad (4.4a)$$

The mass ratio for oblique hull (M_{G3}) and. Non-oblique armor (M_{G1}) can be shown as:

$$R_{M(G3)} = \frac{A6 - A1 + (A1 + A7)\cos\theta}{(A6 + A7)\cos\theta} \qquad (4.4b)$$

e) The Energy Required for Penetration (Penetration Resistance)

The hull that requires higher energy to penetrate is considered to have a good protection capability. The ballistic limit of a projectile can be determined in terms of the kinetic energy needed to penetrate the hull (Armor Penetration Formulas, 2020). The Armor Penetration Formulas (2020) was modeled to predict the total loss of incidence energy (with zero residual velocity after piercing) and stop the armour piercing projectile for protecting the crew inside the hull. Therefore, the formula of energy required to penetrate any oblique armor plate (regardless of effective thickness) would be:

$$E_{(G2,G3)} = 8.025\frac{td^2F^2}{\cos^2\theta} \tag{4.5a}$$

For non-oblique hull (G1) at θ = 0°:

$$E_{G1} = 8.025\,td^2F^2 \tag{4.5b}$$

Where, E_{G1} = kinetic energy needed to penetrate non-sloped hull; E_{G2} = kinetic energy needed to penetrate sloped hull; t = actual hull thickness; d = projectile diameter; F = F-coefficient (dimensionless); θ = oblique angle of hull.

However, the modeled formula (Eqn. 4.5a) does not consider the effective thickness of the oblique-angled hull that was reported by Amare and Karmakar (2021) and Yap (2012). The armor-piercing projectile that comes from a horizontal direction should also consider the increase of effective thickness (penetration distance) instead of the actual thickness (Rahman et al., 2017; Yap, 2012). Therefore, the formula should be modified by substituting actual thickness (t) to $t_e \approx t/\cos\theta$ (see eq. 2). Thus, the modified formula of energy required to penetrate oblique armor plate (G2 and G3) will be:

$$E_{(G2,G3)} = 8.025\frac{td^2F^2}{\cos^3\theta} \tag{4.5c}$$

f) Penetration Resistance for Oblique Hull w.r.t. Non-Oblique Hull

For comparing the penetration resistances of the oblique hull (G2 and G3) w.r.t. non-oblique hull (G1), the energy ratio ($R_{E(G2,\,G3)} = E_{(G2,\,G3)}$: E_{G1}) required to penetrate the hull plate can be formulated by substituting Eqn. 4.5b & Eqn. 4.5c:

$$R_{E(G2,\,G3)} = \frac{1}{\cos^3\theta} \tag{4.6}$$

Since $|\cos^3 \theta| < 1$, the ratio $R_{E(G1,G3)}$ will always exceed 1 (Yap, 2012). This implies that penetration resistance of obliqued hull (G2 and G3) will always be greater than G1.

g) Penetration Resistance to Mass Ratio

Similarly, penetration resistance to the mass ratio of obliqued hulls (G2 and G3) w.r.t non-oblique hull (G1) was formulated to investigate the effect of hull obliquity (on its mass) for improved protection capability. It can verify the relative change of penetration resistances w.r.t mass (in terms of hull obliquity). The ratio ($R_{G2} = R_{E2}$: $R_{M(G2)}$) of energy required for penetration (energy absorption) of the oblique hull (G2) to its mass was formulated by substituting Eqn. 4.4a and Eqn. 4.6 as:

$$R_{G2} = \frac{A6 + A7}{(A6)\cos^2\theta + (A7)\cos^3\theta} \tag{4.7a}$$

Similarly, the ratio ($R_{G3}= R_{E(G3)}$: $R_{M(G3)}$) of energy required to penetrate the oblique hull (G3) to its mass was formulated by substituting Eqn. 4.4b and Eqn. 4.6 as:

$$R_{G3} = \frac{A6 + A7}{(A6 - A1)\cos^2\theta + (A1 + A7)\cos^3\theta} \tag{4.7b}$$

4.2.5 Problem definition of optimization

The optimal design variable is the oblique angle θ, and the objective function is used to maximize the penetration resistance to mass ratio, R_i (θ) of the oblique hull structure w.r.t. non-oblique hull (G1). The constraints of the objective function were defined briefly as follows:

1. $g_1 = B_{G1}(\theta)|_{\theta=0°} - B_{max} \leq 0$. This implies that the width of the rectangular hull structure (G1) at an oblique angle, θ=0°, should not exceed the maximum allowable width, B_{max}=2.5, which should be defined by transportability and mobility factors (Gillingham and Patel, 2013).

2. $g_2 = B_{G2}(\theta)|_{A1=0} - B_{max} \leq 0$. This implies that any geometric hull structure's (G2) width at A1 =0 should not exceed the maximum allowable width.
3. $g_3 = B_{G3}(\theta)|_{A1=c} - B_{max} \leq 0$. This implies that any geometric hull structure's (G3) width at a particular value c of A1 should not exceed the maximum allowable width.
4. The roof height (A6) (Figure 4.3) should exceed the minimum roof height ($A6_{(min)}$), determined using anthropometry of the user populations (to accommodate a wide range of the seated army personnel or infantry troops).
5. The base width (A7) (Figure 4.3) should exceed the minimum base width ($A7_{(min)}$) that was determined by anthropometry of the user populations seated back to back in the LAV.
6. The height of the lower rectangular portion of the oblique hulls, determined by the seat height (A1) (Figure 4.3), should not exceed the maximum seat height ($A1_{(min)}$) to protect the upper portion of the body (upper limb) of a wide range (95%) of soldier population.
7. The design variable θ shall always be positive and should not exceed 60° (Rubin and Yarin, 2002).

The general optimization problem was addressed as follows:

Find: θ

$$\text{Maximize}: F_i(\theta) = R_{Gi}(\theta), \quad i = 1,2,3 \tag{4.8a}$$

$$\begin{aligned}\text{Subjected to}: g_i &= B_i(\theta) - B_{max} \leq 0, \quad i = 1,2,3\\ A6 &\geq A6_{(min)}\\ A1 &\leq A1_{(max)}\\ A7 &\geq A7_{(min)}\\ \theta_{min} &\leq \theta \leq \theta_{max}\end{aligned} \tag{4.8b}$$

MATLAB optimization toolbox was employed for plotting the results of this non-linear optimization problem (Pavlovic et al., 2017).

4.3 Result and discussion

In this section, the effect of oblique angles of the presented geometries of hulls on different attributes viz. penetration resistance in terms of the required energy for penetration of the hull, masses of the presented hulls penetration resistance to weight ratio, hull width, roof height, and base width were analyzed and explained thoroughly. After verifying the effect of hull obliquity on the attributes mentioned above, the optimum angles were evaluated for all three geometric hulls. The analytical models were also confirmed using experimental data reported by other researchers.

4.3.1 Effect of oblique angle on crew protection and mass of the hull

The influence of oblique angle on both crew protection and mass of the hull was investigated analytically with considering space occupancy. The space occupancy was constrained by A6= 1.36 m, A7= 1.65 m, and A1 = 0.36 m (see Table 3.5) with varying hull width (w).

a) Effect of oblique angle on penetration resistance of the three geometries

The penetration resistance ratio between obliqued and non-obliqued hull (R_E, Eqn. 4.6) was plotted at different oblique angles (Figure 4.4a).

For the same wall thickness and length, the energy required for penetration of non-oblique hull approximately increased by twice at 40° and eight times at 60° when compared to the non-oblique hull, G1 (see Figure 4.4a). The two oblique geometries (G2 and G3) showed no difference in penetration resistance regardless of their mass variations. Therefore, the protective capability can be improved using either of them. Consequently, it can be said that obliquity is one of the most crucial factors that increase the protective capacity of the hull structure from the piercing projectile that comes from the horizontal direction. Vemuri and Bhat (2011) also noted that the diamond-shaped (obliqued) hull deflects energy from sources causing minimum damage to the hull.

b) Effect of oblique angle on masses of hulls in the presented geometries

The mass ratio of the obliqued and non-obliqued hull structures (R_M, eqn. 4.4) were plotted at different oblique angles (Figure 4.4b).

From Figure 4.4b, it can be noticed that as the oblique angle increases, the mass ratio (between obliqued and non-obliqued hull) also increases. The mass change at a larger angle was relatively higher than at a smaller angle. Further, G2 exhibits somewhat larger values as compared to G3. It implies G3 to be more advantageous as it gives the same protection capability with minimum weight. In general, the hull obliquity increases its mass w.r.t. non-oblique hull, which is undesired for effective mobility of the LAVs. The increased overall weight (with increased obliquity) of the LAV decreases its mobility and increases material cost. Moreover, mobility is crucial as it provides the fast movement of the LAVs during military operations such as carrying, patrolling, scouting, transporting, and combating (Wong, 2009). Therefore, penetration resistance to mass ratio (between obliqued and non-obliqued hull) is vital to decide the worthiness of providing hull obliquity over increased hull weight (see the next section).

c) *Effect of oblique angle on penetration resistance-to-mass ratio*

The combined effect of penetration resistance-to-mass ratio (R_i, Eqn. 4.7) was evaluated at different oblique angles, as shown in Figure 4.4c.

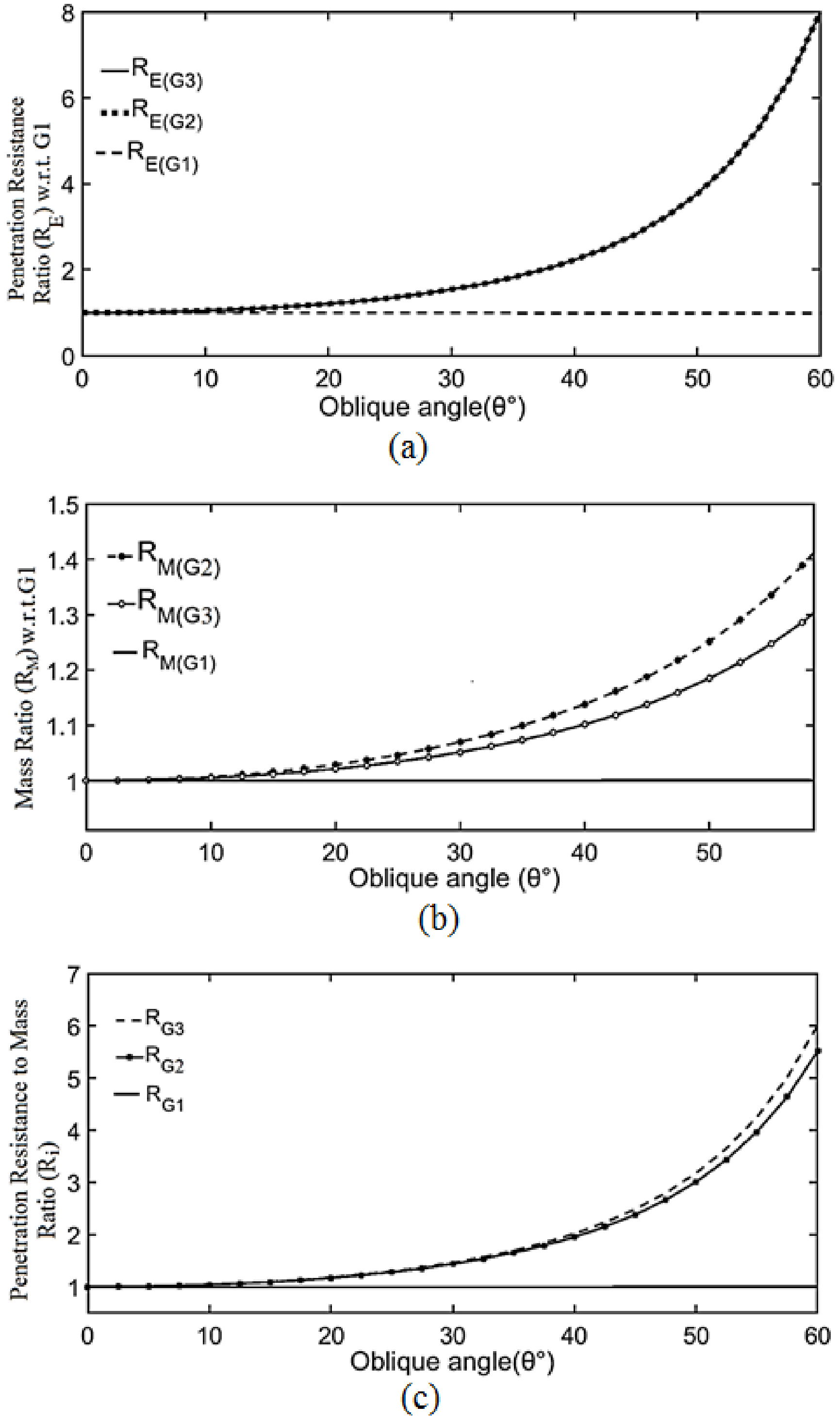


Figure 4. 4: Effect of oblique angle on (a) penetration resistance (b) mass ratio (c) penetration resistance to mass ratios

In both obliqued geometric hulls, the R-value is greater than 1, and grows exponentially with higher values of oblique angle (Figure 4.4c). The G3 exhibits slightly greater penetration resistance to mass ratio (R) values than G2 and thus more preferable than G2. In general, an obliqued hull was conceived to have higher crew/occupant protective capabilities in military operations. Park (2017) also noted that the penetration resistance in obliqued hulls (with the same thickness and material type) is relatively higher than in the non-obliqued plate. The obliqued hull has a higher incident angle that increases the penetration distance of the hull. Since LAVs are utilized in dangerous environments during carrying, scouting, patrolling, and combating, the improved protective capabilities have their justification (Vemuri and Bhat, 2011).

4.3.2 Effect of oblique angle on hull width and interior space

The variation in constraints (B, A6, and A7) was graphically tested w.r.t oblique angle. The globally accepted value of the maximum allowable width constraint, B_{max}= 2.5 m, was decided based on a previous study by Trajkovski et al.(2018), while the values of A6 and A7 were taken as 1.36 m and 1.65 m as per occupant space dimensions in terms of user anthropometry (Table 3.5). The graphs were plotted, two of them fixed, and one as an axis of ordinates with oblique angle (θ).

a) Effects of oblique angle on the width of the hull

For fixed/constrained values of A6 =1.36 m, A7=1.65 m, and B_{max}=2.5 m, the effects of oblique angle on vehicular hull width (w) were investigated and presented as shown in Figure 4.5a.

From Figure 4.5a, for the constrained values of A6, and A7, it was evident that the hull width G2 and G3 had a direct linear relationship with an oblique angle. The larger values of oblique angle lead to higher hull width. However, G3 exhibits a relatively smaller hull width than G2 for the same hull obliquity of any angle (except 0°). Therefore, G3 is desirable to have a compact hull from its size aspect.

b) Effects of Oblique Angle on Roof Height

For the fixed value of B = 2.5 m, A7=1.65 m, and $A6_{(min)}$=1.36 m, the hull's roof height (A1) of the hull at different oblique angles was investigated graphically in Figure 4.5b.

From Figure 4.5b, it was observed that the roof height in both G2 and G3 had an inverse relationship with an oblique angle. The larger values of oblique angle lead to lower roof height of the oblique hull. Therefore, it affects the occupant space height as the obliquity of the hull increases. However, G3 exhibits a relatively larger roof height than G2 in the same obliquity. It is desirable to have an adequate hull space whenever the larger oblique angle is required for survivability enhancement.

c) Effect of Oblique Angle on Base Width of the Hull

Similarly, for the fixed value of B = 2.5 m, A6= 1.36 m, and $A7_{(min)}$ = 1.65 m, the base width (A7) of the hull was also explored at different oblique angles, as shown in Figure 4.5c.

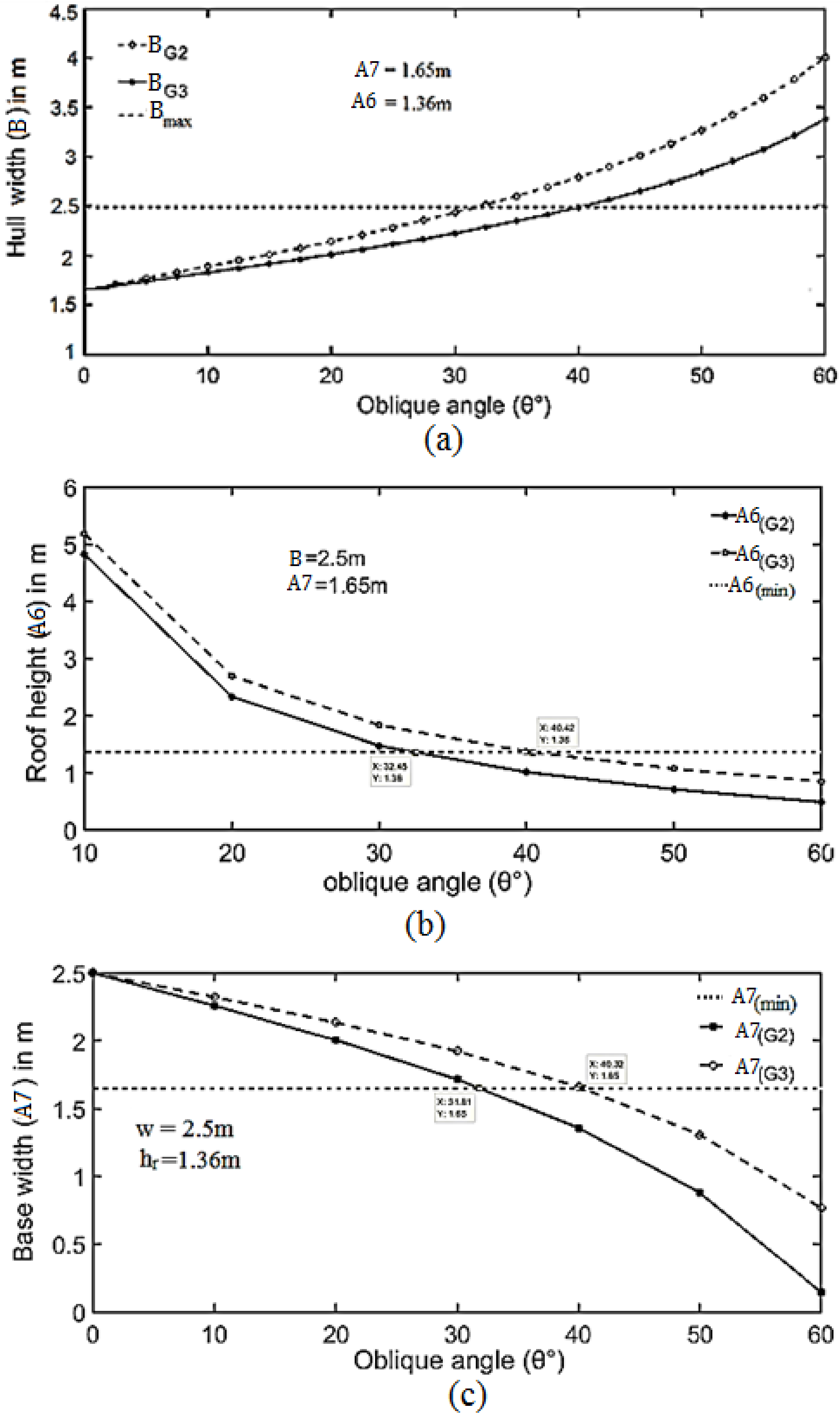


Figure 4. 5: Effect of oblique angle on base (a) hull width (b) roof height (c) base width

From Figure 4.5c, it was observed that the base width in both G2 and G3 had an inverse relationship with an oblique angle. The larger the oblique angle, the lower the base width of the hull. Therefore, as the obliquity of the hull increases, the base width of occupant space decreases. However, G3 shows a relatively larger base width compared to G2 for the same obliquity and overall hull width. Hence, G3 can be the suitable alternative as it increases the base width without affecting other parameters (oblique angle, hull width, and roof height). Therefore, it may increase infantry troops' legroom and footrest space (in back to back sitting position) (see Figure 4.2a).

4.3.3 Optimum oblique angle and its corresponding penetration resistance for the three geometries

As discussed in previous sub-sections, the plotted result in Figure 4.4c revealed that the higher penetration resistance-to-mass ratio (R) can be obtained at a larger oblique angle. Also, the effect of change in oblique angle was constrained by maximum hull width (B_{max}) (Figure 4.5a), minimum roof height ($A6_{(min)}$) (Figure 4.5b), and minimum base width ($A7_{(min)}$) (Figure 4.5c). The values of B_{max}, $A6_{(min),}$ and $w_{b(min)}$ respectively were decided to be 2.5 m (Trajkovski et al.,2018), 1.36 m, and 1.65 m (Table 3.5). Based on these values, the optimum (maximum) oblique angle for the three geometries was found using Eqn: 4.1a, 4.1b, and 4.1c. Following the determination of optimum angles in all geometric hulls, penetration resistance-to-mass ratio, $R_{(G1,\ G2,\ G3)}$ (in Eqn. 4.8) was determined. The optimum oblique angles and corresponding $R_{(G1, G2, G3)}$ were presented in Table 4.1.

Table 4. 1: Optimum oblique angles and corresponding penetration resistance-to-mass ratios among three geometric hull models

Geometric hulls	Optimum oblique angle*	$R_{(G1, G2, G3)}$
G1	0°	1
G2	32°	1.51
G3	40.4°	2.03

* For the value of A6=1.36m, A7=1.65m, B=2.5m & A1=0.36m

As shown in Table 4.1, the maximum optimal angles for G2 and G3 came out to be 32° and 40.4°, respectively. The corresponding maximum attainable penetration resistances to mass ratios were found to be 1.51 and 2.03. It implies that the protection capability of G3 was improved by double while an additional half improved G2 to the non-obliqued hull, G1. This can substantially improve hull protection capability without varying mass and mobility.

4.3.4 Verifications of the analytical models

The analytical models were compared with experimental results of energy absorptions (penetration resistance) for armor plates reported by Jena et al. (2010) (Figure 4.6). As shown in Figure 4.6a, the experimenter (Jena et al., 2010) aimed to investigate the effect of oblique angles on the penetration of Al-7017 plates with non-deformable steel projectiles at a velocity of 840.15 m/s at different angles of impact (0°, 15°, 30°, 45°, and 50°). Primarily, to compare their experimental results (see Figure 4.6a) with ours (in term of the penetration resistance ratio, R), the experimental result at each aforementioned angle was determined in terms of R-value by dividing the energy absorption at each oblique angle with the energy absorption at 0° (320 Joules) (see Figure 4.6b).

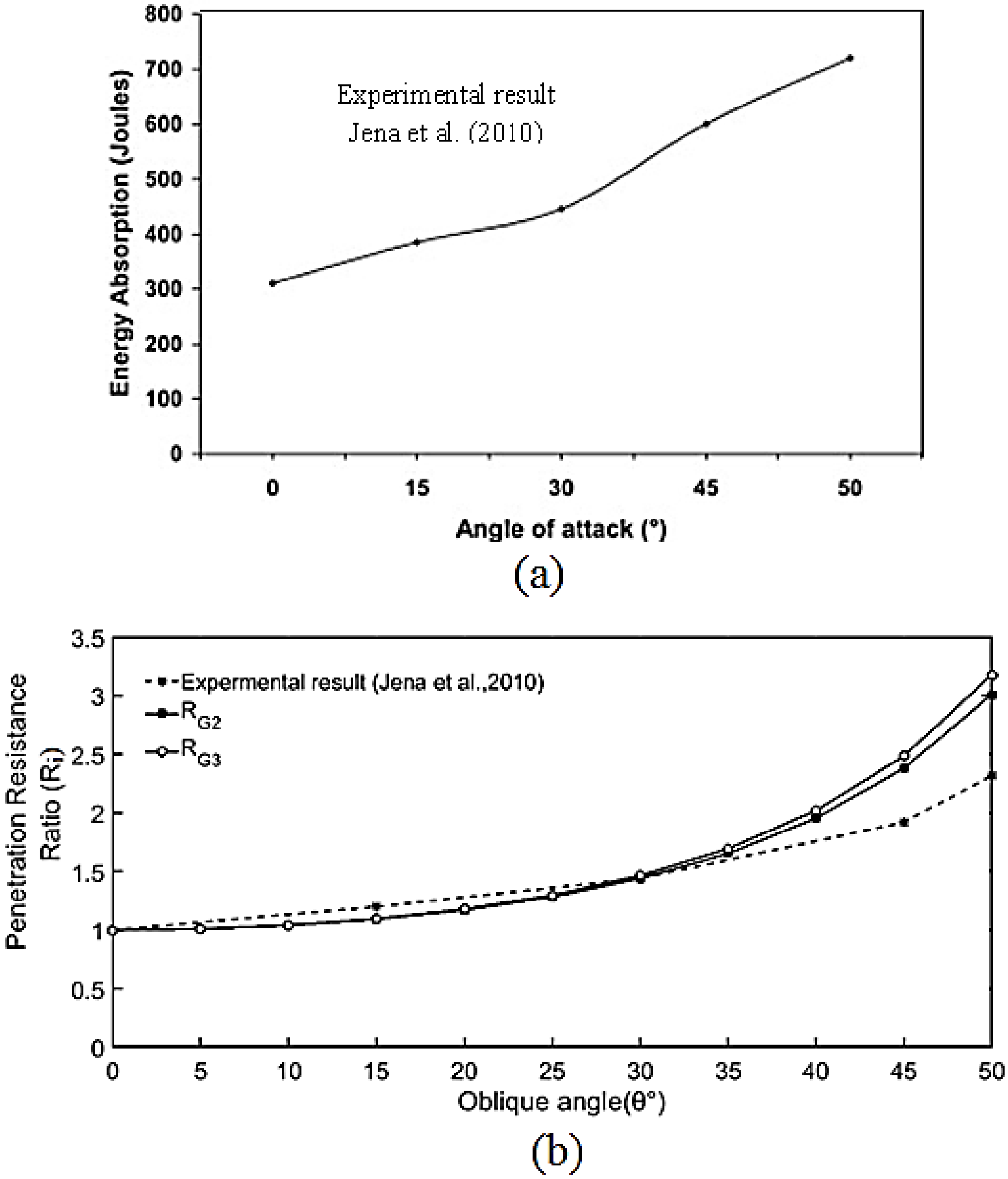
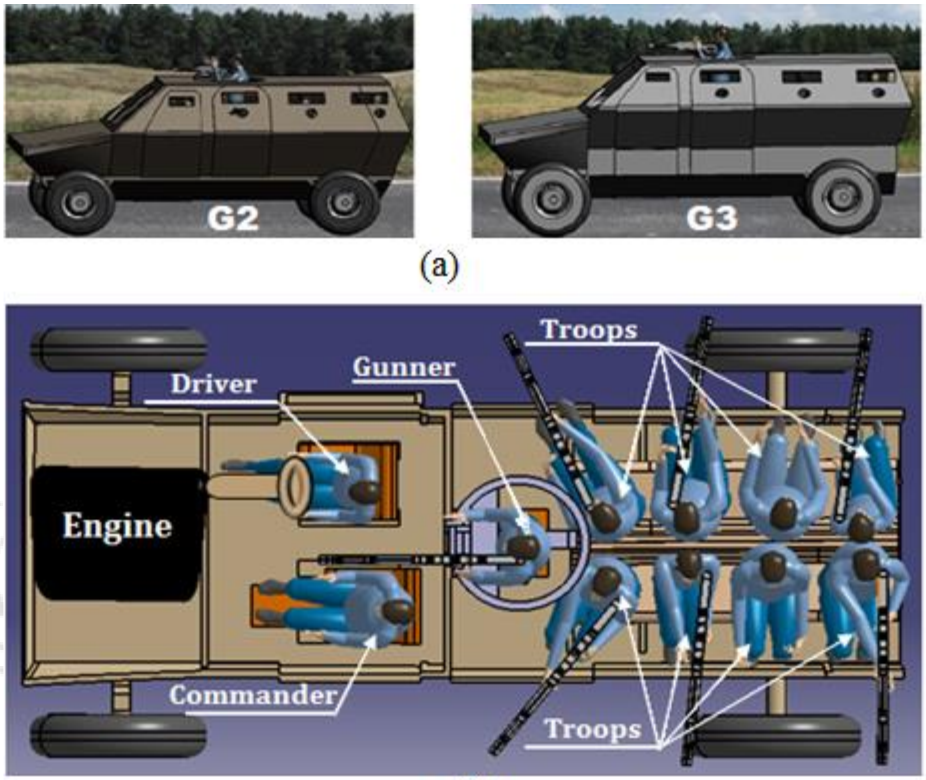


Figure 4. 6: Data verifications of energy absorption (a) Experimental result *(Jena et al., 2010)* (b) Comparison of analytical result with experimental results

From Figure 4.6a, the experimental result of energy absorption grows exponentially with higher values of oblique angle (Jena et al., 2010). From Figure 4.6b, it was evident that the penetration resistance (energy absorption) in both obliqued hulls (G2 and G3) has a slight variation with experimental data (Jena et al., 2010). Therefore, the analytical results were found to be a reasonable agreement with the experimental results even though the effect of obliquity on mass was not taken into consideration in the experimental study reported by Jena et al. (2010). Therefore, the protective designs against armor-piercing (AP) projectiles impacts shall also be considered to improve the LAV hull protection to increase the survival chances of the occupant/crew.

4.3.5 The optimized models of proposed vehicles and overall dimensions of LAVs

Apart from optimizing geometries of the vehicle hull for accommodating the specific user populations, the complete models of both proposed geometries (G2 and G3) and the accommodation workspaces for squad numbers and the main components/engine were presented as shown in Figures 4.7a and b. The proposed geometric hulls were supposed to be adopted with standard compartments/component sizes such as engine housing, powertrain/transmission system, wheels and tyres, ground clearances, turrets, radiators, and chassis. The occupant space length (L) was provided to be 420m to accommodate 11 total crew and troops, including drivers for vehicles used for standing gunners as shown in Figure 4.7a. However, the accommodation capacity of the vehicle for seated gunner is expected to be reduced to 9 members in the same length (L=420m) since the 360^0 traversed turret, and seated gunners needs additional space compared to firing workspace in standing posture. Hence, the overall length, width and height (L x B x H) were determined to be 550, 250 and 206 cm, respectively, taking into account the size of space occupancy of hull, front compartment for engine housing, power transmission system, blast protection V-plate and ground clearance of vehicle. The main components/engine, overall dimensions and specifications of different vehicle models from Ethiopia (veh-1, veh-2 and veh-3) and global standard vehicles were described **Appendix 3 and 4**.



(a)

(b)

Figure 4. 7: Proposed DMU with (a) complete models of G2 and G3 (b) the four workspaces along with the 11 crew/troop manikins

4.3.6 Manufacturability aspects for proposed models

Traditionally, the armoured hull of fighting vehicles has been fabricated from high-strength steels (Lenihan et al., 2019). Even though some hull components such as vehicle turrets require casting process, armoured hull is usually produced in the form of sheet metal plates called rolled homogeneous armour (RHA). Metal Arc Welding (MAW) and metal inert gas welding (GMAW) are widely used in the process of joining armour plates (Cabrilo et al., 2018). Corner welding joint is common in the oblique hull structure of metal armoured vehicles, as shown in Figure 4.8, the same as our proposed model geometries (see Figure 4.7). Therefore, unless there is a hidden factor, the manufacturability of those proposed vehicle models is not a major issue. Some standard sizes, such as the chassis dimensions, require adaptations to the existing manufacturing facilities and standards based on the hull base width of 1.65 m (A7) and length (L), which may define the width and length of the chassis.


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Figure 4. 8: Hull structure of existing Ethiopian armoured vehicle called APC *(Photo taken from Bisoftu Automotive and Locomotive Industry, Ethiopia)*

In general, apart from the optimal design of the oblique hull model required to enhance protection capability, ergonomic factors are the other desired requirements. Inappropriate hull geometry and hull obliquity may lead to excessive hull width, reduced protection capability and mobility, and adversely affect space occupancy adversely[1]. Different models of LAVs were reported in various literature without considering the optimal solutions of design variables for different physiques (Park, 2017). As a result, the enhancement of protection capability, mobility, and comfortable space of the hull are vulnerable to reduce.

This study was not carried out without limitations. Though various studies reported numerical simulations and experimental tests to investigate the protection capabilities in LAVs (Kim et al., 2007; Trajkovski et al., 2018; Wiśniewski and Żochowski, 2013), there must be to have a need to evaluate optimal hull obliquity parameters for effective occupant space/ergonomics at its attainable minimum weight. Therefore, this research was conducted to analytically study the obliquity of LAV armour plate to explore its tangible benefits for comfortable occupancy and minimum weight and improved protection capabilities. Future directions may include validating these results using physical experimentation (similar to Dikshit, 2013) and numerical simulation (similar to Park, 2017) at different vicinities of the hull. The mass incurred due to the hull obliquity and form geometry should also be considered during experimental validation for crew protection capability of the hull from AP rounds. Therefore, before experimental validation, one shall be cautious about using the results obtained in this study to conceptualize LAVs at their attainable minimum weight and maximum protection capability. The proposed geometries may still require some changes (particularly at the top portion of the hull) even though the simple geometric design and simplified mathematical equation were used for this study. The present study only addresses the optimal design of the side hull. Thus, further studies may be needed to analyze the obliqued features at the bottom, front, and back of the LAV.

Overall, the hull's increased protection capability results from the proportional increase of effective thickness and deflection angle. Perhaps this is the reason to design an armoured vehicle with obliqued hull structure. Therefore, to minimize terrorist attacks on military troops, significant efforts should be made to improve the performance of LAVs (Wibneh and Karmakar, 2021). The present research focuses on optimal hull design with ergonomics consideration along with protection enhancement.

4.4 Conclusion

The current study demonstrated that the small variation of oblique angle on hull geometry would substantially change the protection performance and space occupancy of LAVs. The optimal design of LAV was carried out in a way that hull obliquity can be utilized to improve the protection capability without affecting mass/mobility and space occupancy. When the hull is supposed to be pierced by the horizontal projection of launched projectiles/bullets, the study confirmed that the penetration resistance of G2 (with an optimal oblique angle of 32°) could be improved almost by half, without affecting its mass/mobility. Similarly, G3 (with an optimal oblique angle of 40.3°) can be improved by double when compared with a non-oblique hull. This research will encourage engineers/designers to evaluate the protective capabilities of the LAVs while considering ergonomic aspects.

On the contrary, the V-shaped hull geometry's main drawback is reducing the LAV's interior space and increasing its mass. Therefore, a new geometric shape was presented as an optimal design concept. It provided increased penetration resistance and effective space occupancy without affecting weight. Considering specific user populations (Ethiopian army personnel) in this study, we proposed well-suited space occupancy for a wide range (5^{th}p to 95^{th}p) of military users. The methodology used to analyze the optimal parameters can be used to set the standard when developing the conceptual design of LAVs.

5

Ergonomic Validation of Digital and Physical Workspace Mock-Ups of Light Armoured Vehicle

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Abstract

Compact workspace in armoured vehicles can create dimensional incompatibility to accommodate a wide range of user populations. The study aims to examine the compatibility of predicted workspace dimensions of Light Armoured Vehicle (LAV) using digital and physical evaluations to provide ergonomic recommendations regarding design dimensions. The purpose was to ensure the accuracy of the predicted ergonomic design dimensions according to anthropometry of the Ethiopian army early in the design of new LAVs. Physical and digital models were made following the workspace dimensions (as a function of static and dynamic anthropometry) proposed by previous studies. DMU was interfaced with human manikin based on anthropometries (5th p female and 95th p male values) of the Ethiopian army population to test the dimensional compatibility. CATIA V5 software was employed for developing digital human and vehicle models, while the PMU was tested by using 13 Ethiopian army personnel (six males and seven females). By integrating the DMU and PMU evaluation results, we validated the dimensional compatibility of LAV. The intended vehicular workspaces for space adequacy, concerning view field, reaching, and manipulative needs, were found to be ideally compatible with the target users (Ethiopian army personnel) to accommodate 90% (for adjustable units) and 95% (non-adjustable) of them. Hence, the

proposed twenty-two basic design dimensions of LAV workspaces (for the driver, gunner, commander, and the rest of the infantry troop) were ensured to be compatible with the target users during digital and physical evaluation. Our findings indicate that the newly proposed design dimensions can be utilized as design standards for fabricating Ethiopian LAVs. The occupational compatibility between vehicular workspace dimensions and anthropometry can reduce the occupational risk involved and improve the crew operational efficiency. The study design used in the present research can also be utilized for designing vehicles other than combating LAVs.

Key words: physical ergonomics; digital human modeling; digital mock-up; physical mock-up; vehicular workspace; Ethiopian soldier; anthropometry

5.1 Introduction

The interior workspace design in a combat vehicle poses substantial design challenges, especially when the interior spaces are intended to be compacted (Rahman et al., 2017). Light armoured vehicles (LAVs) carry the soldiers during patrolling and combating missions (Wibneh et al., 2021a). Therefore, while designing LAVs, the designer needs to focus on ergonomic considerations related to seat comfort, reachability, and operational comfort among gunner, commander, driver, and other crew members. The ergonomic evaluation of the vehicle can ensure anthropometric compatibility of the interior workspace in the extended field of view, and reachability to control units (Brkić et al., 2015). Anthropometric compatibility of a workspace increases the safety and performance of the users by minimizing the exposure to physical risk factors such as awkward posture contact stress (Eyal et al., 2013; Wibneh and Karmakar, 2021). Li and Haslegrave (1999) suggested that the vehicles should be designed in taking account of the maximum accommodation capacity of the workspaces and user comfort. It may also help achieve a vehicular workstation eminently suited for the users involved in military task missions (Sinha et al., 2021). Therefore, the ergonomically designed LAVs may facilitate user performance, comfort, and safety while accomplishing a difficult combat mission.

The anthropometric compatibility of a vehicular workspace can be evaluated using two ergonomic approaches. First, the conventional evaluation approach requires a PMU / prototype to evaluate anthropometric design compatibility by the test subjects (Soon et al., 2015). Although this process is time-consuming, quite expensive (Helander, 2000), and may be subject to accident risk (Koradecka et al., 2010), it ensures practical effectiveness (in terms of error detection, functionality, usability, etc.) in a real environment (Aromaa et al. 2014). The second approach to test anthropometric compatibility is virtual evaluation using DHM. It is a proactive evaluation technique performed before fabricating the physical prototype during the conceptualization stage. CAD-based virtual evaluation allows testing a product in the early design phase, which reduces development cost and time (Aromaa et al., 2014). Nowadays, CAD-based human modeling and simulation technology (CATIA, DELMIA, JACK, RAMSIS) have emerged as commercially available advanced tools used by many industrial sectors (Karmakar et al., 2012; Demirel et al., 2021). Even though the context of the use is better delivered in DHM due to visualization of the ability to perform the real task, both kinds of mock-ups (MUs) are needed when evaluating ergonomic issues and validating user requirements (Aromaa et al., 2014).

Many studies employing Computer-aided design (CAD) based virtual evaluation of vehicular workspaces have been carried out (Ahmed et al., 2019, Jung et al., 2009 and Yang et al., 2007). However, only a few of them investigated interior workspace of military vehicles by employing digital human modeling (DHM), and were mainly focused on egress-ingress (Sabbah et al., 2009), reachability (Naddeo et al., 2014), vision analysis (Karmakar et al. 2012), spinal load analysis (Maradei et al., 2016), head and lateral clearance (green et al., 2004), comfort analysis (Porter and Gyi, 1998, Krist 1994), and posture analysis (Kent, 2008). While evaluating survivability, firing power, and mobility of combat vehicles, none of the studies concerned about ergonomic aspects. Particularly in Ethiopia, designing army vehicles is quite challenging as currently no anthropometric database is available and anthropometric variability was evident across ethnicities and nationalities (Wibneh et al., 2020). In a prior study (Wibneh et al., 2021a), existing Ethiopian LAVs were incompatible in their ergonomic design of accommodating varied anthropometry of the Ethiopian military.

For developing any workspace suitable for user anthropometry, three ergonomic design considerations need to be identified. The workspace may be designed for the “maximum individual size (95th p-value)” or for the “minimum individual size value (5th p-value)”. Theoretically, workspace dimensions in both design principles can accommodate 95% of the user population. Lastly, "designing for an adjustable range" considers both the 5^{th} p and 95^{th} p-value to accommodate a wide range (90%) of the user population (Wibneh et al., 2021a).

The study aims to examine the accommodation compatibility of ergonomically designed vehicular workspace early in new LAVs. The virtual (DHM) and physical model of twenty-two proposed interior workspace dimensions were verified as per the wide range of anthropometry of the Ethiopian military. Compatibility evaluations such as clearance, comfort, reach, vision analyses were conducted to test the proposed intervention in a human-centered design perspective. Validation of LAV MUs developed by the predicted workspace dimensions helps address the research question (RQ-6).

RQ-6: How much percentage of the Ethiopian army personnel can the army vehicle accommodate after an intervention has been made?

5.2 Research workflow

The present investigation is the next part of a longitudinal study. Figure 5.1 demonstrates the strategy we followed as we progressed in evaluating the interior workspace of Ethiopian LAVs. An anthropometry survey of Ethiopian army personnel was conducted in the prior studies (Wibneh et al., 2020; 2021b). Conventional research was conducted about the match/mismatch assessment according to user anthropometry on the three existing and widely used Ethiopian LAVs (veh-1, veh-2 and veh-3) was carried out (Wibneh et al., 2021a). Following match/mismatch assessment, Wibneh et al. (2021a) predicted design dimensions according to the anthropometry of the Ethiopian military. As crew protection is an uncompromising aspect in LAVs, an optimal design analysis of obliqued hull structure to ensure comfortable occupancy of the crew and higher protection capability from the gunfire was done (Wibneh et al. 2021c). In this study, we validated the anthropometric compatibility of LAV workspaces which were developed as per the predicted design dimensions (Wibneh et al., 2021a) by virtual and physical ergonomic evaluations. This particular study has been conducted with two phases: phase 1 and phase 2 studied the anthropometric compatibility of digital and physical workspace MUs of LAVs, respectively.

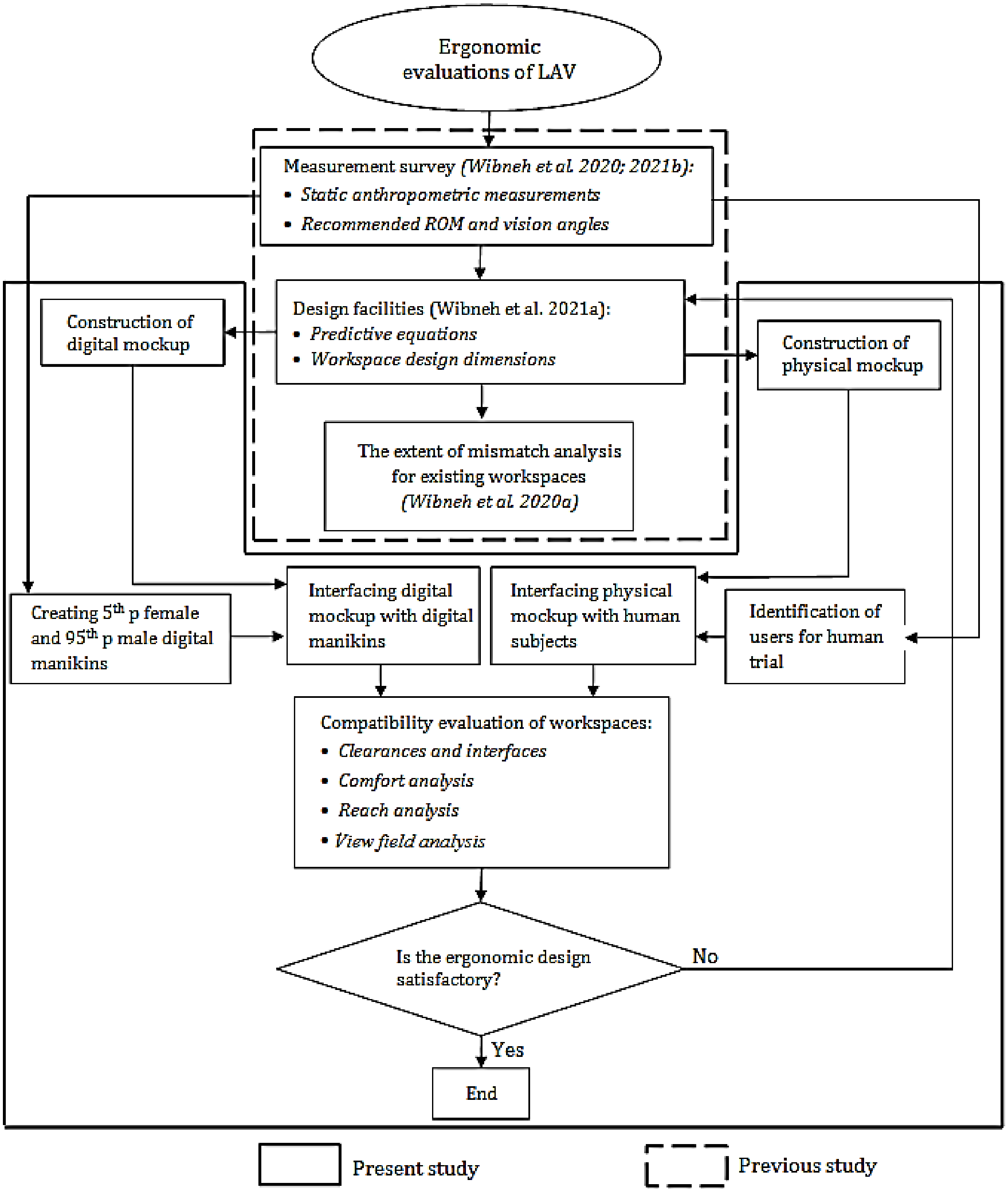


Figure 5. 1: Anthropometric compatibility evaluation framework of LAV

5.3 Phase 1: Ergonomic evaluation of LAV employing DMU

5.3.1 Methodology

The virtual evaluation approach of DMU started with facilitated design requirements such as predicted design dimensions for customizing the LAV MU, optimal design specifications of exterior/hull structure design, and generation of Ethiopian solder manikins to interface with DMU.

5.3.1.1 Design requirements for DPU of LAV

a) Predicted workspace design dimensions: We utilized anthropometry data of the Ethiopian army for predicting workspace dimensions of the LAVs (Wibneh et al., 2021a). In the subsequent study (Wibneh et al., 2021a), workspace design dimensions considering anthropometry and ROM of Ethiopian soldiers were predicted for customizing the DHM of the vehicle. Table 5.1 shows twenty-two predictive equations and their respective indicated design dimensions that are directly associated with the anthropometric and ROM variables of the users. Four workspaces viz. crew seat, driver, gunner, and commander workspaces were considered for modeling and evaluation, as shown in Figure 3.3. Thus, those design dimensions predicted by subsequent studies (Wibneh et al., 2021a) would be validated by virtual means (using DHM) to reduce the uncertainty of their acceptance.

Table 5. 1: Predicted design dimensions for customization of digital and PMU of vehicle (Wibneh et al., 2021a)

Workspace dimensions	**Predicted design values of workspaces dimensions**			
	Gunner	**Driver**	**Commander**	**Infantry troop**
A1	36.5	NA	36.5	36.5
A2	46	46	46	46
A3	38	38	38	38
A4	49.5	49.5	49.5	49.5
A5	96	96	96	96
A6	136	136	136	136
A7	165	NA	NA	NA
B1	NA	57-67.5*	NA	NA
B2	NA	33.5	NA	NA
B3	NA	19.68	NA	NA
B4	NA	58.64-70*	NA	NA
B5	NA	61.5-74*	NA	NA

B6	NA	65-87*	NA	NA
B7	NA	46	NA	NA
B8	NA	93.5	NA	NA
B0	NA	32	NA	NA
C1	42.5	NA	NA	NA
C2	20-36*	NA	NA	NA
C3	63.5-80*	NA	NA	NA
C4	139-169*	NA	NA	NA
C5	79.5	NA	NA	NA
D1	NA	NA	63.5-80*	NA

All measurements are in cm unless specified.
** Dimensions of the adjustable unit; NA=not applicable.*

b) Design vehicle hull structure: the sloped geometric structure of the crew protective hull may affect space occupancy (A6 and A7) of the crew seated back-to-back, and their protection/safety from gunfire was also investigated (Wibneh et al., 2021c). Thus, the hull structure was also considered during a comprehensive design of the vehicle model. From the different geometric design options, the sloped hull structure (G2) shown in Figure 4.8a was adopted for our illustration.

c) DMU *of LAV:* The digital LAV mock-up was then constructed using CATIA V5 software, shown in Figure 4.8. It was conceptualized by the workspaces' pre-defined design dimension (refer to Table 5.1) as per the Ethiopian army's static anthropometric and ROM measurements (Wibneh al., 2021a). The workspaces in the digital model consist of four workspaces (Figure 3.2): workspaces for infantry troop, gunner, driver, and commander. The vehicle was designed with adjustable units such as a horizontally adjustable driver, a vertically adjustable gunner seat, and a sliding platform for standing gunner. The adjustability was provided to accommodate the army population's wide ranges (5th to 95th p) during carrying, driving, and gunfire.

5.3.1.2 Generation of digital manikins

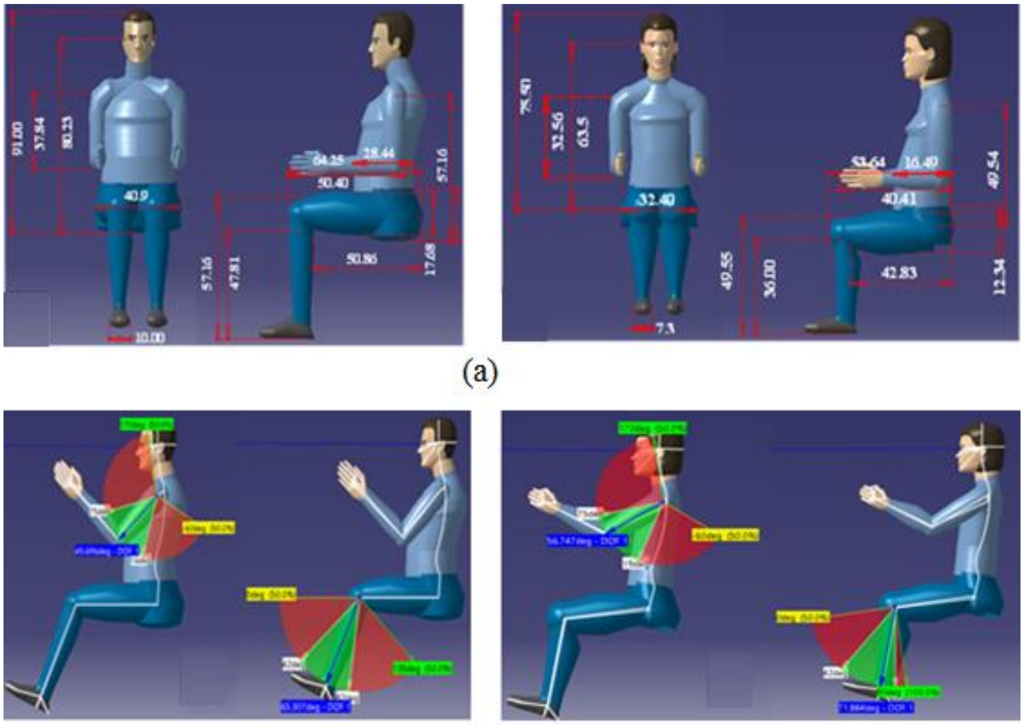
We utilized anthropometry data of the Ethiopian army to generate digital manikins. Two digital human models/manikins (5th p female and 95th p male), matching Ethiopian army anthropometry, were created to evaluate the task in the workspace generated (Reed, 2005) using CATIA V5 software (Figure 5.2a). For that, data about 32 relevant anthropometric dimensions of 310 Ethiopian army personnel were collected in a prior survey (Wibneh et al., 2020; Wibneh et al., 2021b). All the 31 Ethiopian anthropometric dimensions (excluding mass) were utilized to customize the American manikin inbuilt in the software.

The comfort/ discomfort ROMs required to perform routine tasks while standing/ sitting posture are already available in previous literature (Krist, 1994; Porter, 1998 and Tilley, 2002). Table 5.2 presents different ranges of comfort body joint angles while standing and sitting (driving). Therefore, after generating manikins (based on Ethiopian army anthropometry), seating comfort and discomfort zones of different body joints were defined as illustrated in Figure 5.2b based on ranges of movement in Table 5.2. The 'green' color defined the comfort zone, while the 'red' color defined the discomfort zone.

Table 5. 2: Comfort zones of the body joint angles/ROM and field of view in working posture

Body joint and view angles	**Recommended ROMs in degree**		
	Standing posture	**Seating/Driving posture**	
	Ranges (Tilley, 2002)	**Ranges** (Porter, 1998)	**Median** (Krist, 1994)
Torso orientation (θ_1)	0-10	Oct-30	20
Shoulder joint (θ_2)	-50	19-75	22
Elbow joint (θ_3)	15-100	86-164	127
Knee joint(θ_4)	45-85	99-138	119
*Down view angle (θ_5)		0-15	15
*Up view angle (θ_6)		0-15	15
Neck (θ_7)	0-15	-36	---
Hip joint (θ_8)	60-85	90-120	99
Ankle joint (θ_9)	90-115	80-113	103

**Fostervold et al. (2006); Peacock & Karwowski (1993); Van Cott (1972)*



(a)

(b)

Figure 5. 2: Illustrations for customizing 95th p male and 5th p female manikins according to (a) static anthropometric dimensions of Ethiopian army personnel (b) Global standard ROMs of comfort/discomfort zones

5.3.1.3 Analysis of workspaces using DHM

Following the design of the DMU and manikins, the anthropometric compatibility of workspaces for the LAV mock-up was evaluated by the generated manikins. The adequacy of occupant spaces and reaching distances were evaluated by 5th p female and 95th p male manikin of Ethiopian soldiers depending on the characteristics of the workspaces. Ergonomic evaluation of the MU workspaces started with: a) observation of the spatial arrangement of driver's and occupants' seats for acceptance of sitting and operational accommodation; b) an assessment of space clearances such as clearance dimensions for headroom (C-1), lateral clearances for foot room w.r.t. side hull (C-2), thigh room clearances w.r.t. steering wheel (C-3), knee room clearances between knee and steering wheel/dashboard (C-4), and clearance for popliteal area w.r.t. front seat edge (C-5) and lateral clearance of the seat (C-6); c) reachability study of the driver, gunner, and commander towards various controls (steering wheel, speed control pedals, various knobs, and switches of control dashboard, turret handle, visual obstruction through sight devices for gunner and commander); d) comfort/ discomfort during driving, sitting, firing, viewing field; dials or controls inside the vehicle; visibility towards the road ahead.

5.3.2 Results

After incorporating human model/manikin with DHM of the vehicle, the ergonomic design characteristics like space clearance, arm reach, comfort/discomfort, reachability and driver’s view field had been tested and presented.

5.3.2.1 Accommodation test

Figure 5.3 shows the 5th p female and 9th percentile male manikins incorporated with DMU to validate workspaces whether they would accommodate a wide range of user populations. The essential clearance spaces are pointed by rows such as headroom (C-1), lateral clearances for foot room (C-2), thigh room clearances (C-3), knee room clearances (C-4), clearance for the popliteal area (C-5), and lateral clearance (C-6) were checked. Apart from C-5 and C-6 (tested by considering 5th and 95th p females, respectively), all room clearances were tested by considering 95th p male manikins (Wibneh et al. 2021a).

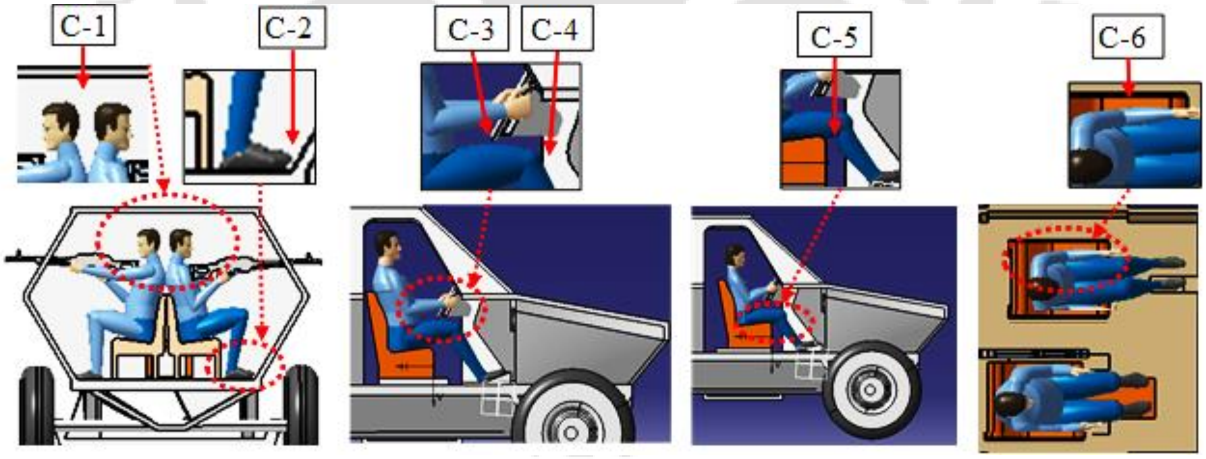


Figure 5. 3: Accommodation test of DHM with 5th p and 95th p manikins

Note. *C-1- headroom clearance; C-2 - foot room clearance; C-3- thigh room clearance; C-4- knee room clearance; C-5- clearance of popliteal area; C-6- lateral seat clearance*

As it was observed from Figure 5.3, the accommodation test by both extreme body size (5th p and 95th p) manikins depicted that the room clearances of digital LAV mock-up are sufficient to avoid body striking with the vehicle interior components/units. Therefore, the workspaces developed by the predicted design dimensions are well-matched with the target population (Ethiopian soldiers). Furthermore, the adequacy of workspace dimensions provided with the allowable clearances (C-1, C-2, C-3, C-4, C-5 and C-6) would be confirmed to accommodate the recommended percentage (90% for adjustable units and 95% for fixed units) of target populations (Wibneh et al., 2021a).

5.3.2.2 Comfort/discomfort evaluation

Comfort/discomfort analysis for a) standing gunner manikins in vertically adjustable seat/platform (Figure 5.4a) b) seated gunner manikins in vertically adjustable seat c) driver manikins in horizontally adjustable seat d) commander manikin in the vertically adjustable seat were conducted as shown in Figure 5.4. To evaluate the comfortability of the workspaces for wide ranges of user populations, the boundary values (5^{th} p female and 95^{th} p male) of manikin were interfaced with the digital LAV mock-up.

Figure 5. 4: Comfort/discomfort analyses of a) gunners in standing posture with 5th p female and 95th p male manikins b) gunners in sitting posture with 5th p female and 95th p male manikins c) driver with 5th p female and 95th p male manikin d) driver with 5th p female and 95th manikin.

The adjustable platform of the gunner in standing posture (Figure 5.4a) allows virtually accommodating at least 90% of the target populations (Ethiopian soldiers) as per our design specifications. The sliding platform had the boundary values (5th and 95th p) according to the proposed dimensions of standing eye height data from previous anthropometric database

(Wibneh et al., 2020). It can now be adjusted by tall (95th p) manikin to a lower most position for better comfort, while if lifted upward, it can be more comfortable to the short manikin.

The MU (Figure 5.4a) shows a comfortable workspace for the 5th p female at the upmost position of the gunner in sitting posture. In contrast, the bottommost position is comfortable for the 95th p male. However, red-colored neck and face indicate that topmost and bottommost seat positions are uncomfortable for 95th p male and 5th p female gunners, respectively. Therefore, the adjustability in gunner seating may help the Ethiopian soldiers' wide range (5th to 95th p values) to easily reach the sighting device with a minimum body flection during firing operations.

The two driver manikins showing the full green color for females at the rearward most position and the 95th p male at the rearward most position (Figure 5.4c) indicate that the forward most position of the seat is comfortable for the 5th p female. Rearward most position of the seat is comfortable for the 95th p male during steering and pedaling/braking operation. However, the 95th p male manikin got discomfort as the seat moved from its rearward position. Furthermore, the knee of 95th p manikin would not have enough clearance at forward most position so that the position of the seat has no adequate space between knee and control dashboard for accommodating larger user unless the seat is adjusted to rearward depending on the size of the buttock to knee length. On the other hand, as evident, the 5th p female manikin does not reach into the pedal accelerator for operating at the rearward most position. Similarly, the steering operation was not also in the discomfort zone for the short user, so the seat needs adjustment forward to accommodate a wide range of army population.

After modification was made on commander workspace, the topmost position of the seat for 5th p female manikin and the lowest position for 95th p male manikin are comfortable viewing a field by the commander, as evident from Figure 5.4d. However, at the upper most position, the 95th p manikin was susceptible to neck flexion and body discomfort in the sighting device for view field. The 5th p manikin at the lowest position could not reach the sighting device.

5.3.2.3 Reachability evaluation of DMU

The driver's reaching distance for operating the control dashboard was evaluated for anthropometric compatibility of the modified DMUs with target populations as shown in 9a.

The reaching distance by 5th p female manikin at forward and rearward most position and 95th percentile male manikin at the rearward most position of the adjustable seat were enclosed by the pink color envelopes to show the maximum reach distance of the thumb without body flection and extension. The reachability of the control dashboard is the key unit that is to be checked by the 5th percentile female at the forward-most position of the adjustable seat and 95th percentile male at the rearward most position, as shown in Figures 5.6a and b.

Figure 5. 5: Reachability analysis of the driver workspace of DMU (a) with 5th p female manikin at forward-most position (b) with 95th p male manikin at rearward most position (c) with 5th p female manikin at rearward most position

Figure 5.5a and b showed that the 5th p manikin at the forward most position and 95th p manikin at the rearward position could easily reach the control dashboard without moving the body forward. However, the shorter female manikin could not reach the control dashboard as the seat was moved back from the forward position, as shown in Figure 5.5c.

5.3.2.4 View field analysis

Figure 5.6a checked the obstructions made by the front/engine compartment of the DMU vehicle using a 5th p female manikin to see the front road easily within 15^0 below the horizontal line of sight. On the other hand, Figure 5.6b checked the obstructions made by the upper edge of the windshield called daylight opening point using 95th p male to see the traffic light easily within a field of view 15^0 above the horizontal line of sight (Peacock and Karwowski, 1993; Van Cott and Kinkade, 1972). Figure 5.6c shows the obstruction distance of the front of the road from the driver's eye point. The maximum obstruction distance of the DMU was obtained by measuring it from the driver eye point to a point where an obstruction on the front road ends in AutoCAD calibrating tool.

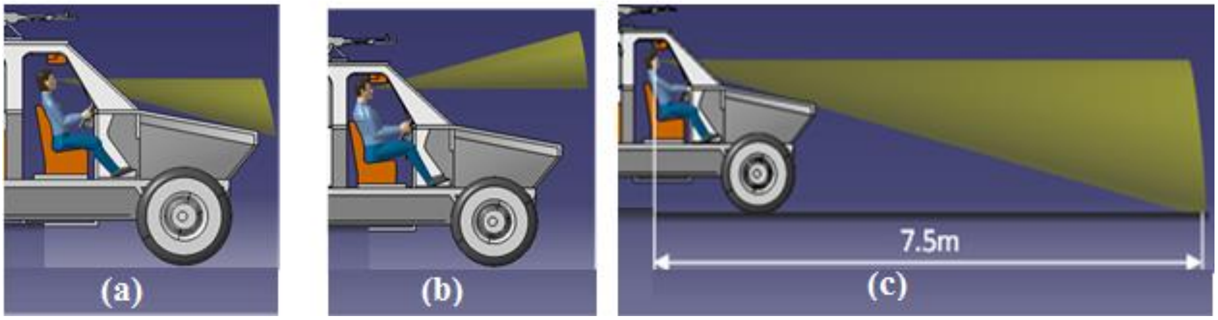


Figure 5. 6: View field analysis of the driver workspace by (a) DMU with 5th p female at a forward most position to see the front road (b) DMU with 95th p male at the rearward most position to see the traffic light as an example (c) DMU with 5th p female to know the maximum obstruction distances of the front road.

From Figure 5.6a and b, the field of view analysis of the manikins revealed that 5^{th} percentile female and 95^{th} percentile male army manikin can see through the windshield at least 15^0 above and 15^0 below the horizontal line of sight without any obstruction. Similarly, the maximum obstruction distance to see the road/street was investigated by 5^{th} p/extreme small female. Obstruction distances to see the front road by the 5^{th} p/ smaller female driver were found to be 7.5m, as shown in Figure 5.6c. Therefore, the proposed model can reduce the obstruction design problems to accommodate the wide range of users (Ethiopian soldiers) with a minimum obstruction distance to see the front road without neck extension.

5.4 Phase 2: Ergonomic evaluation of LAV employing PMU

5.4.1 Methodology

The physical ergonomic evaluation approach of PMU started with facilitating evaluation requirements such as, predicted workspace design dimensions (Table 5.1) for construction of the LAV PMU, optimal design specifications of exterior/hull structure construction (Wibneh et al., 2021c) and identification of subjects that represent Ethiopian solders' anthropometry for user trial.

5.4.1.1 Modeling of PMU

Similar to DMU, PMU (Figure 5.7) was also constructed using pre-defined design dimensions. Based on the design recommendations presented in Table 5.1, the following components were taken into consideration in the PMU of LAV: a) sliding platform: the adjustable sliding platform in accordance to standing and seated, b) Gunner workspace: adjustable seats provided for gunners, c) Commander workspace: adjustable seats provided for the commander, d) Driver workspace: adjustable driver seat was provided to adjust the seat with respect to the foot pedal, steering wheel, and control dashboard. Every component was provided unit scale dimensions of dummy models.

Figure 5. 7: The newly proposed PMU of LAV

5.4.1.2 Identification of subjects involving limited user trial

In reality, it is impossible to find out an individual with specific percentile (say 5th or 95th) values for all the anthropometric dimensions (Porter et al., 2004). In traditional anthropometric compatibility evaluation, large number of participants would be required to represent a 5th or 95th value of different body dimensions. However, a user trial involving a large number of participants with intended percentile values is a tedious, time-consuming, and costly affair and is often not practically feasible. The unavailability of Ethiopian female soldiers in the institute was another design constraint for this study. Therefore, the user-trial of a PMU of light armored vehicle (LAV) used by the Ethiopian army involved few users from an ergonomic perspective. The 12 key variables such as stature, sitting height, popliteal height, popliteal length, bideltoid breadth, hip breadth, elbow rest height, arm length, foot length, foot breadth, handbreadth, and mass were found from PCFA and regression analysis (Amare. et al., 2021b), and were taken into consideration during the selection of volunteers. A total of 13 subjects were finally identified who represented the extreme measurement values (close to 5th or 95th p) of those key variables, as shown in Figure 5.8. These volunteers could be deployed for user trials to confirm compatibility (accommodating wide ranges of user populations) from an ergonomic perspective considering anthropometric variability (Roebuck et al., 1975). The anthropometric measurements of each subject's identified variables and their respective extreme values (close to 5th and 95th p) were presented. The body measurement procedure was based on Wibneh et al. (2020). Since the physical evaluation is done in India and no Ethiopian female soldiers were available in the institute, Indian women with similar Ethiopian female anthropometric characteristics were asked to volunteer in the user testing.

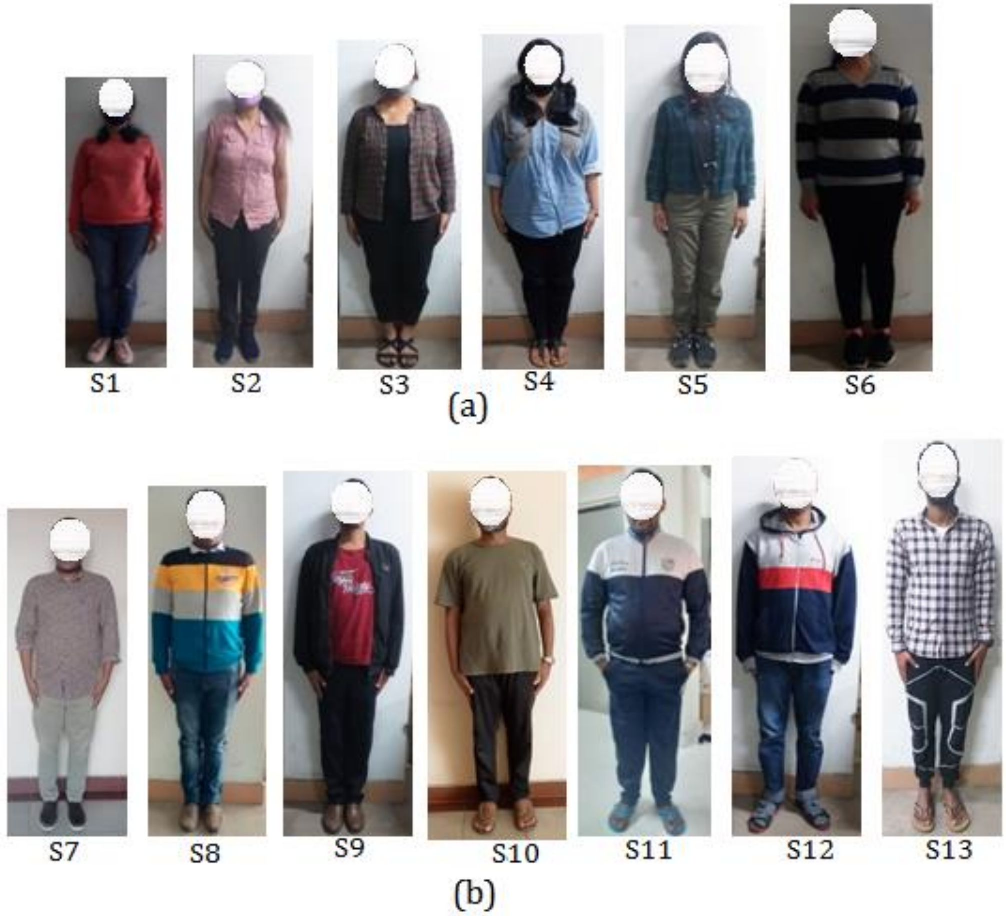


Figure 5. 8: The representative human subjects for 5^{th} and 95^{th} p values of the key anthropometric variables (a) females (b) males

5.4.1.1 Evaluation techniques for the PMU

Following the proper identification of subjects for limited user trials, the compatibility testing of the PMUs was conducted with the identified subjects. The ergonomic design characteristics such as, space clearance, arm reach, posture condition, and view field analysis of the crew in operational activity had been evaluated through observation of graphical representations (illustrative photo pictures) of man-machine interaction man-machine interactions. During user trial testing, the participants were asked to volunteer with casual shoes and clothing, and their appropriate sitting/standing and working postures were evaluated through an observational study (Aromaa et al., 2014). Apart from the observational test, a measurement test was done for the clearance dimensions (C-1, C-2, C-3, C-4, C-5, and C-6) with the GPM; Switzerland made standard anthropometric set used by Hsiao et al. (2005).

The following ergonomic needs were validated for each working posture adopted by users through observational and measurement studies:

- Whether the body joint angles are in comfort ranges w.r.t. neutral positions
- Match of the workspace sizes w.r.t. individual sizes
- Whether various body rooms are sufficient for the users
- Whether there is no collision/striking of body parts with workspace units.

5.4.2 Results

5.4.2.1 Anthropometric measurements of identified variables for each identified subjects

The anthropometric measurements of the 12 identified variables for subjects (n=13) were presented in (Table 5.3). The boundary (close to 5th and 95th p) values belonging to each subject were identified by an asterisk.

Table 5. 3: Measurements for key anthropometric variables of human subjects utilized for user testing of PMU.

Key anthropometric variables		Females						Male						
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
1	Stature	152*	158	157	166	167	172.5	170	175	176	177	180**	182**	183
2	Arm length	66*	69	67.5	73.5	72	78	78	82**	80	81**	80.5	82**	79.6
3	Sitting height	76.5*	78	80.5	80	81	85.8	82	86	84.5	85.2	90**	90**	90.5**
4	Elbow rest height	19	21.5	15.5*	22.5	19.5	19.3	20.5	21	21.5	22	25.3	26.5**	21.3
5	Bideltoid breadth	37.5	36.5*	43	43.5	39	41.5	48.5**	47	44	46	48	46.25	47.5**
6	Hip breadth	40	40	41.5**	43.5	35	42**	40.5	41	34*	39	40.3	41.5**	36
7	Popliteal height	36	37	35*	34*	38	45	42.5	44.5	43.5	43.75	46.7**	44.5	47.5**
8	Buttock to knee length	54.5*	58	58	57	59	62.5	58.5	62	63	63.5**	63.5**	63.8**	61.4
9	Hand breadth	6.9*	6.7*	6.6*	7.8	7.3	7.9	7.8	8.5	8.0	8.6	9.6**	8.5	8.5
10	Foot length	23.4	21.7*	21.7	25	22	25.1	24	26	26	26.5**	26.8**	27.1**	26.5**
11	Foot breadth	8.2	7.6	7.9	9.4	7.2*	8.8	8.5	9.0	9.0	9.5**	9.5**	9.5**	9.4**
12	Mass (kg)	54*	62	65	92	60	80	74	84**	62	77	88	85**	70

All measurements are in cm unless specified.

**Measurement values close to the 5th percentile for an anthropometric database of Ethiopian soldiers.*

***Measurement values close to 95th percentile for an anthropometric database of Ethiopian soldiers.*

From Table 5.3, no subject represented extreme (close to 5th or 95th p) values of all the 12 anthropometric variables. The majority of 5th percentile values of the variables were represented by S1 (06 variables) while S11 (07 variables), S12 (09 variables), and S13 (05 variables) represented the majority of 95th percentile values of all the variables. The major representative subjects (S1, S11, S12, and S13) were taken to illustrate graphical representations of man-machine interfacing during testing and were presented for observational study even though these subjects would not represent all anthropometric variables.

5.4.2.2 Compatibility test of man-machine interfaces

The ergonomic design characteristics such as space clearance, arms reach, state of the posture, and view field analysis of the crew in operational activity were evaluated by observing the graphical representations (illustrative photo pictures) of man-machine interfaces. Since reporting all the representative subjects (n=13) is quite tedious, we used only subjects (such as S1, S11 S12, and S13), which represent the majority of the extreme (close to 5th or 95th p) values of the key identified variables for illustrations of photographic representation. S1 was used for the representation of the 5th p-value while we used either S11, S12, or S13 for representation of 95th p values for each workspace validation test depending on their body variability and workspace characteristics

a) *Gunner workspace in standing and seating posture:* Following the MU testing by all the 13 subjects, the fitness evaluation of the workspace (vertically adjustable gunner standing platform /seat) of the PMU was illustrated by S1 and S13. S1 was preferred for graphic representation of 5th p values since stature family called standing eye height (Wibneh et al., 2021b) and sitting height are quite important (see Table 5.1 and Table 5.4) to evaluate the firing workspaces in standing and sitting posture, respectively while we used S13 for representation of 95th p values as shown in Figure 5.9a and b.

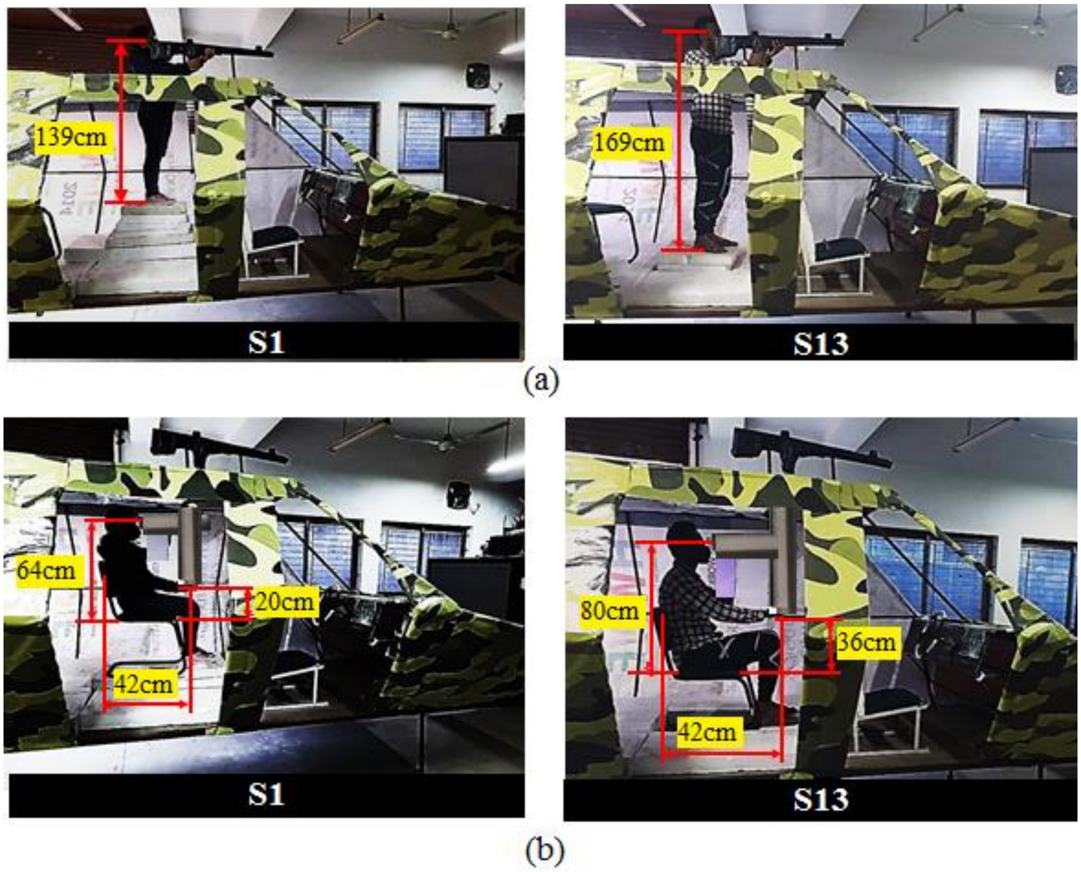


Figure 5. 9: Anthropometric compatibility test of firing workspace for (a) standing posture (b) sitting posture

While aiming and firing the turreted machine gun in LAV, the experience of high lumbar flexion existed by the taller person in the preliminary investigations (Figure 5.9) has now been resolved, as shown in Figure 5.9a. Whereas, the short gunner who could not reach the sight alignment for aiming and firing could easily reach it without body stretching since the standing platform is adjusted upward from its lowest position as per the height of the sighting device and the eye height for the users. The sliding platform had the boundary values (5th and 95th p) according to the proposed dimensions of stature data from the previous anthropometric database (Wibneh et al., 2021a). It can now be adjusted by a tall (95^{th} p) user to a lower position for better comfort. While lifted upward, it can be more comfortable to a short user.

Similarly, the seated gunner (Figure 5.9), who may cause hip flexion due to shorter seat height and higher elbow flexion due to the wrong position of (gunfire) turret rotating handle, has now gotten appropriate posture and comfort ranges by the shorter user at the topmost seating position. In contrast, the lowest position is comfortable for the taller user (Figure 5.9b).

Therefore, the adjustability in gunner seating may help the Ethiopian soldiers' wide range (5th to 95th p values) to easily reach the sighting device with a minimum body flection during any firing operation. Along with the height of the sighting device, the height of the turret handle is also adjusted; therefore, the topmost position of the seat is more comfortable for the short user to traverse the turreted gun using turret handle, while if moved downward, a lower most position has better comfort for the tall user.

b) *Evaluation of driving posture:* In this case, the physical model was tested by all identified subjects mentioned in Figure 5.8 and illustrated by the two extreme users (S1and S12). Figure 5.10a presents the driver interface during steering and pedaling operations. The participants were told to adjust their seats horizontally to obtain a comfortable driving posture.

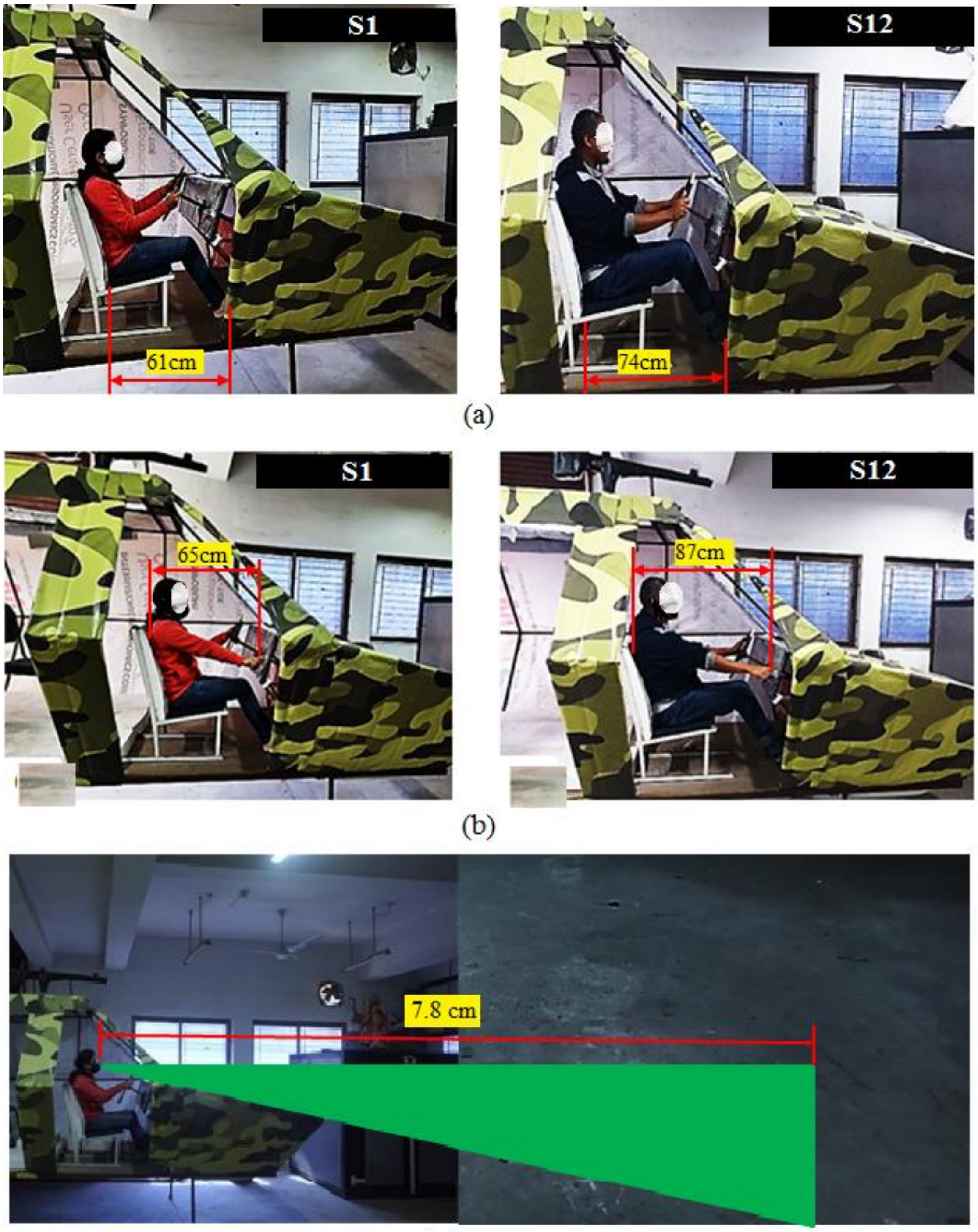


Figure 5. 10: Driver posture adopted during (a) steering and pedaling operation (b) reaching to control dashboard (c) looking into front road by the small girl

Inappropriate position of the seat w.r.t. the steering wheel that causes extension of the driver's elbow extension during steering operation (see Figure 1.2), has now resolved using a horizontally adjusted seat aiming with accommodation of wide ranges users shown in Figure 5.10a. It indicated that the forward most position of the seat is comfortable for the 5th p female, and the rearward most position of the seat is comfortable for the 95th p male during steering and pedaling/braking operation. There is no interface detecting between the knee and the control dashboard at the respective positions.

From observation of user testing, the following points were confirmed apart from the points above:

- All the seat dimensions (seat cushion depth, width and height, backrest, and height) were acceptable.
- Adopted driving posture by the individual shows that angles at various body joints are in comfort range as defined by Porter and Gyi (1998).
- The headroom for the vehicle is sufficient for uses to avoid head striking with roof during jolts/ jerks.
- The legroom for the vehicle is sufficient for users for normal pedal operation.

Therefore, the horizontally adjusted seat with the range of the pedal distances (61 to 74 cm) determined by 5th percentile female and 95th percentile male body sizes can accommodate the army's wide ranges (5th to 95th percentiles) population during steering and pedaling operation.

c) Reachability evaluation: The control dashboard reachability is the crucial unit to be checked. Thus, it was analyzed by those identified subjects and illustrated by the two extreme users (S1and S12) in Figure 5.10b. The smaller user at the forward-most position and the larger user at the rearward most adjustable seat position were evaluated to validate its accommodation for wide ranges of users with a body size between S1and S12 without body flection and extension.

As investigated in the preliminary study of existing vehicles (see Figure 1.2), the reaching distance for operating the control on the dashboard was quite far from the point where the scapula rests for the smaller user. However, it is now easily reachable for the short user at the forward-most position and the tall user at a rearward most position to operate it without moving the body forward from the seat's back support, as shown in Figure 5.10b.

d) View field: The front compartment of the PMU that was constructed as per the given design dimension and view angles was also checked its recommended obstruction distance using a smaller user (S1) to see the front road easily within 15^0 below the horizontal line of sight. Figure 5.10c shows the obstruction distance of the front of the road from the driver's eye point. The maximum obstruction distance of the MU was obtained by measuring it from the driver's eye point to a point where an obstruction on the front road ends.

From Figure 5.10c, the field of view analysis of the manikins revealed that smaller users could see the front road at a minimum distance of 7.8m. Therefore, the new design model can reduce such problems to see the front road by the wide range of users (Ethiopian soldiers) with a minimum obstruction distance without neck extension.

5.4.2.3 Physical ergonomic evaluation using measurement test

The identified 13 subjects, which represent the wide anthropometric range (5th to 95th p values) of users, were utilized for validating workspaces to accommodate a wide range of user populations. The basic space clearances which ought to be checked through measurement tests were C-1, C-2, C-3, C-4, C-5, and C-6, as shown in Figure 5.11. The clearance measurements between the body parts of those identified 13 subjects and the workspace units/components were presented in Table 5.4. The allowable clearances provided by Wibneh et al. (2021a) were also presented along with the measured clearance dimensions.

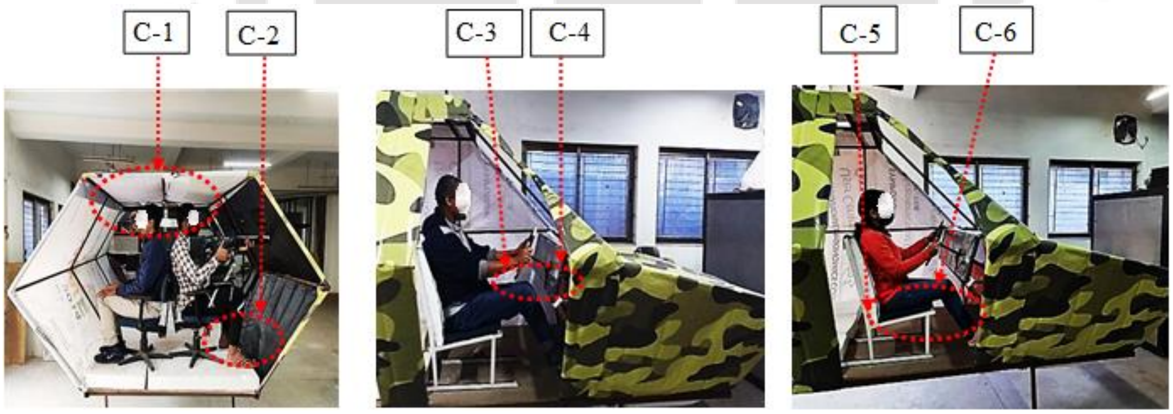


Figure 5. 11: Accommodation test of PMU

Table 5. 4: Clearance measurements between the user body parts and workspace units/components of LAV MU

Subjects used for testing	**Space clearances for PMU**					
	C-1	**C-2**	**C-3**	**C-4#**	**C-5**	**C-6**
S1	20.5	5.3	6.8	5.4	5.2	6.0
S2	19.7	6.5	6.6	5.8	5.4	5.7
S3	18.5	6.2	3.5	5.5	5.0	4.6
S4	12.5	3.8	3.0	5.1	5.5	2.8*
S5	15.0	6.0	5.4	4.8*	6.6	10.5
S6	11.0	2.9	2.8	4.6*	8.5	4.5
S7	12.0	3.0	3.2	6.2	7.4	5.5
S8	10.0	2.5	2.8	7.4	8.2	5.0
S9	12.0	2.6	5.7	6.2	9.8	11.5
S10	10.8	2.6	4.6	6.0	8.4	6.7
S11	6.5	2.1*	1.9*	4.7*	10.7	5.7
S12	7.0	2.2*	2.3	5.5	13	4.5
S13	6.8	3.0	3.2	6.8	11.5	10.0
AC	5.0	2.5	2.0	5.0	5.0	4-5

All measurements are in cm unless specified.

C-1- headroom clearance; C-2 - foot room clearance; C-3- thigh room clearance; C-4- knee room clearance; C-5- clearance of popliteal area; C-6- lateral seat clearance

AC-allowable clearances (Wibneh et al., 2021a)

**The measurement value less than allowable space clearance*

#Adjustable clearance as a result of driver seat adjustment

In the case of user testing of a proposed physical model, the workspaces could adequately accommodate all users, as shown in Figure 5.11 and Table 5.4. Even though the actual space clearances are still less than the allowed clearance (AC) for some workspace units, for example, C-2 – S11 and S12, C-3 – S12, C-4 –S5, S6 and S11, and C-6 – S4, all the 13 testing subjects were accommodated without any interference. Hence, the allowance clearances provided by the authors (Wibneh et al. 2021a) are ideally sufficient to accommodate the wide ranges of user populations without striking/interfering into the MU units as long as the systematically identified subjects were considered to represent the extreme anthropometric variability of the target populations.

5.5 Discussions

In this study, an attempt was made to design LAV to reduce the risk of discomfort and musculoskeletal disorders to increase the operational efficiency of the crew members such as driver, gunner, commander, and seated squads in combating mission. Design validation was made to ensure the compatibility of the recommended workspace dimensions with the user populations to reduce the ergonomic design flaws investigated by Wibneh et al. (2021a) and a preliminary study. The purpose was to demonstrate the appropriateness of anthropometric design dimensions and their respective predictive equations (Wibneh et al., 2021a) to use in the future as national/global standards.

Anthropometric variability of humans has a significant impact on the space adequacy of the vehicle interior to accommodate wide ranges of a target population. The design of a vehicle interior is a primary concern for safety and accommodation (Parkinson et al., 2006). Therefore, the new model was developed to accommodate wide ranges of the user populations (Ethiopian soldiers) with the intent to have adequate clearances for users' head, popliteal area, thigh, knee, and foot with respect to the workspace units/components, thus preventing the body from contact with workspace units as shown the validate results in Figure 5.11 and Table 5.4.

In the case of gunner safety, the position of the standing platform with respect to the sight vision device affects the firing posture comfortably to accommodate the wide ranges (5th to 95th p) of the army population from the shortest to tallest without/with minimum discomfort during the gunfire. Hence, the height of the gun sight device from adjustable/sliding platform in standing posture was determined to be C4 = 139 to 169cm (with vertical stroke length 30cm), as shown in Figure 5.4a and 5.10a. Furthermore, the gunner standing platforms can be made as the quick-folding back mechanism to allow soldiers to sit and stand safely during transport and combating scenarios (Hamid, 2020). Similarly, the vertical adjustable seat of the gunner and commander ranged from 64 to 80cm sight device height can accommodate the wide ranges of potential soldiers without (with a minimum) body flection during firing and sighting operation as it was explored in both DMUs (Figure 5.4b) and PMUs (Figure 5.9b).

Driver comfort was adversely affected by body size and seat position relative to the foot pedal, steering wheel, and control dashboard (Reed et al., 2013). Therefore, driver workspace configurations were produced in a vehicle MU by varying the seat position relative to the foot pedal, as shown in Figure 5.4c (DMU) and Figure 5.10 (PMU). The workspace was provided with the minimum horizontal adjustment of the driver seat with ranges of 61.5 to 74cm pedal distances from the seat reference point to accommodate wide ranges of Ethiopian soldiers with minimum discomfort during steering pedaling and control dashboard operating. Grandjean

(1980) also suggested a global standard of 15cm horizontal adjustment of the seat to accommodate wide ranges of the user population. Therefore, it may also be recommended to provide up to 15cm horizontal adjustment with adjustment ranges from 60 to 75cm pedal distances; nevertheless, 12.5 (ranges from 61.5 to 74cm) is adequate to accommodate 90% of the soldier populations. In general, when the pedal distance is too far, either the shorter person tends to slide forward or stretches the leg to reach into the pedal, increasing discomfort on the unsupported back and the stretched limbs (Naweed et al. 2020). The driver should be comfortable whilst sitting and performing driving tasks and not be subjected to causing fatigue in deriving from prolonged static muscular tension (Jagannath and Balasubramanian, 2014).

In general, control operation on vehicular dashboards and pedals is a stressful activity. Its design and position with respect to the seat play an important role in maintaining the driver's comfort and driving efficiency (Hsiao et al., 2005). Controls that are inconvenient to reach or difficult to operate may potentially result in manipulating fault (Grandi et al., 2022). In this context, the vehicle's dashboard and pedal shall be within the driver's reaching envelope to achieve safety and comfort. Hence, the drivers (5th p female to 95th p male) can easily operate on the control units of the proposed model with easy reach into them as the seat is adjusted forward-backward within recommended limits of B5 = 61 -74cm as shown in Figure 5.10b.

In the case of view field analysis, the vertical field of view by the driver was designed to be 15^0 above and 15^0 below the horizontal line to see the front road and traffic signals within a comfortable viewing zone (Van cott and Kinkade, 1972) as it was demonstrated in Figure 5.5a and b and Figure 5.10b. Peacock and Karwowski (1993) also pointed out that 14^0 above or below the horizontal line in the vertical plane is a comfortable zone for eye movement. Furthermore, the maximum obstruction distance to see the front road by the driver is maintained to be the 11-meter field of view from the driver's eye point to the obstruction ends as it was suggested by Vehicle Standards Instruction (2017). Therefore, the proposed LAV at a distance of 7.5 meters (Figure 5.10c) is within the acceptable ranges, to see the front road in comfortable viewing ranges.

Findings from the current studies showed that the design dimensions and their predictive equations presented in conventional study (Wibneh et al. 2021a) were confirmed to be suitable design standards for the construction of comfortable vehicular workspace according to the user population. Therefore, the design modification and evaluation using digital and actual environments were made to enhance the dimensional compatibility of the workspace for the users in work. The new vehicular model was designed to accommodate 90 (for adjustable units), and 95% (non-adjustable) of the Ethiopian army within a considerable minimum bound errors resulting from the combined effect of diverse anthropometric variables (Roebuck et al., 1975) and other design assumptions. Fernandez (1995) also noted that when developing a particular workplace design, the demands of the task would ideally be held within the capacity of a certain percentage of the working population so that 75 to 95 percent of the population shall be accommodated.

To sum it up, adequate space for the users in an appropriate working posture has great importance to increase the worker's comfort, efficiency, safety, and health issues (Wibneh et al., 2020; Sutalaksana and Widyanti, 2016). This results in enhancing an efficient working performance in a military operation in addition to the reduction of the muscular disorder risk during combating missions (Punchihewa et al., 2016).

This study had been conducted to validate the proposed workspace design dimensions, which were recommended to use in the development process of LAVs in the longitudinal study of Wibneh et al. (2021a). However, this study is not conducted without limitations; therefore, some limitations which need to be investigated further were also informed in this section. In the present study, the ergonomic evaluation using DHM was performed by adopting two percentile values (5th percentile female and 95th percentile male) of Ethiopian soldiers to compensate for anthropometric diversity. However, the combined effect of diverse anthropometric variables may affect the workspace/product design to accommodate the expected percentages (90 to 95%) of the populations (Roebuck et al., 1975), and thus a multivariate statistical approach can also be used for defining the extreme body size. The static anthropometric data were gathered from specific (Ethiopian army personnel) users. However, the globally accepted ROM measurements and vision angles were taken from the literature for the determination of workspace dimensions since the measurements were not performed due to time and budget constraints. Size compactness was given importance equally with ergonomic aspects in our developed LAV. Thus, the space clearances provided the armed soldiers equipped with weapons, body armor, protective helmet, and carry cases. Due to the unavailability of Ethiopian female soldiers in the institute where the PMU was made, female subjects from the Indian population with similar Ethiopian female anthropometric data characteristics were purposively selected for physical, ergonomic evaluation. Even though the basic design dimensions and their predictive equations are considered in the current study, other workspace dimensions (predictive equations) can be considered depending on equipment/units used in vehicle interiors.

5.6 Conclusion

The study ascertained that the final design in both digital and PMUs was well-suited for wide range (5th p to 95th p) of the target army personnel as the result of the suitable design dimensions and their respective predictive mathematical models. The ergonomic evaluation of vehicle interior in both DMU and PMU evaluation ensured the newly proposed workspace dimensions (predictive equations). In both evaluation methods, the interior designs of functional and essential needs such as easily reaching the steering wheel, pedals, control dashboard, visual needs, firing operations, and accommodation of spaces were considered ergonomically safe and comfortable. The present study encourages engineers/designers to evaluate proactive implementations of ergonomic design principles at the conceptual stage of vehicle development and validate those applicable mathematical models using virtual and physical ergonomic evaluations. This study is also helpful to use the predictive equations as global standards for vehicles design other than LAVs, particularly for driver workspace and passenger seat design if anthropometric data and ROM measurements are established for the target user populations. Apart from validating the recommended workspace design dimensions, the study is also helpful to identify a minimal number of volunteers using the extreme anthropometric values (5th or/and 95th p values) of the identified key variables. The volunteers could be deployed for user trials to ensure compatibility from an ergonomic perspective. Such an evaluation technique involving fewer participants would confirm accommodating wide ranges of user populations and reduce the cost, time, and resources for physical trial.

6

General Discussion and Conclusion

Abstract

This chapter summarized and presented an overview of the research being studied. Salient findings of the present research, fulfillment of the objective, hypothesis testing, and the key contributions of the thesis are presented in this chapter. Future research directions based on the study's limitations were given along with the conclusion.

6.1 Overall discussion of the research

In the present research, a design intervention was made on the Ethiopian LAVs to better comfort space occupancy and enhanced crew protection with minimum attainable weight. In previous studies (Greenley et al., 1999; Madhu and Bhat, 2011; Wibneh et al., 2021a), there were insufficient design requirements to establish the intervention of crew protective and ergonomic design aspects. The major concern for this research study is the unavailability of anthropometric variables and ROMs of Ethipoian army for designing workspace dimensions of LAVs (Odhuno-Otieno, 2016). As there are also differences in anthropometric measurements with other nations, it would significantly impact Ethiopian army personnel's ergonomic design of equipment and workspaces (Wibneh et al., 2020). The compact workspace in armoured vehicles and obliquity of the hull structure also affect the adequacy of space occupancy. Therefore, design intervention of ergonomic and crew protective issues was the major concern in this study. As a result, ignoring ergonomic and safety aspects in the vehicular design of fighting vehicles was susceptible to dimensional mismatch with the user populations either at the national or global level (Madhu and Bhat, 2011). Hence, to fulfill these design limitations, the compatibility of anthropometric and

ROM of the user populations with the comfortable working posture of the gunner, infantry troop, driver, and the commander has been described by facilitating and etablishing the basic crew protective ergonomic design requirements of LAVs. Following those concerns, the two hull geometries (G2 and G3) of LAVs have been presented towards achieving the highest protection capability and comfortable occupant space for the targeted users without affecting the mobility/mass of LAV for better ergonomic and protection aspects. Systematic design validations and experimentations of the proposed models through DHM and human trial were made to ensure the compatibility of proposed design dimensions. The study addresses the baseline information of key design concepts to be adopted in the ergonomic design of the obliqued hull structure of fighting vehicles for better performance, comfort, and safety of the crew and troops while accomplishing a difficult combat mission.

The overall framework of the current research was divided into six phases:

- Anthropometric surveying for both male and female Ethiopian soldiers from different ethnic groups and age levels followed with comparison test cross-nationals (India, Korea, and the USA).
- Identification of key anthropometric variables (the minimum data set) that represents the rest of required large variables for a PMU testing of LAV with limited source of users for trial.
- Proposing the key workspace design dimensions with due consideration of anthropometric and ROM measurements of the target populations, compared with existing Ethiopian armoured vehicles.
- Optimal design of the vehicle to achieve comfortable workspaces and crew protective hull structure at minimum attaianable weight.
- Validation of the proposed model employing digital and physical ergonomic testing for dimensional compatiblity issues of the vehicles.

The study of the anthropometric survey in **chapter 2** has potential scientific merit in developing an anthropometric database of Ethiopian populations, especially for army personnel. This is the first anthropometric database developed in Ethiopia as there was no other reported study about establishing an anthropometric database in Ethiopian army populations. Furthermore, it is purely an observational study connected to occupational supports for working as members of defense sectors. The study design reported the development of anthropometric database for Ethiopian army personnel and investigated the variability with other countries. The study in the chapter above can also provide good information on data collection and statistical analysis of anthropometric data, which the Ethiopian community can utilize. Identifying representative variables (a minimum data set) for large sets of variables to simplify anthropometric data survey, analysis, and user testing of PMUs (**chapter 5**) is also the first of its kind.

In the study of the association between anthropometric diversity of Ethiopian army personnel and the workspace dimensions, there was no other reported research for predicting design dimensions of LAV workspaces in terms of anthropometric variables and ROMs. Only some other ergonomic studies, such as the driver workspaces in trucks and tractors (Halder et al., 2017 and Yadav et al., 2017) were studied. Therefore, the proposed baseline predictive models and design methods in **Chapter 3** are the first of their kind to help ergonomists and designers understand the association of anthropometric diversity and workspace dimensions in the ergonomic design of the LAVs. Particularly, the design methods for formulating predictive equations to relate workspace dimensions and anthropometric variables were helpful for designers to bridge a network between the interior design of the vehicle and crew/troops' comfort issues. Therefore, the dimension predicted from the present research can serve as a reference for designing the interior workspaces of Ethiopian LAVs. Furthermore, the proposed design dimensions and their respective predictive mathematical models can be used as national and international standards for future vehicular workspace designs.

Different models of LAVs were reported in various literature without considering the optimal solutions of design variables and geometric factors for different physiques (Park, 2017). As a result, the hull's enhancement of protection capability, mobility, and space adequacy by proposing suitable geometric models are vulnerable to reduction. The methodology used in **Chapter 4** to analyze the optimal parameters to enhance desired characteristics (crew protection capability, space adequacy, and mobility) is also the new design approach. It can be used to set the standards and proposed geometric models when developing the conceptual design of LAVs.

6.1.1 Salient Findings

The following are salient findings of the study regarding the design intervention of Ethiopian LAVs:

- In an anthropometric survey of Ethiopian soldiers, significant variations were observed when the anthropometries of Ethiopian army personnel were compared between age, ethnicity, and cross-nationals (Table 2.7, 2.9, and 2.10). Hence, the variations in geographical factors could significantly impact the ergonomic design of equipment and vehicular workspaces of Ethiopian army personnel.

- The 12 relevant anthropometric variables that account for those 32 measured variables were identified (Table 2.3 and 2.5). The findings of PCFA and regression analysis also depicted that there is a possibility to identify less key anthropometric variables that represent the overall anthropometric variability of the population for simplifying anthropometric surveys in the future at diverse and extensive levels PMU testing with limited user trials.

- A high dimensional mismatch (in terms of the accommodating capacities of LAVs) between the existing and predicted design dimensions was observed. This indicates that the incompatibilities between vehicular space dimensions and army personnel's anthropometry must be addressed to avoid adverse occupational health consequences (Table 3.6).

- Regarding safety issues, the hull's crew protection capabilities from the horizontal strike of AP rounds were significantly improved for the two proposed models, when compared with existing vehicles without affecting the space occupancy and mobility of LAV (Table 4.1).

- The intended vehicular workspaces (W1, W2, W3, and W4) for space adequacy, the need for view field, reaching, and manipulative needs were found to be ideally compatible with the target users (Ethiopian army personnel) to accommodate 90% (for adjustable units) and 95% (non-adjustable) of them. Hence, the proposed twenty-two basic design dimensions of LAV workspaces were confirmed to be compatible with the target user populations during digital and physical evaluation.

6.1.2 Fulfillment of the objectives

The relevant findings obtained in the analytical and experimental study, along with the fulfillment of objectives, are listed below:

Objective 1: *To develop an anthropometric database for Ethiopian army personnel for ergonomic design of workspaces and equipment.*

Detail description of the measurement procedure and the findings of the anthropometric survey have been described in **chapter 2** of the thesis (see Table 2.2). The study of this objective was also published by the same authors, **Wibneh et al. (2020).** Thus, this particular study fulfilled research **objective 1**.

Objective 2: *To identify the most influential anthropometric variables which represent the large sets of required variables for simplifying ergonomic design analysis of LAVs*

A total 12 key anthropometric variables were identified from 32 measured variables using PCA and regression analysis (see Table 2.3 and 2.5). The detailed procedures and methods to identify the key variables from large sets of variables are described in **chapter 2**. The study for this particular objective was also got published by the study authors **Wibneh et al. (2021b)**. Thus, the study for research **objective 2** was fulfilled.

Objective 3: *To study the dimensional compatibility of LAV workspaces compared with anthropometric characteristics of Ethiopian army personnel*

The twenty-two basic design dimensions that comply with ergonomic principles were predicted as a function of anthropometric variables and ROMs (see Table 3.5). This study objective was described thoroughly in **chapter 3** and published by the same authors, **Wibneh et al. (2021a)**. Thus, research objective- 3 was fulfilled.

Objective 4: *To investigate the influences of hull obliquity on crew protective, mobility, and ergonomic aspects of LAV design using an optimal design approach*

The three geometries of the hull structure were investigated thoroughly to evaluate the crew protection capability without affecting space occupancy and mobility/weight of the LAV (see Table 4.1). Objective 4 has been described in **chapter 4** and published by the authors, **Wibneh et al. (2021c).** Thus, research **objective 4** was fulfilled.

Objective 5: *To evaluate an ergonomic design of LAV workspace using DMUs and PMUs evaluation for validation purpose.*

Detail description and the findings have been described in the **chapter- 5** of the thesis. The study of this objective is **under review.** Thus, research **objective 5** was fulfilled.

6.2 Testing of Hypothesis

The following two hypothesis formulations were addressed in objective wise of the preceding chapters (chapter 2, 3, 4, and 5) to answer the 6 research equations.

Hypothesis 1: *Anthropometric difference of Ethiopian army personnel compared to other countries has a significant impact on dimensional compatibility of the army vehicular workspace that would be developed by following the standards of other countries.*

Hypothesis 1 comprises three research questions **(RQ-1, RQ-2, and RQ-3),** and its proposed solution was fulfilled and established by addressing them as shown below:

Research Question-1(RQ-1): The 32 anthropometric measurements were taken from 250 male and 60 female Ethiopian soldiers (four different ethnic groups at various age levels) following standard measurement protocol, and they were developed in terms of range, mean, standard deviation, percentile values (5th, 50th, and 95th) for vehicular workspace design. Thus, we can apply such accessible measured anthropometric data for the conceptual design of equipment and workspaces to reduce the possible miss-match with the size of Ethiopian army personnel. Significant variations were found (see Table 2.10) when the anthropometry was compared with cross-nationals (India, Korea, and the USA). This finding indicates that variations in geographical factors among nations could significantly impact the ergonomic design of equipment and workspaces of Ethiopian army personnel. Therefore, the study suggests the need for redesigning the army equipment and facilities used by Ethiopian soldiers, taking into account the soldiers' anthropometry.

Research Question-2(RQ-2): The total 12 key anthropometric variables were identified from 32 measured variables using PCA and regression analysis (see Table 2.3 and 2.5). Hence, 12 independent anthropometric variables, which can represent 32 variables, were utilized for user testing of PMUs when few subjects considered human body size diversity. These are the six most dominant anthropometric variables, variables having less commonality, the less correlated variables, and the key and targeted variable in many studies called mass, as listed in Table 6. 1.

Moreover, most of the anthropometric variables can be predicted using six influential variables. Therefore, **the research question (RQ-2) was addressed and fulfilled.**

Research Question-3(RQ-3): A high mismatch (in terms of the accommodating capacities of the three LAVs) between the existing and predicted design dimensions was observed in the analysis (see Table 3.6). The percentage matches for most workspace dimensions were found to be less than 75%. The research findings indicate that the incompatibilities between vehicular space dimensions and army personnel's anthropometry can have severe consequences for occupational health (Lee et al., 2020; Ross, 2011). Therefore, the LAVs should be redesigned according to the anthropometry and ROM dimensions of Ethiopian soldiers. The predictive equations which relate workspace dimensions with anthropometric dimensions and ROMs are also the noticeable findings for the proposed design dimensions of LAV workplaces. Therefore, the baseline predictive models and design methods suggested in this first-of-its-kind research would be helpful for ergonomists and designers to understand the synthesis of anthropometric diversity and workspace dimensions in the ergonomic design of the LAVs. Therefore, **the research question (RQ-3) was addressed and fulfilled.**

Hypothesis 2: *Proper design modifications with considerations of suitable workspace dimensions and appropriate hull obliquity would significantly increase crew protection and comfort without affecting space occupancy of the crew and mobility/weight of the vehicle.*

Hypothesis 2 again comprises three research questions **(RQ-4, RQ-5 and RQ-6),** and its proposed solution was fulfilled and established by addressing them as shown below:

Research Question-4 and 5 (RQ-4 and RQ-5): From three investigated geometric models (one non-obliqued hull, G1, and two obliqued hulls, G2 and G3), the higher protection capability and comfortable occupancy for the targeted users were achieved by both G2 and G3 without affecting the mobility of LAV (see Table 4.1). Therefore, the hull's crew protection capabilities from the horizontal strike of AP rounds were improved almost by half and double for G2 and G3, respectively, when compared with G1. Therefore, **the research questions (RQ-4 and RQ-5) were addressed and fulfilled.**

Research Question-6 (RQ-6): The vehicle constructed by the predicted design dimensions using digital and PMU was also validated to ensure its accommodation for the recommended percentages (>75%) of user populations (Fernandez, 1995). Hence, the validated results depicted that all design dimensions had been determined to accommodate at least 90% (for adjustable units) and 95% (for fixed units) of the targeted populations with specific boundary errors (see Figure 5.11 and Table 5.4). This indicates that the proposed dimensions are suitable for the construction of LAV considering ergonomic issues in the future. The framed predictive equations were also established to express design dimensions as a function of anthropometric and ROM measurements of particular user populations. Therefore, **the research question (RQ-6) was addressed and fulfilled.**

6.3 Key contributions of the present research

The present research work enriches the existing knowledge of the human factors/ergonomics in LAV design by establishing the required design guidelines for the intervention of ergonomic and crew protective aspects.

6.3.1 Contribution to knowledge-base

An anthropometric survey for target users is one of the baseline information for ergonomic design and analysis of equipment and workspaces. Therefore, the compiled database of the anthropometric measurements of Ethiopian soldiers is helpful for researchers to acquire basic knowledge in the process of data collection, analysis, and interpretation. Those basic anthropometric variables can be used and referred by designers and researchers for their anthropometric measurements of specific user populations in workspace design of army vehicle. The key anthropometric variables which were identified using PCFA and regression analysis from other dependent variables can be utilized by other researchers to simplify the anthropometric survey in the involvements of large anthropometric variables and sample sizes. The study is also helpful for ergonomists and designers to enrich their knowledge about understanding the synthesis of anthropometric diversity with workspace dimensions in ergonomic design of vehicular workspace designs. Designers/engineers will be well expertized in ergonomic concepts as they know and apply the baseline protocols in their ergonomic design of facilities. The proper design approaches and procedures in optimal design of LAVs will be the basic guidelines during conceptual design stages for the intervention of ergonomic issues and crew protective aspects. Hence, the establishment of design philosophy for conceptual developments of vehicle models in ergonomic design considerations and enhancement of crew protection capability is used as knowledge bases. The design and analysis approaches of the man-machine interface using DMU and PMU testing are also the baseline information of LAV development.

6.3.2 Contribution towards methodological perspective

The major methodological protocols that can provide visible contributions for researchers in the process of anthropometric survey consist of sample size calculation, anthropometric measurement tools, procedures and techniques, selection of the required anthropometric variables for design of army vehicles, reliability assessment of measurements to avoid errors occurred by measuring instruments and observer, and techniques for data analysis. From the methodological aspects of data analysis, the statistical analysis of anthropometric measurements consists of normality testing using skewness and kurtosis, national wise comparison test with India, Korea and USA using significant t-test and variable reduction activities using PCFA and regression analysis including analysis and documentation of mean, SD and percentiles (5th, 95th, or 5th-95th p) values of functional anthropometries for both male and female. Simplifying anthropometric measurements is expected to make a significant methodological contribution to the variable reduction process in the research design of the anthropometric survey and other applications involving many variables and sample sizes.

The match/mismatch analysis of existing vehicular workspace dimensions compared to predicted design dimensions (determined by predictive equations) is considered the novel methodological contribution of its kind. Predictive equations formulated as a function of anthropometric variables and ROMs can be utilized as a design standard globally and nationally. Design intervention of ergonomic issues and crew protective aspects (such as dimensions of occupant space, hull obliquity, geometric factors, and mobility aspects) of the vehicle was considered to be design constraints to enhance crew protection without affecting space occupancy and mobility/mass so that it helps to provide as a methodological basis. DHM has been used in many literature surveys to test DMU. However, PMU testing was also performed to use small sample sizes as needed to check the design intervention of both ergonomic and crew protective aspects.

6.3.3 Contribution to the defense sector

The defense sector contributions come up with design guidelines in particular for Ethiopian army vehicles with due consideration of ergonomics, and protection/safety are listed as below:

- As a result of this research, it is the first of its kind anthropometric study, and thereby the development of the anthropometric database for the male Ethiopian army personnel has been initiated. Therefore, developing and packaging anthropometric databases for Ethiopian army personnel is one of the contributions of the Ethiopian defense society to design defense equipment and workspaces.
- Based on the adequate sample size estimation principles, it is recommended to include more army personnel in the near future for a much more reliable database. Until additional studies, the current anthropometric database may be considered for designing military equipment and workspaces.
- In the variable reduction technique, identifying the representative anthropometric variables/ predictors is helpful for the reduction of a large number of variables. At the same time, data collection is constrained by a lack of resources, manpower, and financial support. It is also used for reducing the number of human subjects for user testing of PMU/prototypes.
- The Ethiopian defense vehicles manufacturers can utilize for fabricating LAVs considering the comfort and safety of the soldiers. The measurement predicted from the present research could serve as a design guideline for designing the interior workspace of Ethiopian LAVs.
- This research will encourage engineers/designers to evaluate the protective capabilities of the LAVs while considering ergonomic aspects. The methodology used to analyze the optimal parameters can set the standard when developing the conceptual design of LAVs. Therefore, the optimal design intervention can be utilized as a design guideline for the design of Ethiopian army vehicles.
- The present study encourages engineers/designers to evaluate proactive implementations of ergonomic design principles at the conceptual stage of vehicle development and validate

those applicable mathematical models using virtual and physical ergonomic evaluations. Therefore, the study helps establish the design philosophy for the vehicle model at the conceptual stage to enhance crew protection capability and ergonomic design considerations.

6.4 Scope for Future research based on current limitations

The anthropometric data were collected from 250 male and 60 female Ethiopian soldiers with limited sources and time constraints based in agreement with the recommended sample size while conducting anthropometric studies (ISO 7250-1: 2017). However, the experiment may require a large sample size in a data survey to provide reliable results when the apprehensive sectors give exceptional support. The developed anthropometric data is also limited to 32 measurements, and may not be sufficient for designing ergonomic fit military products other than vehicular design due to the constraints above to measure more anthropometric variables. Although no attempt was made in current research, it will be interesting to investigate the biomechanical characteristics, body range of motion, and strength capabilities among the army personnel in future studies.

Even though the user testing using different (from smaller to larger) body sizes of participants is also possible to conduct (Wibneh et al., 2022); it has to be better to increase the 13 subjects to take into account the diverse characteristics of the user populations for human trials of PMU. Therefore, it is recommended to involve large testing subjects in user trials of the PMU for reliable assessment of the proposed PMU. Even though the ergonomic evaluation of LAV is considered the only objective evaluation for anthropometric compatibility of the LAV to the user populations, subjective assessments may also be required. The functional PMU called prototype has to be made to test the static and dynamic conditions (effects of working duration, vibrations, temperature, etc.) of the vehicle, both objective and subjective. In anthropometric compatibility study, more ergonomic variables such as energy/force exertion effect on muscle, tissue compression, satisfaction, comfort, perceived job performance, and health and safety consequences would be helpful to take into account for reliable assessment of the workspaces by user trials.

Apart from ergonomic evaluation issues, the safety issues to protect the crew from firing bullets also need an extensive investigation experimentally and numerically to validate the benefits that we achieved in our analytical results and findings. However, the present analytical approach is a baseline for the optimal design of the hull at the conceptual design stage, taking into account space occupancy, protection capability, and mobility at the minimum attainable weight.

6.5 Conclusions and recommendations

This research work was the first attempt to propose appropriate design dimensions with proper procedures and design protocols for an ergonomic design of Ethiopian LAVs. In the present research, an attempt was made to develop the required anthropometric databases (for the ergonomic design of vehicular workspace) of Ethiopian army personnel for both males (aged: 18–52 years) and females (aged: 18–30 years) from various races. A comparison test of the collected data was made with other countries (India, Korea, and the USA). The results showed that the anthropometry of the Ethiopian army varied significantly with respect to other nations. Subsequently, a high mismatch between the existing and anthropometric design dimensions was observed in the analysis. The percentage matches for most workspace dimensions were found to be less than the recommended percentage (<75%). The research findings indicate that the incompatibilities between vehicular space dimensions and army personnel's anthropometry can severely affect occupational health. Therefore, the design modification of LAV based on anthropometric design dimensions would be necessary for advancing the user-compatible workspaces in operational activities inside the vehicle. The ergonomic design and evaluation of the interior of an army vehicle which was substantially aided by digital human modeling (DHM) software and PMU evaluation method, ensured the fitness of the newly proposed workspace dimensions for the Ethiopian army population.

Similarly, the study considered the forms/geometries of the hull structure that enhances its protection capability for the crew from firing bullet/AP rounds without affecting space occupancy and mobility/mass. Hence, Ethiopian defense vehicle manufacturers should fabricate the LAVs considering both ergonomic and protection issues of the soldiers. The present study encourages engineers/designers to evaluate proactive implementations of ergonomic design principles in the conceptual phase of the vehicle design process using virtual ergonomics evaluation and validating those applicable mathematical models and proposed design dimensions using user testing of PMUs.

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Appendix

Appendix 1: The relevant workspace dimensions with their corresponding descriptions (refer to Table 3 and 4)

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 footrests to the hull roof.

Base width (A7): The hull space width is usually measured on 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): The horizontal distance from SRP to the dashboard position along with the knee.

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

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

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

Daylight opening distance (B10): is the horizontal distance from the headrest 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 handles 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): The vertical distance from SRP to the turret handle.

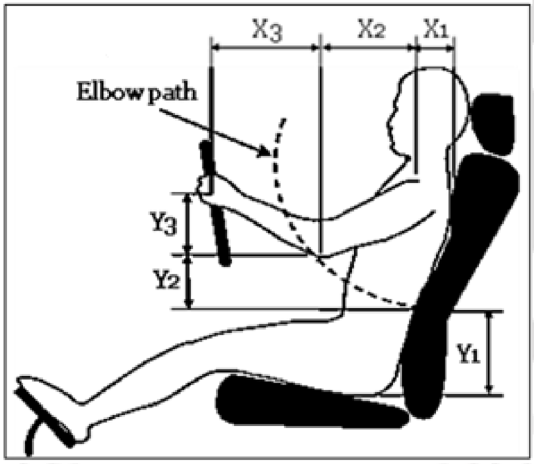
Height of sight vision device for seated gunner (C3): The vertical distances from seat reference point to display of sight device.

Height of sight vision device for stood gunner (C4): The vertical distance from the standing platform (pedestal) to the sighting device.

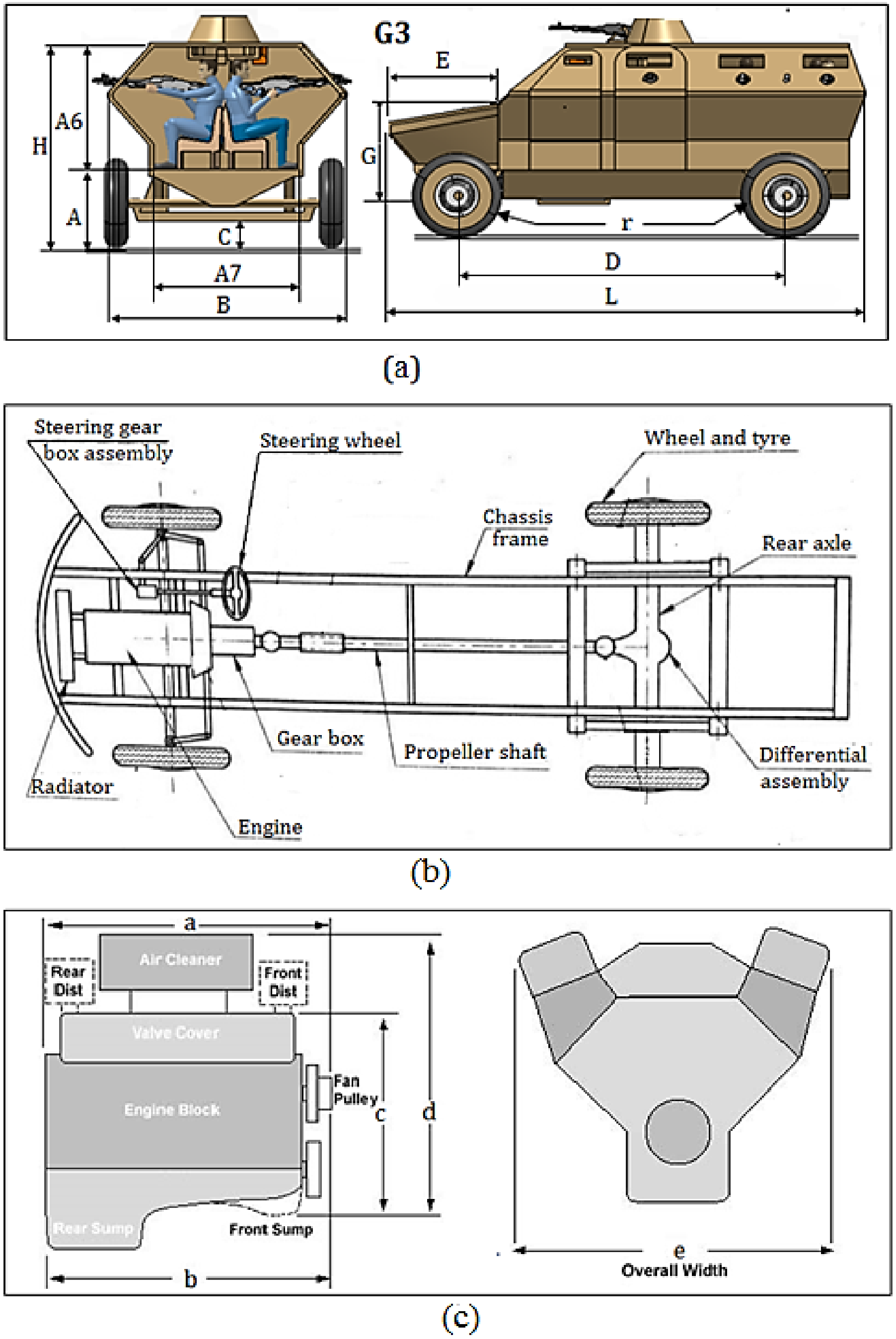
Top hatch diameter (C5): The opening diameter at the top for the gunner's hatch during the firing task.

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

Appendix 2: Segmentation of steering wheel position of driver workspace (refer to Table 3.3)



Appendix 3: Proposed models of LAV with (a) overall dimensions (b) subsystems of vehicles (c) dimensional drawing of the V8 diesel engine (See Appendix 4)



(a)

(b)

(c)

Appendix 4: Overall dimensions and specifications (refer to Appendix 3)

Table: The overall key dimensions and specifications of proposed models along with existing LAVs and global standard vehicles

Dimensions	***Veh-1**	***Veh-2**	***Veh-3**	**Glob-1**	**Glob-2**	**Glob-3**	**Proposed models**
A	80	70	70	NA	NA	NA	70
A6	150	130	135	NA	NA	NA	136
A7	195	185	215	NA	NA	NA	165
B	200	220	280	240	250	222	250
C	40	33	40	40	37	26.6	30
D	300	310	190	330	290	330	300
E	100	85	105	NA	NA	NA	112
G	120	55	70	NA	NA	NA	130
H	230	200	210	240	218	210	206
L	500	570	670	535	586	550	550
r	50	50	60	54.5	NA	50	100
Specifications	***Veh-1**	***Veh-2**	***Veh-3**	**Glob-1**	**Glob-2**	**Glob-3**	**Proposed models**
Crew and troops	10	7	13	8	11	9	11
Firing posture	Standing	seated	Seated/ standing	Standing		Seated/ standing	Seated/ standing
Wheels and tyres	4	4	6	4	4	4	4
Engine power (h.p.)	330	160	320	180	160	190	NA
Armament	7.62 mm machine gun	7.62 and 14.5-mm machine-gun	12.7mm machine gun	7.62 mm machine gun or 30 mm launcher	7.62 or 12.7 mm machine gun mm	12.7 mm machine gun mm	12.7 mm machine gun mm
Engine type	V-8 (Diesel engine)	Diesel engine	V-8 (Diesel engine)	V-6 (Diesel engine)	V8 Diesel engine	V-8 (Diesel engine)	V-8 (Diesel engine)
Engine dimensions	**AMC 360/401**	**Buick 400/455**	**Cadillac 472/500**	**Chevy 396/454**	**Ford 427 SOHC**	**Mopar V10**	**Pontiac 455**
a	72	72.5	75	76	80	92	74
b	73	75	76	76	85	92	80
C	53	55	71	79	75	58.5	67.5

D	54	75	80	82.5	85	NA	82.5
E	74	57.5	71	67.5	80	62.5	67.5

NA-not available

All measurements are in cm unless specified;

**existing Ethiopian LAVs used in assessment study;*

Glob-1-Russian global standard LAV called Tiger GAZ-2330 (Source: Global Defence & Security News, 2016); Glob-2- Italian global standard LAV called Type 6614 APC (Source: Army Guide, 2015a). Glob-3-Turkey international standard LAV called cobra (Source: Army Guide, 2015b)

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