Occupational Ergonomics 11 (2013) 137–151
DOI 10.3233/OER-140213
IOS Press

Effect of seat orientation on ingress/egress joint kinematics and reach envelope

Christopher W. Moore[a], Ashish D. Nimbarte[a,*], Sudhakar Rajulu[b], Xiaopeng Ning[a] and Steve E. Guffey[a]

[a]*Industrial and Management Systems Engineering, West Virginia University, Morgantown, WV, USA*
[b]*Johnson Space Center, National Aeronautics and Space Administration, Houston, TX, USA*

Abstract.
BACKGROUND: Little is known about ingress/egress requirements and forward reach for workstations with horizontal seats. This research explored differences between ingress/egress kinematics and reach due to seat orientation.
METHODS: 10 participants performed ingress/egress tasks using three seat orientations (horizontal with 90° and 120° seat angles, and vertical with 90° seat angle) and planar reach tasks in three anatomical planes using horizontal and vertical seats with 90° seat angle. An optical motion capture system was used to record kinematic data. Marker data was processed and modeled to estimate peak joint angles and ranges of motion of several body joints. For reach tasks, marker data of the clavicle and finger were used to plot reach capacity.
RESULTS: Ingress/egress joint kinematics differed greatly between horizontal and vertical seats, while few differences existed between the horizontal seat orientations. Peak angles and ranges of motion during ingress/egress of the horizontal seats were significantly higher than the vertical seats, often by a factor of 3–4. The direction of motion affected several peak angles and ranges of motion, but to a lesser extent than seat orientation. Reach was unaffected by seat orientation.
CONCLUSION: This study's findings suggest that ingress/egress of horizontal seats is more stressful for the body, especially the shoulders and lower back, than regular upright seats.

Keywords: Ingress, egress, recumbent seats, kinematics, reach envelope

1. Introduction

A number of areas benefitted from the application of ergonomic principles [1–4]. However, one area that has been largely overlooked is space-travel, including design of space modules and extra-vehicular activities. Until research was conducted in 2000 to determine the important ergonomic factors in spacecraft cabin design, crew modules of spacecraft were designed to minimize structure, weight, and volume [5]. Even in current designs, size is still an important consideration in crew module design. For example, the crew module of the upcoming Orion spacecraft has a volume of approximately 15 m^3 and will hold up to six people [6]. While this space may be sufficient when positioned into a seat, movement could be challenging and uncomfortable. Designing the spacecraft module with a comfortable, ergonomically-correct seat and controls that are easy to reach without using abnormal body position is important to relieve some of the physical and mental stress experienced by the user.

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[*] Corresponding author: Ashish D. Nimbarte, Industrial and Management Systems Engineering, West Virginia University, PO Box 6070, Morgantown, WV 26506-6107, USA. Tel.: +1 304 293 9473; Fax: +1 304 293 4970; E-mail: Ashish.Nimbarte@mail.wvu.edu.

Unlike many seats that are used on a daily basis, spacecraft seats are positioned horizontally instead of vertically. This requires different techniques for ingress and egress which may require different biomechanical movements. For instance, in most upright seats, the user can move in front of the seat and lower their pelvis into it. In a recumbent seat, ingress is typically done from a supine position. Ingress from a supine position requires using the arms and legs to lift and move the torso into the seat. Kinematics during ingress and egress of upright seats has been well-researched, especially in regards to comfort and ease of ingress/egress of various types of vehicles including passenger automobiles [7,8], heavy trucks [9,10], and military helicopters [11]. However, the results of these studies have little relevance to applications involving horizontal seats.

The horizontal seats, such as those used in the spacecraft, are not adjustable like many upright seats and therefore may also affect the reach ability of the users. When ingressed, the back of the horizontal seat supports most of the upper body weight and maintains a constant contact with the user's torso. This, along with the effect of gravity, is expected to have a substantial effect on the reach ability of the user. Additionally, the control placement further complicates the reach ability issues for workstations that use horizontal seats. Controls located within easy reach of the seated user could hinder ingress and egress. However, if the controls are moved farther from the seat to allow easier ingress and egress, the controls may be difficult to reach.

The existing research on the normal sitting and standing reach involves use of experimental [12–14] and analytical [15,16] methods. This research has either led to the development of software models [10,16] that can be used to ergonomically assess a workstation or led to the development of charts/databases [14] that can be referenced during workstation design. While the normal standing and sitting reach is well documented in the literature, little is known about the effect of horizontal or recumbent posture on the reach.

The purpose of this study was twofold. First, the study compared the kinematics of major joints between ingress/egress of horizontal (recumbent) and vertical (upright) seats. Second, the maximal planar reach was compared between the horizontal and vertical seats. It was hypothesized that ingress/egress of the horizontal seats will require higher ranges of motion and higher peak angles compared to the vertical seats. Additionally, reach in the horizontal seats was hypothesized to be lower than in the vertical seats.

2. Methods

2.1. Approach

In this study, ingress/egress and reaching tasks in vertically and horizontally oriented seats were evaluated using a lab-based simulation. An optical motion capture system was used to record three-dimensional locations of retro-reflective markers placed on anatomical landmarks of the participant's body. Joint kinematics and reach in three anatomical planes were computed using the marker data.

2.2. Participants

Ten healthy, male participants with mean (± sd) age, height, weight of 24 (± 2.3) years, 174 (± 7.7) cm, and 73.3 (± 7.0) kg, respectively, were recruited for participation in this research. Potential participants were excluded if they were unable to perform the tasks or had any deformity or physical issue that would not allow use of the motion capture marker set. Consent was obtained from the participants via a consent form approved by the local Institutional Review Board.


(a) (b) (c)

Fig. 1. Left: Vertical seat platform. Center: Horizontal seat platform with seat angle of 120°. Right: Horizontal seat platform with a seat angle of 90°. These platforms were designed to stabilize the seat during ingress/egress and reach tasks. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/OER-140213)

2.3. Apparatus

2.3.1. Optical motion capture system

An eight-camera Vicon optical motion capture system (MX Series, Vicon Motion Systems, Oxford, UK) was used to record the dynamic ingress/egress and reach tasks. This system uses infrared light to track small, retro-reflective markers and report their coordinates in 3D space.

2.3.2. Motion analysis software

Vicon Nexus 1.7.1 software was used to capture and process the data recorded by the motion capture camera system. Experimental tasks were captures at a rate of 100 frames per second.

2.3.3. Kinematic computation software

C-Motion Visual3D 4.8.9 (C-motion Inc., Germantown, MD, USA) was used to model the three-dimensional (3-D) marker data from the ingress/egress tasks.

2.3.4. Custom horizontal and vertical seat platforms

Two seat platforms were designed for this research (Fig. 1). The first secured an automobile seat with the seat back in a vertical position and included a strap that allowed the user to be secured to the seat during vertical reach tasks. The second secured the seat in a horizontal position and allowed the angle of the automobile seat to be adjusted to 90° and 120°. There was space to the left of the seat for the subject to lay supine.

2.4. Experimental design

The ingress/egress and reach portions of this research both used a 2×3 full factorial design. The ingress/egress tasks compared three seat orientations (horizontal with a 90° seat angle, horizontal with a 120° seat angle, and vertical with a 90° seat angle) and two tasks (ingress and egress). Dependent variables were the peak joint angles and ranges of motion of the hips, knees, shoulders, and trunk. Reach tasks, however, compared only two seat orientations (90° horizontal, 90° vertical) and three tasks (planar reach in the sagittal, transverse, and frontal anatomical planes). Dependent variables for the reach tasks were three extreme points for each arm of each planar reach task.

Fig. 2. Subject in the full custom set of 62 retro-reflective markers. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/OER-140213)

2.5. Data collection

2.5.1. Subject preparation

In order to accurately determine the joint angles, the markers on each body segment must be accurately tracked and precisely follow the movement of the segment. Therefore, upon arrival, the participant was instructed to change into tight-fitting, spandex shorts and remove their shirt. The spandex shorts also helped ensure that the markers were not hidden during the capture. Subjects were then shown the step-by-step progression to be used during ingress and egress and given ample time to practice. Sixty-two retro-reflective markers were affixed to specific landmarks of the body (Fig. 2) to allow accurate modeling of the dynamic trials within C-Motion Visual3D. Finally, a 5-second static posture trial with the subject in the standard anatomical position was captured for use in the analysis.

2.5.2. Experimental tasks

Two sets of experimental tasks were performed in this research, ingress/egress tasks and planar reach tasks. First, the participant performed ingress/egress tasks with a seat mounted in three different orientations: horizontal with a 90° seat angle (H90), horizontal with a 120° seat angle (H120), and vertical with a 90° seat angle (V). In an effort to control variation, participants performed the ingress/egress tasks following step-by-step progressions. During ingress of the horizontal seats, the participants began by lying supine to the left of the seat with their hands on their abdomen. When prompted to begin the task, the participant performed the ingress task following the progression depicted in Fig. 3. The participant was then prompted to egress, which followed the reverse of the ingress progression. During ingress of

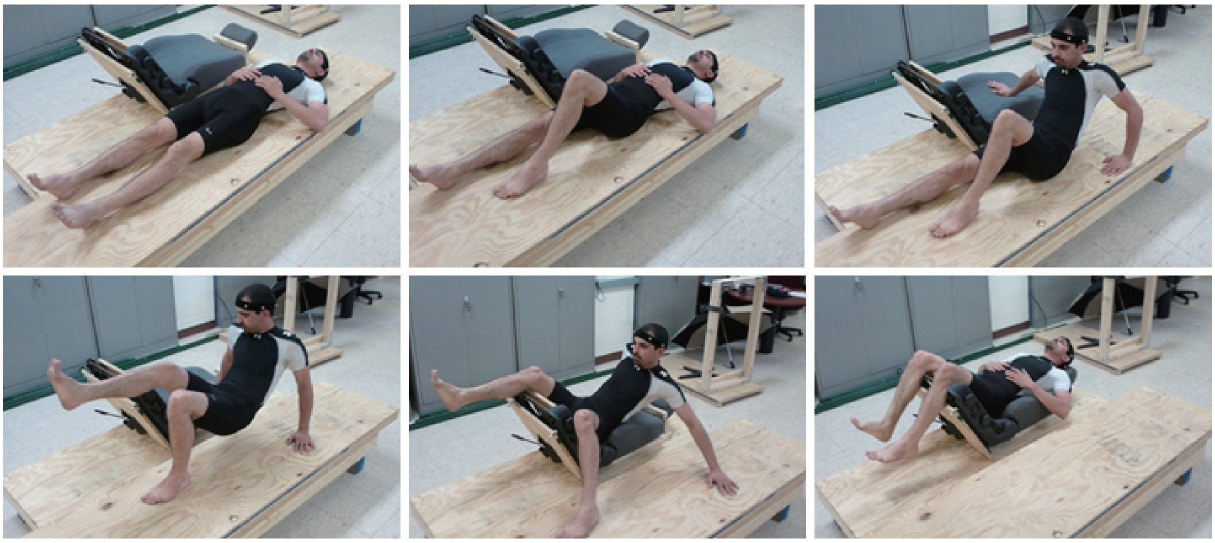


Fig. 3. Progression used to ingress into the horizontal seats. Egress followed the reverse of this progression. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/OER-140213)

the vertical seat, the subject began by standing to the left of the platform with the hands on the abdomen. When prompted to begin, the participant moved the right foot and body in front of the seat, then lowered the pelvis into the seat and returned the hands to the abdomen. The participant was then prompted to egress, which was done using the reverse of the ingress progression. Each trial was repeated three times, the order of the tasks was randomized, and subjects were given sufficient time to rest between tasks.

The planar reach tasks were performed in H90 and V seat orientations. In these tasks, the participant was instructed to move the extended arm through its full range of motion in each of the three anatomical planes (frontal, sagittal, and transverse). For each reach task, two trials were completed with each arm.

2.5.3. *Data processing*

Data collected from the two sets of experimental tasks underwent different processing techniques. However, for both sets of experimental tasks, the initial data processing occurred in Vicon Nexus. Within Vicon Nexus, each dynamic trial was processed by first labeling each marker with its unique identifier (i.e. RELB for right elbow). Gaps in the marker data were filled using the built-in gap-filling algorithms in Vicon Nexus and the data was exported for further processing.

After the ingress/egress trials were processed in Vicon Nexus, the static trial was used to create a model of the participant in C-Motion Visual3D. Each body segment is modeled based on markers on the endpoints of the segment as well as additional tracking markers on each segment [17]. Each segment is assigned a local XYZ coordinate frame that follows the right-hand rule with the Z-axis following the length of the segment. The resulting model was applied to each dynamic trial to produce a fully-modeled representation of the subject performing each task. In-built functionality of the Visual3D software allowed the computation of frame-by-frame, three-dimensional joint angles of the hips, knees, shoulders, and trunk by performing Euler angle calculations between the local coordinate frames of the relevant segments. Angle data was used to determine the peak angles and ranges of motion.

After the reach data were processed in Vicon Nexus, the trajectories of the finger and clavicle markers were extracted from the full marker data. In each reach task, the movement was only along 2 axes, therefore the third coordinate was ignored. The remaining data was transformed such that the clavicle was at

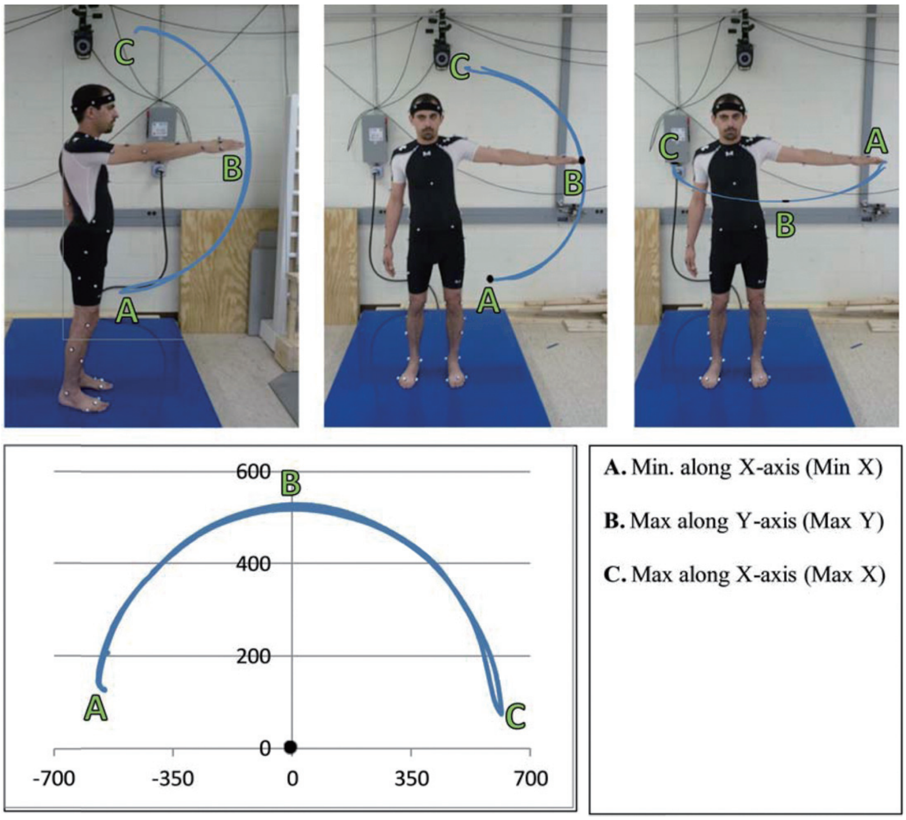


Fig. 4. Top: Extreme point definitions for each of the anatomical planes (left to right: sagittal, frontal, and transverse). Bottom: Example plot of transformed reach task data. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/OER-140213)

the origin (0,0) in each frame. The data from the finger marker was transformed such that, when plotted, the resulting plot was parabolic opening downward with the starting position on the left. After performing this transformation, three extreme values (minimum and maximum values along the horizontal axis and maximum value along the vertical axis) were extracted and used in the analysis. Figure 4 shows the definitions of the three extreme points for each anatomical plane and an example plot of transformed data for a planar reach task.

2.5.4. Statistical analysis

A two-way ANOVA (analysis of variance) was performed to test the effect of seat orientation (H90, H120, V90) and direction of motion (ingress, egress) on the peak joint angles and ranges of motions. Seat orientation and direction of motion were treated as the fixed effects and participants as a random factor. Effect of seat orientation on reach was also assessed using two-way ANOVA. Seat orientation and the anatomical plane (frontal, sagittal, transverse) of motion were treated as the fixed effects and participants as a random factor. Normality of data was verified using Kolmogorov-Smirnov's normality test and the equal variance assumption was verified using Lavene's test. Significance level was set to 95%. Significant main and/or interaction effects were further evaluated by conducting comparison between means using Tukey's HSD all-pairwise comparison test. All analyses were performed using Minitab statistical software (Minitab Inc., State College, PA).

Table 1
Main effect of seat orientations on the peak joint angle (P) and range of motion (ROM). Numbers in parenthesis represent one standard deviation

	Motion	Seat Orientation – Mean° (SD)			p-Value
		Horiz. 120°	Horiz. 90°	Vertical	
Trunk	Flexion (P)	62.96 (14.54)	67.32 (14.13)	43.36 (16.78)	**0.000***
	Right Lateral Bending (P)	8.68 (4.81)	14.40 (8.57)	7.58 (3.37)	**0.000***
	Left Lateral Bending (P)	23.09 (6.48)	16.34 (6.34)	4.33 (3.30)	**0.000***
	Lateral Bending (ROM)	31.77 (6.97)	30.74 (7.69)	11.90 (3.56)	**0.000***
	Right Rotation (P)	9.42 (7.08)	10.00 (7.18)	7.50 (4.80)	0.494
	Left Rotation (P)	22.41 (5.72)	19.73 (6.31)	6.33 (2.81)	**0.000***
	Rotation (ROM)	31.83 (9.38)	29.73 (7.58)	13.83 (4.51)	**0.000***
Right shoulder	Flexion (P)	33.96 (20.68)	36.30 (18.42)	−4.44 (16.58)	**0.000***
	Extension (P)	62.78 (15.81)	61.29 (17.54)	24.28 (11.15)	**0.000***
	Flexion/Ext. (ROM)	96.74 (27.24)	95.16 (23.99)	19.84 (17.12)	**0.000***
	Abduction (P)	63.81 (9.11)	64.02 (11.17)	30.50 (6.33)	**0.000***
	Adduction (P)	1.97 (9.93)	1.53 (9.83)	−13.50 (7.41)	**0.000***
	Abd./Add. (ROM)	65.78 (12.41)	65.56 (12.20)	17.00 (7.75)	**0.000***
	Internal rotation (P)	44.90 (17.30)	46.99 (19.57)	24.24 (16.93)	**0.000***
	External rotation (P)	44.01 (25.62)	42.58 (24.64)	1.02 (17.59)	**0.000***
	Rotation (ROM)	88.91 (29.21)	86.82 (28.29)	25.26 (13.00)	**0.000***
Left shoulder	Flexion (P)	12.55 (15.62)	13.10 (14.84)	−2.37 (15.72)	**0.000***
	Extension (P)	61.71 (11.41)	64.97 (10.53)	23.32 (7.68)	**0.000***
	Flexion/Ext. (ROM)	74.42 (17.53)	79.16 (19.23)	20.95 (15.76)	**0.000***
	Abduction (P)	64.43 (13.41)	64.65 (12.67)	35.24 (6.61)	**0.000***
	Adduction (P)	−2.62 (7.73)	−0.97 (7.43)	−18.44 (7.75)	**0.000***
	Abd./Add. (ROM)	61.81 (17.46)	63.68 (15.22)	16.80 (7.45)	**0.000***
	Internal rotation (P)	26.58 (23.26)	25.36 (21.05)	21.58 (22.46)	**0.004***
	External rotation (P)	53.21 (31.63)	54.59 (23.84)	3.48 (20.45)	**0.000***
	Rotation (ROM)	75.38 (20.67)	79.01 (18.57)	25.06 (13.93)	**0.000***
Right hip	Flexion (P)	65.63 (12.51)	74.91 (16.75)	64.07 (16.32)	**0.000***
	Abduction (P)	17.09 (10.26)	18.63 (11.71)	20.83 (4.56)	0.162
	Internal rotation (P)	2.96 (8.99)	4.04 (9.51)	−0.87 (8.57)	**0.006***
	External rotation (P)	22.27 (10.75)	23.14 (11.50)	22.31 (9.16)	0.273
	Rotation (ROM)	25.24 (8.05)	27.18 (8.74)	22.70 (8.70)	**0.001***
Left hip	Flexion (P)	61.06 (12.12)	68.29 (15.29)	66.19 (15.78)	**0.000***
	Abduction (P)	40.86 (6.59)	39.91 (6.73)	24.89 (5.41)	**0.000***
	Internal rotation (P)	10.58 (13.80)	11.44 (15.15)	0.75 (15.17)	**0.000***
	External rotation (P)	21.70 (15.56)	21.75 (15.73)	21.94 (16.94)	0.388
	Rotation (ROM)	32.28 (9.67)	33.19 (9.84)	22.69 (7.81)	**0.000***
Right knee	Flexion (P)	83.17 (16.95)	91.43 (14.81)	85.71 (9.12)	**0.000***
	Internal rotation (P)	25.96 (10.67)	28.72 (13.38)	20.91 (8.14)	**0.000***
	External rotation (P)	21.00 (8.88)	20.61 (8.90)	10.69 (10.75)	**0.000***
	Rotation (ROM)	46.90 (12.14)	49.33 (13.30)	31.60 (12.31)	**0.000***
Left knee	Flexion (P)	107.30 (14.85)	108.12 (16.98)	82.45 (7.37)	**0.000***
	Internal rotation (P)	30.13 (11.14)	32.90 (13.36)	22.76 (12.57)	**0.000***
	External rotation (P)	17.73 (12.89)	19.12 (9.41)	5.09 (10.50)	**0.000***
	Rotation (ROM)	47.86 (14.31)	52.02 (17.05)	27.85 (7.94)	**0.000***

3. Results

3.1. Ingress/Egress

There were 43 dependent variables included in the ingress/egress analysis. Seat orientation played a major role in the kinematics of ingress/egress, significantly effecting 39 of the 43 kinematic variables ($p < 0.01$; see Table 1). Except, right rotation of the trunk ($p = 0.494$), abduction ($p = 0.162$) and

Table 2
Main effect of direction of motion on the peak joint angle (P) and range of motion (ROM). Numbers in parenthesis represent one standard deviation

	Motion	Direction of Motion – Mean ° (SD)		p-Value
		Ingress	Egress	
Trunk	Flexion (P)	60.06 (17.41)	58.03 (18.65)	0.300
	Right Lateral Bending (P)	9.10 (5.02)	11.89 (8.15)	**0.000***
	Left Lateral Bending (P)	16.10 (9.39)	14.52 (9.37)	**0.016***
	Lateral Bending (ROM)	25.20 (10.38)	26.41 (11.38)	0.245
	Right Rotation (P)	10.23 (6.87)	7.93 (6.15)	**0.037***
	Left Rotation (P)	16.30 (8.30)	17.50 (8.84)	0.607
	Rotation (ROM)	26.53 (12.05)	25.44 (9.33)	0.215
Right shoulder	Flexion (P)	29.28 (26.23)	18.54 (24.49)	**0.000***
	Extension (P)	53.56 (25.47)	49.18 (19.78)	**0.031***
	Flexion/Ext. (ROM)	80.81 (44.80)	67.72 (37.40)	**0.000***
	Abduction (P)	56.27 (18.41)	52.73 (16.82)	**0.002***
	Adduction (P)	−1.36 (12.15)	−3.75 (10.69)	**0.023***
	Abd./Add. (ROM)	54.91 (25.98)	48.97 (22.91)	**0.000***
	Internal Rotation (P)	43.72 (21.51)	35.85 (18.68)	**0.000***
	External Rotation (P)	35.91 (31.36)	26.76 (27.90)	**0.001***
	Rotation (ROM)	77.45 (41.16)	62.61 (32.93)	**0.000***
Left shoulder	Flexion (P)	7.55 (16.46)	9.35 (17.15)	0.473
	Extension (P)	48.67 (17.83)	55.19 (23.46)	**0.000***
	Flexion/Ext. (ROM)	56.90 (28.15)	64.80 (33.63)	**0.001***
	Abduction (P)	50.45 (13.47)	62.30 (19.21)	**0.000***
	Adduction (P)	−8.65 (8.85)	−4.22 (11.94)	**0.000***
	Abd./Add. (ROM)	41.80 (18.32)	58.08 (28.57)	**0.000***
	Internal Rotation (P)	24.96 (21.40)	24.43 (23.14)	0.652
	External Rotation (P)	30.11 (28.09)	49.55 (37.69)	**0.000***
	Rotation (ROM)	55.07 (23.72)	69.85 (33.92)	**0.000***
Right hip	Flexion (P)	67.58 (16.96)	69.68 (14.83)	0.415
	Abduction (P)	16.08 (7.47)	21.40 (10.99)	**0.000***
	Internal Rotation (P)	2.97 (9.89)	1.66 (8.54)	0.169
	External Rotation (P)	21.44 (10.75)	23.82 (10.32)	**0.004***
	Rotation (ROM)	25.04 (10.47)	25.48 (6.21)	0.270
Left hip	Flexion (P)	64.75 (14.15)	65.60 (15.25)	0.914
	Abduction (P)	34.58 (8.54)	37.50 (10.07)	**0.007***
	Internal Rotation (P)	8.82 (15.18)	7.42 (15.53)	0.474
	External Rotation (P)	21.33 (15.79)	22.26 (16.13)	0.406
	Rotation (ROM)	30.15 (10.79)	29.68 (9.75)	0.927
Right knee	Flexion (P)	86.36 (14.42)	87.53 (15.06)	0.386
	Internal Rotation (P)	24.88 (10.54)	26.32 (12.52)	0.189
	External Rotation (P)	17.68 (11.07)	18.29 (9.79)	0.368
	Rotation (ROM)	42.51 (14.50)	44.61 (14.78)	0.099
Left knee	Flexion (P)	106.96 (17.22)	94.10 (16.63)	**0.000***
	Internal Rotation (P)	27.56 (11.15)	30.64 (14.56)	0.071
	External Rotation (P)	13.94 (11.72)	15.45 (13.34)	**0.039***
	Rotation (ROM)	41.50 (16.40)	46.09 (17.86)	**0.003***

external rotation ($p = 0.273$) of the right hip, and external rotation ($p = 0.388$) of the left hip, the motions of the other segments were significantly affected by the seat orientation. Minor differences were found between kinematics during ingress/egress of the H90 and H120 seats, however the peak angles and ranges of motion were generally lowest in the vertical seat, with the following peak angles as exceptions: right hip abduction and external rotation, left hip flexion and external rotation, and right knee flexion. All analyzed ranges of motion were the lowest in the vertical seat and very large differences were observed for the trunk (16°–24°) and shoulders (45°–77°) between the vertical and horizontal seats.

Table 3
Main effect of seat orientation and anatomical plane on planar reach. Values are mean (SD) reach distance in millimeters of extreme points of planar reach

		Seat orientation		Anatomical plane			P-value	
		Horizontal	Vertical	Frontal	Sagittal	Transverse	Seat	Plane
Right	Min X	647.4 (108.7)	653.6 (91.0)	584.24 (48.53)	591.98 (51.00)	775.52 (37.84)	0.482	**0.000***
	Max X	538.5 (134.7)	524.6 (150.9)	631.00 (56.37)	614.76 (59.18)	346.33 (55.77)	0.16	**0.000***
	Max Y	629.7 (116.4)	609.4 (121.9)	774.27 (39.95)	531.92 (51.06)	548.15 (34.88)	**0.000***	**0.000***
Left	Min X	639.2 (106.2)	628.9 (109.9)	572.47 (45.51)	562.61 (57.04)	774.03 (36.41)	0.074	**0.000***
	Max X	544.1 (135.5)	546.0 (146.1)	637.67 (51.33)	623.73 (59.51)	359.90 (71.70)	0.35	**0.000***
	Max Y	610.7 (118.5)	620.2 (112.9)	766.16 (40.76)	533.59 (38.32)	543.00 (39.59)	0.054	**0.000***

The effect of the direction of motion (ingress vs. egress) was also analyzed for the 43 dependent kinematic variables. Direction of motion had a significant effect on 25 of the 43 kinematic variables (Table 2). Overall, direction of motion had the largest effect on the kinematics of the shoulders, significantly affecting all kinematic variables of the shoulders and all except peak flexion and internal rotation of the left shoulder. Kinematics of the trunk, left and right hips, and left knee were also affected, but to a lesser degree, while the right knee kinematics were unaffected by direction of motion. Of the dependent variables that were significantly affected by direction of motion, the peak angles and ranges of motion were higher during ingress than egress.

Additionally, the interaction of seat orientation and direction of motion played a significant role in 12 of the 31 peak joint angles and 7 of the 12 ranges of motion. The interaction effect charts have been split into two figures. Figure 5 shows the interaction effect on peak angles that have a corresponding range of motion variable, while Fig. 6 shows the interaction effect on peak angles that do not have a corresponding range of motion. Interaction of seat orientation and direction of motion was most significant in the shoulder kinematics, with only the following 4 of the 18 shoulder kinematic variables showing no significant interaction effect: left shoulder flexion and internal rotation and right shoulder abduction and adduction. Additionally, an interaction effect was also found on left and right peak lateral bending of the trunk, left peak hip flexion and abduction and left hip rotation range of motion.

3.2. Reach

Effect of seat orientation and anatomical plane on the three extreme points (Min X, Max X, Max Y) for the right and left arm were analyzed (Fig. 7, Table 3). Reach capacity was affected significantly by anatomical plane ($p < 0.001$). Reach, however, was affected minimally by the seat orientation, with an effect only on Max Y of the right arm, showing a small ($\sim$20 mm), yet significant, increase in reach in the horizontal seats. Additionally, a significant interaction between anatomical plane and seat orientation was found for Max X and Max Y of the right arm, both showing a decreased reach in the sagittal plane while in the horizontal seat.

4. Discussion

This study, for the first time, evaluated and compared the ingress/egress kinematics and the reach for the horizontal seat with a standard upright seat. Overall, the seat orientation was found to have a drastic effect on the ingress/egress kinematics. The direction of motion (ingress vs. egress) affected kinematics of fewer joints, but showed interesting trends between right and left sides. For the planar reach, effect of seat orientation was minimal. However, major differences were observed in the reach between the anatomical planes.

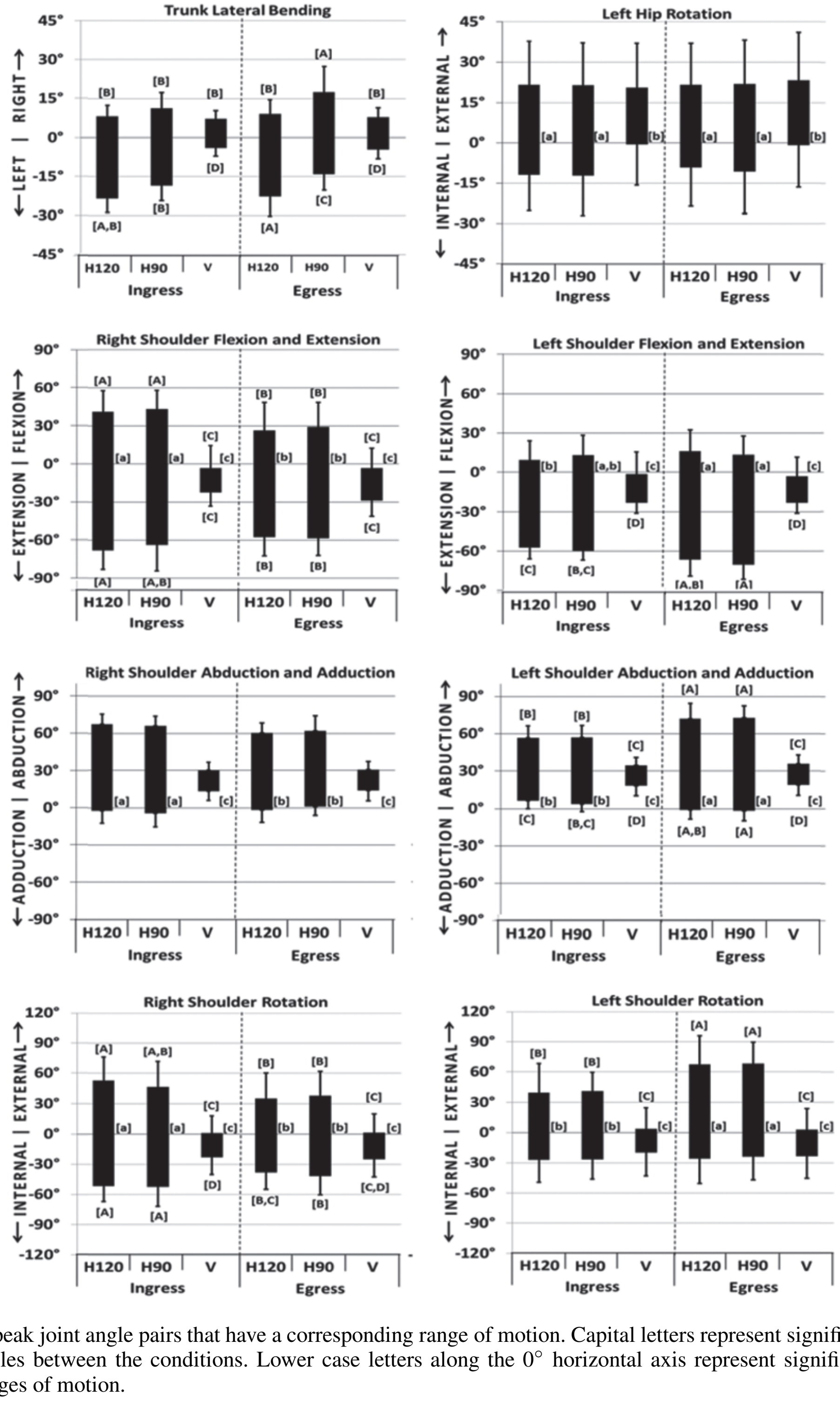


Fig. 5. Plots of peak joint angle pairs that have a corresponding range of motion. Capital letters represent significant differences of the peak angles between the conditions. Lower case letters along the 0° horizontal axis represent significant differences between the ranges of motion.

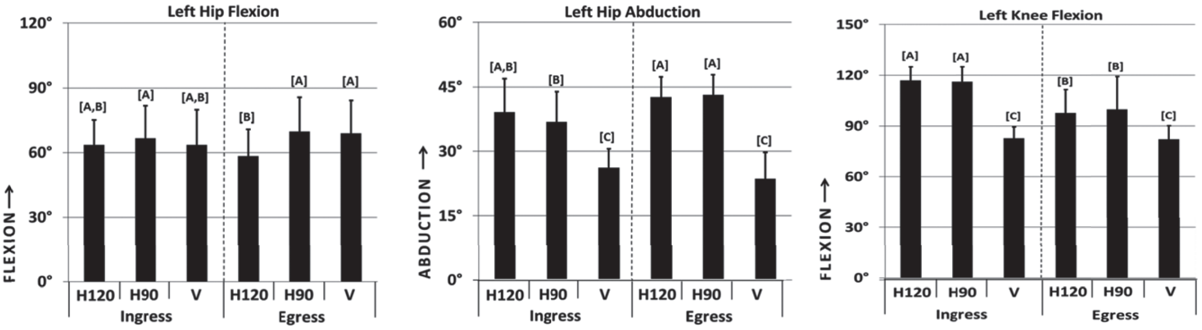


Fig. 6. Interaction plots of peak joint angles that do not have a corresponding range of motion. Capital letters represent significant differences between the conditions.

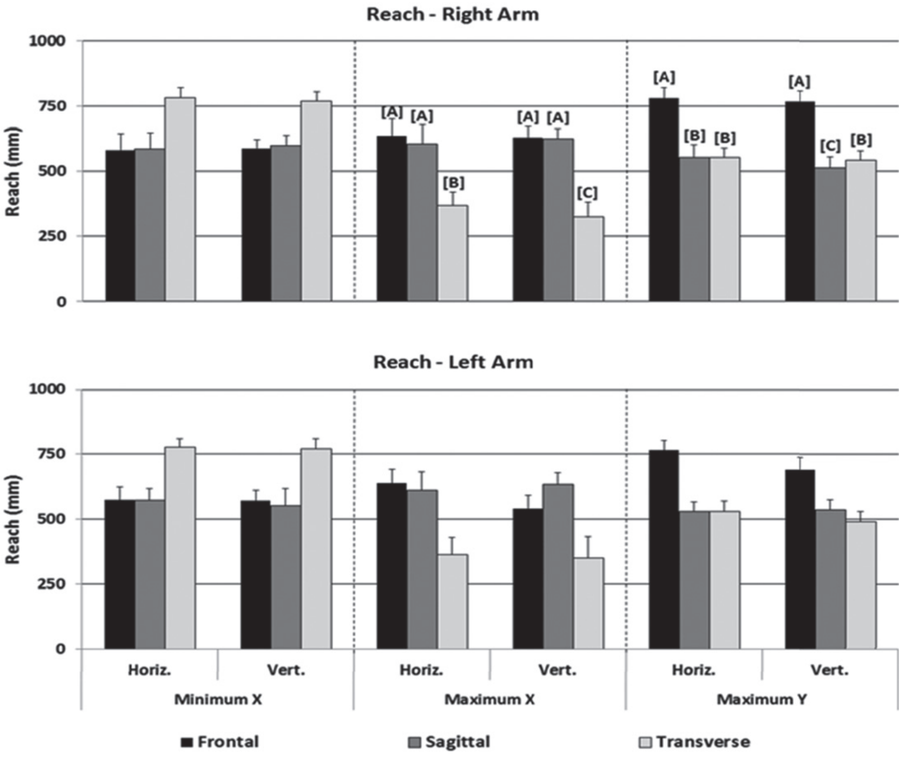


Fig. 7. Plot of extreme points of planar reach for the right and left arms. Capital letters above the bars represent significantly different values due to interaction effect.

4.1. Ingress/Egress

The seat orientation affected the kinematics of the upper body to a greater extent than the lower body. During ingress/egress of a standard vertical seat, the lower body joints (hip and knee) initiate and sustain most of the motion while the upper body (trunk and shoulder) plays a supporting role. However, during ingress/egress of the horizontal seat, a much more active role by the upper body joints was observed.

The peak angles and ranges of motion of the trunk and shoulder joints during ingress/egress of the horizontal seat were significantly higher than the vertical seat, often by a factor of 3 or 4. Furthermore, some of the trunk and shoulder motions involved in the ingress/egress of the horizontal seat required use of awkward postures. The peak trunk flexion and shoulder extension greater than 60°; trunk bending and rotation ROM of about 30°; and, shoulder rotation ROM of about 80°; was observed during ingress/egress of the horizontal seat.

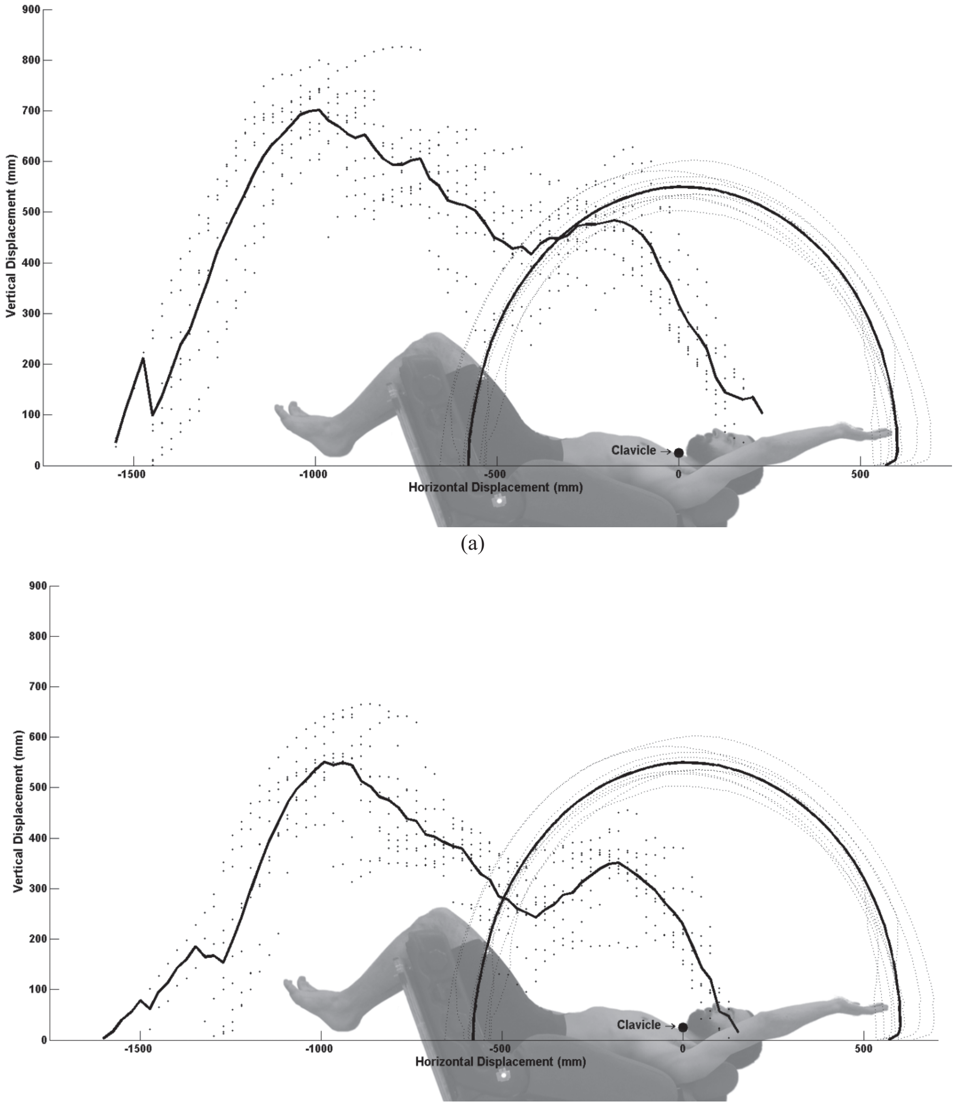
In addition to the increased motion requirement, the need to lift and transfer trunk and pelvis in and out of the horizontal seat may require a greater force exertion by the shoulders and lower back. While the force exertion and the resulting musculoskeletal loading during ingress/egress of horizontal spacecraft seats may not be an issue in weightless conditions, it may increase risk of injuries during the ground trainings. Astronauts undergo intensive ground training in preparation for space travel [18]. During the training, they perform multiple ingress/egress trials while suited in gravity conditions. Suited conditions further aggravate the musculoskeletal demands because of the suit weight and kinematic mismatch between body and suit. Altogether, the findings of this study seem to suggest that the horizontal ingress and egress motions are stressful for the shoulders and lower back.

In this study, participants performed ingress tasks beginning to the left of the seat, and returned to the left side of the seat during egress. Kinematics of the lower body and trunk showed interesting trends due to ingress from the left. The most notable difference was found in abduction of the hip, where left hip angles were nearly double the right hip angles during ingress/egress of the horizontal seats. Left rotation and left lateral bending of the trunk and flexion of left knee were also much more prominent than the corresponding motions of the right side during ingress/egress of the horizontal seats. The higher motion requirement by one side of the body indicates that the direction of motion plays an important role in the horizontal ingress/egress motions and may attribute to excessive unilateral loading during repeated exertions.

4.2. Planar reach

Surprisingly, there was no significant effect of seat orientation on the maximal planar reach. A decrease in the reach for the horizontal seat was hypothesized due to the effect of gravity and weight of the arm. However, by securing the trunk to the vertical seat during the reach tasks, the effect of gravity may have been negated. However, the anatomical plane had a significant effect on the maximal planar reach. The majority of the motion during the reach tasks was handled by the shoulder, while the elbow remained straight. However, in the transverse plane, the shoulder quickly reaches a barrier and the elbow must be bent, decreasing reach across the body. Therefore, the value for this extreme point (Max X) was drastically lower than for the other anatomical planes. This is in agreement with the findings of Sengupta et al. [14]. In the research by Sengupta et al. [14], reach was determined based on radial vectors from a table reference point at 15 cm intervals above table level, which showed that reach across the body (Max X in our research) was significantly lower than forward and lateral reach (Max Y and Min X in our research).

The maximal planar reach for Max Y was found to be much lower in the sagittal plane than the frontal plane. A possible explanation is the shoulder's ability to translate anterioposteriorly (forward and backward) and vertically at the glenohumeral joint. When performing a reach task in the frontal plane, the translation of the shoulder has no effect on the reach, as the shoulder does not have the ability to translate mediolaterally. However, when reaching in the sagittal plane, the ability of the shoulder to translate can have a drastic effect. For example, if the shoulder is translated posteriorly during a sagittal reach task, Max Y would be less than if the shoulder were translated anteriorly. During this research, participants were instructed to move their fully extended arm through the range of motion. The



(a)

(b)

Fig. 8. Ingress (a) and egress (b) plot for control placement guidance. Solid lines represent mean reach and mean ingress/egress volumes. Dashed parabolic line represents mean reach for individual participants. Points represent mean ingress/egress volume required for each user. To determine ingress/egress volume, marker data was stratified into 1 inch intervals and peak values were taken for each trial.

participants were not instructed to translate their shoulder in any certain manner; therefore it is possible that the subjects maintained a more posterior translation of the shoulder during the sagittal reaching task, not reflecting true maximal reach.

4.3. Control placement and other recommendations

For a typical workstation with an upright seat, the seats are either adjustable or, minimally, can be moved inward and outward to allow easier ingress/egress. However, for workstation with horizontal seats space is usually a major concern; therefore the seats are not adjustable making control placement an important consideration. Figure 8 provides some basic control placement guidance for workstations with a horizontal seat. Controls should not be placed in an area that will hinder ingress/egress, but should remain within the available reach area. While the area available for appropriate control placement is limited, with consideration during the design process, it is possible to create a workstation that will allow easy ingress/egress while keeping the controls both within view and within reach.

There are several limitations to this research that need to be acknowledged. The analysis only looked at peak angles and ranges of motion, which provides no information on the overall movement of the body. For example, if the knee begins at 45° flexion, is flexed to 90° degrees, and is extended back to 45° flexion, the additive range of motion would be 90° while our analysis would report a range of motion of 45°. Additionally, ingress/egress was only performed from the left side of the seat. While some drastic differences between the kinematics of the left and right side of the body exist, we have no evidence that these differences are due entirely to the direction of ingress/egress. During this research, an automobile seat was mounted on custom platforms. Typically, horizontal seats often have a flat seat-back, while the automobile seat used in this research was equipped with several back/body support features that are not typical of horizontal seats. In addition to the unsuited condition of the participants, these two factors make this research less representative of a spacecraft cabin. Finally, only males were recruited for this research. Females typically have lower upper body strength and weight than males, which could cause significant differences in ingress/egress kinematics, reach, and ability to perform horizontal ingress/egress.

5. Conclusions

While only a few significant differences were observed for the effect of seat orientation on maximal reach, ingress/egress kinematics of the joints tested in this study were significantly affected by seat orientation. Ingress/egress of horizontal seats, in general, required higher joint angles and ranges of motion than vertical seats. In addition, horizontal ingress/egress required the trunk and shoulder joints to balance the upper body weight in various awkward postures. The direction of horizontal ingress/egress also affected the motions requirements, putting higher demand on one side of the body than the other. As a whole, this research suggests that the use of horizontal seats is more stressful for the body than regular upright seats. Therefore, when repeated ingress/egress of horizontal seats is necessary, it is important to provide sufficient rest between the exertions and also vary the side of entry to avoid excessive unilateral loading.

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