Effects of protective equipment and body borne gear on seated maximum reach envelopes

K. Han Kim, Monica L. H. Jones, Sheila Ebert, Matthew P. Reed

University of Michigan Transportation Research Institute
Ann Arbor, MI, USA

Soldiers in military tactical vehicles perform increasingly diverse tasks, including communication and weapons system control. Personal protective equipment (PPE) and body borne gear (BBG) restrict the soldier's mobility and performance. This study is to quantify the effects of PPE and BBG and their interactions with a seat harness restraint system on seated maximal reach capability. Participants performed a series of maximal reaches, which were recorded using a motion capture system. The results showed that wearing PPE and BBG reduces reach envelope dimensions by 9% and 4%, respectively. Further, wearing a harness decreases reach envelopes by 29% and 17% for the PPE and BBG conditions, respectively.

Practitioner Summary: Wearing a harness and garb significantly reduces seated reach capability, in particular for the regions requiring torso movements. Overall, this study will provide a quantitative tool to optimize vehicle design to improve the comfort and performances of occupants.

Keywords: workspace, range of motion, anthropometry

1. Introduction

Soldiers seated in military tactical vehicles are asked to perform increasingly diverse tasks, including communications and controlling weapon systems. Personal protective equipment (PPE), including body armor and body borne gear (BBG) restrict the soldier's ability to reach.

Reach envelopes have been used to assess the reach capacity and risk of injury for workers, particularly for workspace and vehicle interior design (Reed, Parkinson, & Klinkenberger, 2003; Sengupta & Das, 2000) to optimize control and user interface layouts. Studies have quantified reach envelopes as a function of different anthropometry and work postures (Sengupta & Das, 2000; Wang & Trasbot, 2011). However, the impact of body armor on functional range of motion and task performance has not been well understood.

The current research is to quantify the effects of body armor and body-borne equipment on seated maximal reach capability. Participants performed a series of maximal reaches, from a seated posture, with and without the presence of a seat harness restraint system and while donning a range of PPE configurations. The overall goal is to develop a quantitative model for vehicle design to improve occupants' performance and comfort.

2. Methods

Data were gathered from ten civilian participants (seven females and three males), all right-handed and with no history of musculoskeletal disorders. The mean stature of the participants was 155.5 (SD 10.6) cm and body-mass index (BMI) was 21.4 (SD 2.1) kg/m^2.

A mock-up of a squad seat with dimensions that are typical in a military tactical vehicle was used in this study (Figure 1). The seat was equipped with a 5-point harness to assess the no-harness (NH) versus with-harness (WH) condition. In the WH condition, the upper restraints were fed back into the retractor with the participant sitting back in the seat, then the restraints were locked with a belt lock preventing feed-out. Participants' motions were recorded using a 13-camera VICON optical motion capture system.

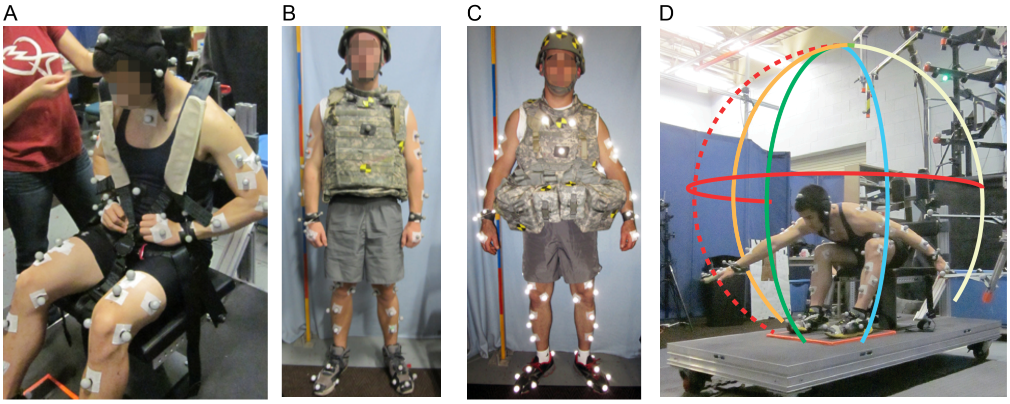

Figure 1. Participant donning 5-point harness in minimally clad garment (MCG: A). Participant wearing PPE (B) and BBG (C). The “virtual” traces of maximal reach motions (D).

Each participant was tested with three levels of garb: minimally clad garment (MCG: Figure 1A), wearing PPE alone (PPE: Figure 1B), and wearing the PPE and BBG (BBG: Figure 1C). Participants did not wear army combat uniform (ACU). The effect of the 5-point harness was also investigated (Figure 1A). Test condition order was randomized by the level of garb and harness. After donning each level of garb and harness, participants performed a series of standardized motions to quantify the available range of motion in the upper extremity and torso. This motion was continuous and involved completing maximal arcs that covered a reach envelope (Figure 1D), which ranged vertically from overhead (0 degree polar angle) to ground. Arc motions were made at 0 (right), 45, 90 (forward), and 135 (left) degree azimuths. Horizontal arcs were made separately at shoulder level from 0 to 135 degree azimuth. Participants were instructed by maintaining the position of the pelvis with respect to the seat and the opposing arm rested to the side throughout the maximal reach motion.

The 3-D coordinates of the right index fingertip were measured from recorded optical marker positions. Reach envelope surfaces () were predicted by a second-order regression model (Equation 1) as a function of the spherical coordinates (azimuth θ and polar angle φ) of the right index fingertip. A least square of error (ε) method was used to determine the coefficients (). The origin of the coordinates was located at the seat H-point (Society of Automotive Engineers, 1991).

(Equation 1)

In order to compare the shapes of reach envelopes in different garb and harness conditions, mean reach distances were estimated for each condition. A mean reach distance was defined as the average of distances to the reach envelope surface predicted by the regression model. Forward and right reach distances were measured by the horizontal distance from the mid-acromion to the corresponding points on the reach envelope surface. Similarly overhead reach distance was the vertical distance from the mid-acromion point to the reach envelope surface (Figure 2). Reach distances were normalized by individual stature. Further, reach distances were analyzed using multivariate analysis of variance (MANOVA) to estimate the main and interaction effects of garb and harness conditions.

3. **Results**

Overall the regression models showed R^2 scores ranging between 0.87 and 0.97. The regression model coefficients and R^2 scores averaged for each garb and harness condition are listed in Table 1.

Repeated measurement MANOVA performed on the reach distance estimates revealed a significant *between-subject* effect of harness restraint (p<0.0001), no *between-subject* effect of garb (p=0.6442), and no interaction between garb and harness (p=0.2809). *Within-subject* analysis determined that the main effects of varying levels of garb (p=0.0131) and the harness restraint (p<00001) were significant.

Table 1. Mean (standard deviation) coefficients and R^2 scores

		R^2													
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
MCG	NH	0.8271	0.1231	1.2264	0.1405	0.093	0.1329	0.0802	0.1468	0.0033	0.0265	-0.0631	0.0405	-0.1712	0.1707
	WH	0.9764	0.0127	1.259	0.0836	0.0067	0.0289	-0.1202	0.0736	-0.0621	0.0103	-0.0232	0.0146	-0.0942	0.0405
PPE	NH	0.8667	0.0643	1.1508	0.1351	0.1922	0.1324	0.0966	0.1487	-0.0314	0.0379	-0.0858	0.0384	-0.1209	0.0761
	WH	0.9745	0.011	1.171	0.1057	0.075	0.0315	0.0467	0.0841	-0.0803	0.0283	-0.0545	0.012	-0.1518	0.0418
BBG	NH	0.8926	0.0468	0.9515	0.1476	0.3167	0.0818	0.3634	0.2557	-0.0467	0.0885	-0.1288	0.0335	-0.2462	0.0966
	WH	0.9626	0.037	1.0843	0.1578	0.1684	0.0772	0.1605	0.127	-0.0966	0.0225	-0.0747	0.0211	-0.1954	0.0478

Figure 2 illustrates reach envelopes from a participant. On average, wearing the harness (WH) decreased mean reach distances by 23%, 29% and 17% for MCG, PPE and BBG conditions compared to the corresponding conditions without harness (NH; Figure 3). Further, wearing PPE and BBG reduces reach envelope dimensions by 9% and 4% respectively. With the harness on, forward reach distances were reduced by 37%, 38% and 28% for MCG, PPE and BBG, respectively. For reaches to the right side, wearing harness did not significantly reduce the reach distance, while BBG reduced the reach distance by 4%.

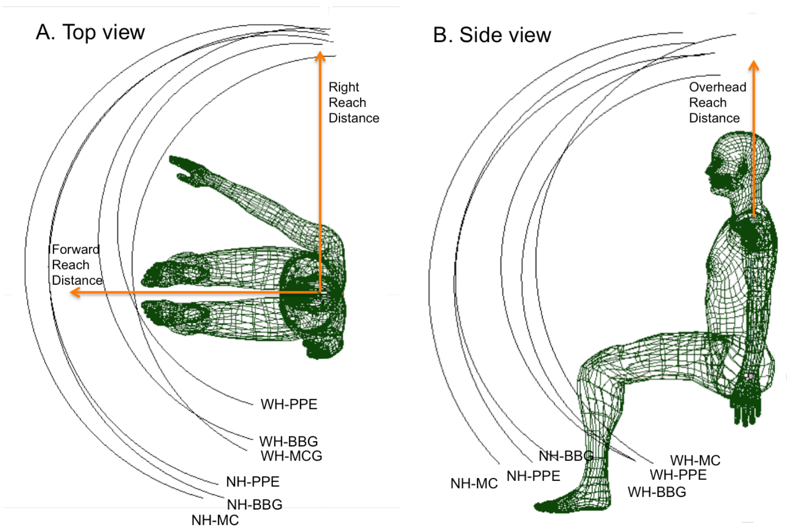

Figure 2. Reach envelopes from a participant (aberrations in the text).

4. **Discussion**

The results showed that the harness and garb significantly reduce seated reach capability, particularly for the regions that require torso movements. Thus the differences between reach distances tend to be larger for the lower regions requiring torso flexion, while such differences are diminished for the overhead reaches and reaches to the right side, in which arm and shoulder motions play a primary role. The findings of this study should be further enhanced by assessing the subjective ratings of reach difficulty and comfort for reaches *within* maximum envelopes. Overall, it is expected that this study will provide a quantitative tool to optimize vehicle designs to improve the comfort and performances of occupants.

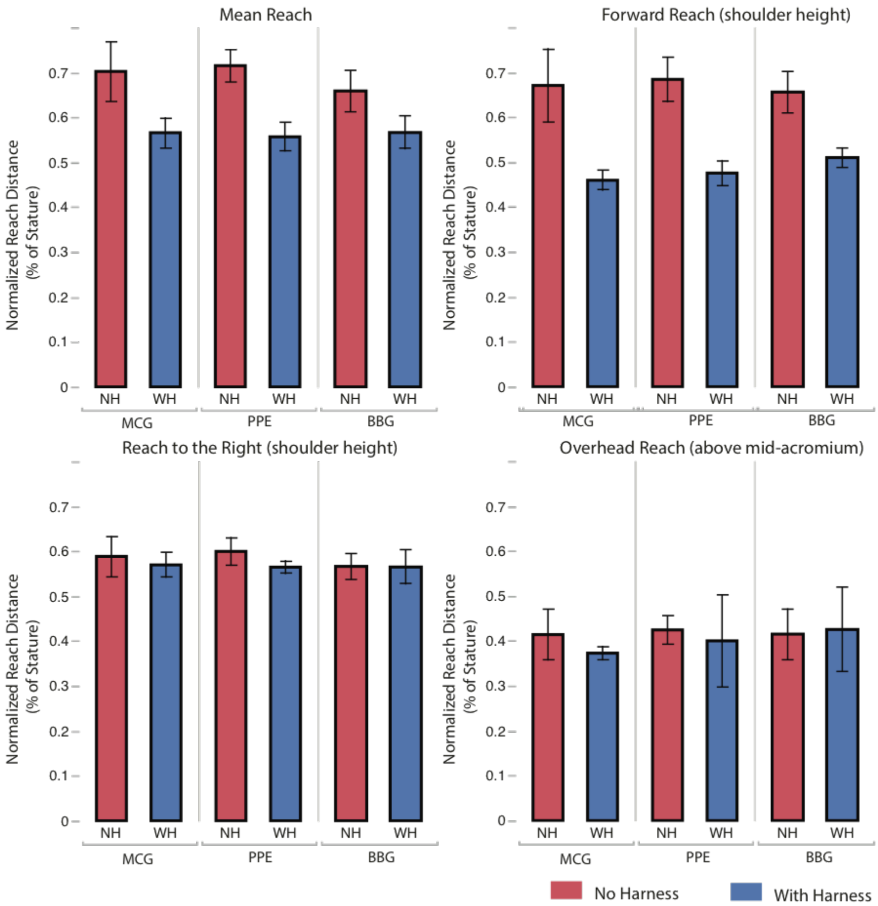

Figure 3. Mean, forward, right, and overhead reach distances (± standard deviation)

Acknowledgements

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